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A Survey for Cognitive Radio Networks

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Abstract— **The rapid growth in wireless communications has contributed to a huge demand on the deployment of new wireless services in both the licensed and unlicensed frequency spectrum. Cognitive radio (CR) is the enabling technology for supporting dynamic spectrum access: the policy that addresses the spectrum scarcity problem that is encountered in many countries. The fundamental task of each CR user in CR networks, in the most primitive sense, is to detect the licensed users, also known as primary users (PUs), if they are present and identify the available spectrum if they are absent. This is usually achieved by sensing the RF environment, a process called spectrum sensing. Spectrum sensing is a key function of cognitive radio to prevent the harmful interference with licensed users. Many factors in practice such as multipath fading, shadowing, and the receiver uncertainty problem may significantly compromise the detection performance in spectrum sensing. In this paper overview of cognitive radio and the CR network architecture is provided. Then main challenges of spectrum management are discussed. We highlight some of the recent information theoretic limits, models, and design of these promising networks. Moreover, a survey of cooperative sensing is provided to address the issues of cooperation method, cooperative gain, and cooperation overhead.**

Index Terms– **Cognitive Radio, Spectrum Sensing, Primary Users, Spectrum Management and Cooperative Sensing**

I. INTRODUCTION

COGNITIVE radio systems basically consist of primary (licensed) and secondary (unlicensed-cognitive) users, secondary users continuously check the frequency bands to determine if there is a primary user transmitting, if not, the band is available and the secondary user can start transmitting its own data. These spectrum holes can occur in two ways, in time or in space. When a primary user is not transmitting at a given time, then there’s a temporal spectrum hole Fig. 1, If a primary user is transmitting in a certain portion of the spectrum at a given time but it is too far away from the secondary user so that the secondary user can reuse the frequency, then a spatial spectrum hole exists.

Dynamic spectrum access is cognitive radio’s most important application, which promises to overcome the apparent spectrum scarcity problem caused by the rigid spectrum allocation and the underutilization of the spectral resources. In the context of dynamic spectrum access, a more pertinent definition of a cognitive radio: Cognitive Radio is defined as an intelligent wireless communication system that is aware of its surrounding environment 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: One: highly reliable communication whenever and wherever needed, Second: efficient utilization of the radio spectrum.

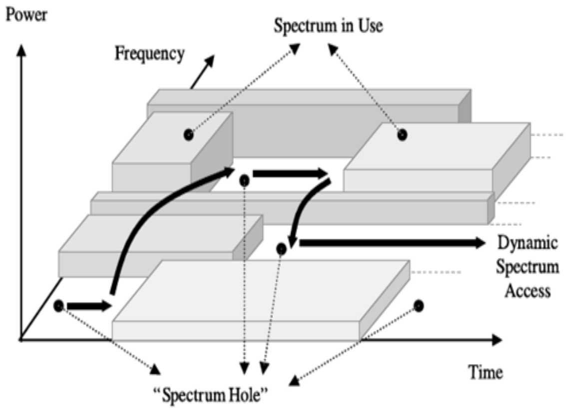

Figure 1. Spectrum hole

The CR is able to make discoveries about its surrounding RF environment by sensing and detecting the spectrum holes that have been left unoccupied by their licensed users. In addition to the task of sensing and detecting holes, the receiver is responsible for the channel estimation. The transmitter adapts its transmission parameters based on the received information from the receiver, and has two targets: to optimize the use of the available holes and not to interfere with the PR. Fig. 2 shows the CR cycle.

Based on the Fig. 2, it is clear that the main difference between CR’s cycle and the traditional radio cycle is the spectrum sensing and its relevant missions in CR. It can be called the backbone of the CR‟s cycle. Spectrum sensing is performed at the physical layer, and can be managed through different upper layers as Medium Access Control layer (MAC) in centralized CR network.

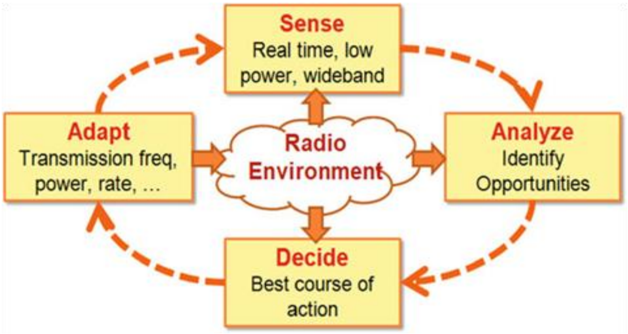

Figure 2. Cognitive Cycle

The main functions of a cognitive radio can be addressed as follows [1], [2]:

- Spectrum sensing is the process of a cognitive radio sensing the channel and determining if a primary user is present, detecting the spectrum holes.
- Spectrum management is selecting the best available channel (for a cognitive user) over the available channels.
- Spectrum sharing is the allocation of available frequencies between the cognitive users.
- Spectrum mobility is the case when a secondary user rapidly allocates the channel to the primary user when a primary user wants to retransmit again.

The rest of this paper is organized as follows: Section II presents evolution and basic issues of cognitive radio. Section III describes popular detection technique. Section IV concludes this paper.

II. COGNITIVE RADIO EVOLUTION AND BASIC ISSUES

A. *Cognitive Rradio Definition*

The term cognitive radio has been coined by Mitola as “an intelligent radio which is aware of its surrounding environment and capable of changing its behavior to optimize the user experience” [3].

CR is an intelligent radio system able to be aware of its surrounding RF environment by using advanced sensing techniques to decide whether there are unoccupied spectrum portions (holes) available; it then changes its transmitting parameters (modulation type, transmission power, bandwidth, carrier frequency) to opportunistically exploit the unused spectrum band. The definition above is called the capability of CR, which is one of the main features of CR. Thus, the capability here means the ability to be aware, adaptive, reliable, efficient, intelligent, and learnable [4]. The learnable word is the ability that CR makes current decision based on the last decisions and the prediction from the history and the mistakes toward effective use of the spectrum holes. Another main feature of CR is the reconfigurability, which can be achieved by using a physical unit for CR. This would allow CR to cover a wide band range in tasks of sensing and communications [4]. Furthermore, as the CR decides which carrier frequency, bandwidth, transmitted power, modulation scheme that will be used in communications to adaptively use the free spectrum toward a given Quality of Services (QoS) achievement, the transmission parameters can be simply modified by tuning the software. Based on these definitions, the main objectives of CR’s development are defined, based on [4], as follows:

- To improve the spectrum efficiency by opportunistically exploiting the unused spectrum portions (holes) at a specific time and location.
- To provide reliable communications at any time, and any place.

The spectrum hole is found by locating specific times or geographical locations not being used by the PR user; it can be used opportunistically at these times and locations by CR users. As CR scans a wide range of spectrum and defines the spectrum holes and adaptively uses them without interfering to the PRs, a more efficient use of spectrum can be achieved and more bandwidth is made available for different wireless services. Therefore, the applications of CR are classified into three categories based on [5], as follow:

- Military applications: Using CR in military wireless communications systems provides more dynamic use of the spectrum that would support the military, by exploiting the underutilized spectrum portions at any time and location. Therefore, in addition to the secure communications; the military will be able to have adaptive and continues communications anywhere [6].
- Public Safety: The infrastructure based communications systems are not robust when disasters or terrorist attacks happen. Therefore, public safety in emergency situations needs to use a system that can detect the spectrum holes and operate in different frequencies, transmission schemes, and bandwidths. Additionally, public safety will be able to contact other different communication systems (i.e., interoperability) when CR is used.
- Commercial and civil sector: more spectrum bandwidths will be available at any time, and any location when CR is used. This would increase the wireless communication networks that provide different services, such as voice, data, video, and images for different sectors. Additionally, such an intelligent system alleviates the complicated tasks within the spectrum management in national and international agencies.

Spectrum sensing:

Spectrum sensing in CR is the technical way that allows scanning of the surrounding RF environment and defines the spectrum holes that can be used opportunistically by CR. Very simply; CR asks spectrum sensing techniques to define the free spectrum portions so as to be adaptively used. However, this simple question introduces different technical aspects and challenges in CR communication systems. Basically, the spectrum sensing in the CRs is classified into:

- The detection of the power leakage that is being emitted from local oscillator (LO) of PR Rx that has been receiving data from the primary transmitter [7].

- The detection of the PR Tx transmitted signal. Recent researches have focused on the PR Tx transmitted signal detection due to the difficulty of the first kind of spectrum sensing, and the weakness of such emitted signals from the PR Rx .

Fig. 3 and Fig. 4 show a representative diagram where CR and PR networks are located in different areas and the frequency that is already licensed to be used by PR which can be used in the other regions at any time. CR here can use the licensed spectrum without interfering with the PR. [8], [9]. Thus, in Fig. 3, the geographical dimension plays the main role in the effective use of f PR.

PR’s transmitted signal can be sensed at the CR’s Rx, in three mains ways. Firstly, by estimating the received energy over a frequency band and catching the PR’s transmitted signal within this band; secondly, by correlating some parameters, which are statistically periodic and priori known at the CR Rx with the received signal, or, finally, by coherently detecting the PR’s signal by the CR Rx, which requires full knowledge about the PR’s signaling. Spectrum hole has been defined in [4] as: “A band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area”.

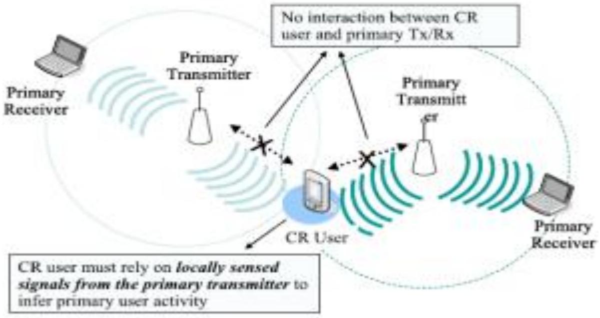

Figure 3. Spectrum sensing techniques transmitter detection

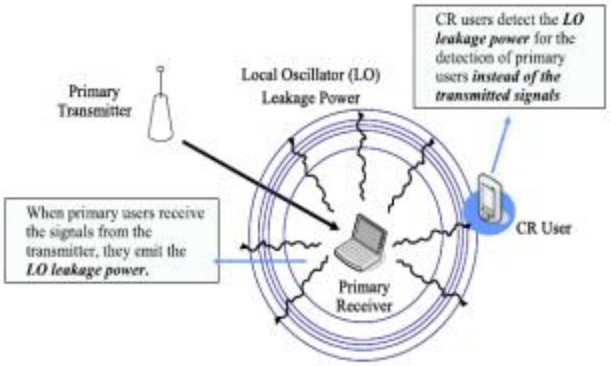

Figure 4. Spectrum sensing techniques receiver detection

Based on this definition, the spectrum hole, which is a frequency dimension, depends on two other dimensions: time and geographical area. This means that the discovered vacant band in a specific time might not be vacant after duration of time. Furthermore, the vacant frequency band in a specific area might not be vacant at another geographical area. In addition to frequency, time and geographical location, the PR’s Tx beam direction is found as another dimension in defining spectrum hole [10]. The different codes in spread spectrum (SS) technologies are also dimensions in defining a spectrum hole as [10]. The azimuth and elevation angles of the PR's beam and the location of PR Tx, are useful for CR communications when they are prior known to the CR user [10]. Prior knowledge of these parameters to the CR user would allow it to use the PR’s frequency band without causing interference. This can be achieved by changing the beam direction of CR Tx [10]. CR can share a PR that is based on SS technologies of the same frequency band and at the same time and same area.

The detected spectrum hole in Fig. 4 is classified as a temporal spectrum hole [11]. In this category, the spectrum hole can be used by CR in time dimension until the PR user claims it again. The CR then has to leave this spectrum hole for its licensed user-otherwise CR cannot exploit this spectrum hole. Another classification of spectrum hole is called spatial spectrum hole [11]. It is clear that under these assumptions, the CR Rx will not be able to sense the transmitted signal from PR Tx, this is because the signal cannot reach the CR Rx.

III. POPULAR DETECTION TECHNIQUES

Sensing techniques are crucial in cooperative sensing in the sense that how primary signals are sensed, sampled, and processed is strongly related to how CR users cooperate with each other. Thus, sensing techniques are one of the fundamental elements in cooperative sensing. The classification of Spectrum sensing techniques is shown in Fig. 5.

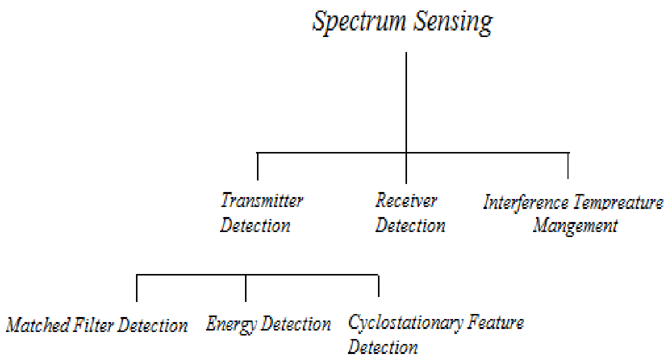

Figure 5. Spectrum sensing techniques

Transmitter Detection:

In transmitter detection, in order to distinguish between used and unused spectrum bands, CR users should have the capability to detect their own signal from a PU transmitter. The local RF observation used in PU detection sensing is based on the following hypothesis model:

$$r(t) = \begin{cases} n(t) & H_0, \\ h\, s(t) + n(t) & H_1 \end{cases}$$

Where r (t) is the signal received by the CR user, s(t) is the transmitted signal of the PU, n(t) is a zero-mean additive white Gaussian noise (AWGN) and h is the amplitude gain of the channel. H_0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band.

On the other hand, H_1 is an alternative hypothesis, which indicates that there exists some PU signal. Three schemes can be used for the transmitter detection in spectrum sensing: matched filter detection, energy detection, and feature detection [12].

a) Matched Filter Detection:

The matched filter is the linear optimal filter used for coherent signal detection to maximize the signal-to-noise ratio (SNR) As shown in Fig. 6, it is obtained by correlating a known original PU signal s(t) with a received signal r(t) where T is the symbol duration of PU signals. Then the output of the matched filter is sampled at the synchronized timing. If the sampled value Y is greater than the threshold k, the spectrum is determined to be occupied by the PU transmission.

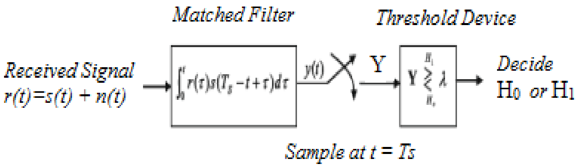

Figure 6. Block diagram of matched filter detection

This detection method is known as an optimal detector in stationary Gaussian noise. It shows a fast sensing time, which requires O (1/ SNR) samples to achieve a given target detection probability [12], [13]. However, the matched filter necessitates not only a priori knowledge of the characteristics of the PU signal but also the synchronization between the PU transmitter and the CR user. If this information is not accurate, then the matched filter performs poorly. Furthermore, CR users need to have different multiple matched filters dedicated to each type of the PU signal, which increases the implementation cost and complexity.

b) Energy Detection:

The energy detector is optimal to detect the unknown signal if the noise power is known. In the energy detection, CR users sense the presence/absence of the PUs based on the energy of the received signals. As shown in Fig. 7, the measured signal r(t) is squared and integrated over the observation interval T. Finally, the output of the integrator is compared with a threshold λ to decide if a PU is present [14].

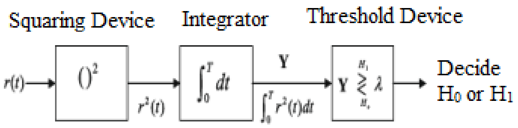

Figure 7. Block diagram of energy detection

While the energy detector is easy to implement, it has several shortcomings. The energy detector requires O (1/ SNR2) samples for a given detection probability [12], [13].

Thus, if CR users need to detect weak PU signals (SNR: _10 dB to _40 dB), the energy detection suffers from longer detection time compared to the matched filter detection. Furthermore, since the energy detection depends only on the SNR of the received signal, its performance is susceptible to uncertainty in noise power. If the noise power is uncertain, the energy detector will not be able to detect the signal reliably as the SNR is less than a certain threshold, called an SNR wall [15]. In addition, while the energy detector can only determine the presence of the signal but cannot differentiate signal types. Thus, the energy detector often results in false detection triggered by the unintended CR signals. For these reasons, in order to use energy detection, CRNs need to provide the synchronization over the sensing operations of all neighbors, i.e., each CR user should be synchronized with the same sensing and transmission schedules. Otherwise, CR users cannot distinguish the received signals from primary and CR users, and hence the sensing operations of the CR user will be interfered by the transmissions of its neighbors.

c) Feature (cyclostationary) detection:

Feature detection determines the presence of PU signals by extracting their specific features such as pilot signals, cyclic prefixes, symbol rate, spreading codes, or modulation types from its local observation. These features introduce built-in periodicity in the modulated signals, which can be detected by analyzing a spectral correlation function as shown in Fig. 8. The feature detection leveraging this periodicity is also called cyclostationary detection. Here, the spectrum correlation of the received signal r(t) is averaged over the interval T, and compared with the test statistic to determine the presence of PU signals, similar to energy detection [12].

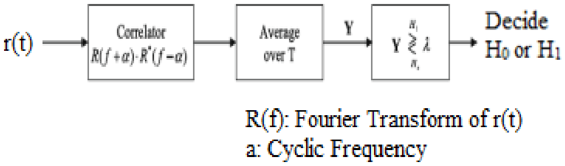

Figure 8. Block diagram of feature detection

The main advantage of the feature detection is its robustness to the uncertainty in noise power. Furthermore, it can distinguish the signals from different networks. This method allows the CR user to perform sensing operations independently of those of its neighbors without synchronization.

Interference Temperature Detection:

The interference temperature is defined to be the RF power measured at a receiving antenna per unit bandwidth. The key idea for this new metric is that, first, the interference temperature at a receiving antenna provides an accurate measure for the acceptable level of RF interference in the frequency band of interest; any transmission in that band is considered to be “harmful” if it would increase the noise floor above the interference temperature threshold as shown in Fig. 9. Second, given a particular frequency band in which the interference temperature is not exceeded, that band could be made available to secondary users. Hence, a secondary device might attempt to coexist with the primary, such that the presence of secondary devices goes unnoticed.

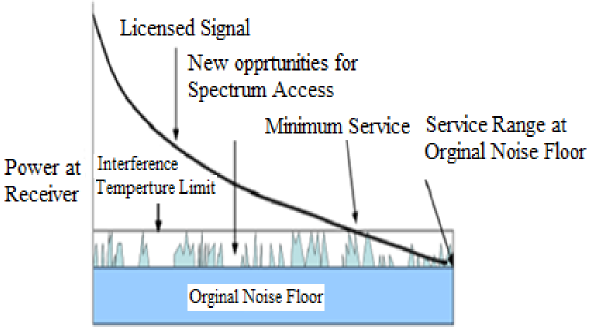

Figure 9. Interference temperature detection

Cooperative spectrum sensing detection:

Cooperation sensing is a proposed solution to the problems that arise during spectrum sensing like fading, shadowing and receiver uncertainty. It is expected that a large network of cognitive radios with sensing information exchanged with each other would have a better chance of detecting the primary user compared to individual spectrum sensing. The operation of this technique can be performed as follows [16]:

- Every CR calculates its own local spectrum sensing measurements independently through Sensing channels and then makes a binary decision (1or 0) on whether the PU is present or not.
- All of the CRs forward their decisions to a common receiver through reporting channels.
- The common receiver fuses the CR decisions using some fusion logic (Xoring or ORing) and makes a final decision to infer the absence or presence of the PU.

d) Advantages of cooperative spectrum sensing:

- Hidden node problem is significantly reduced.
- Increased in agility.
- Reduced false alarms
- More accurate signal detection

e) Disadvantages of cooperative spectrum sensing

Significant requirements of cooperative spectrum sensing are:

- Control Channel
- System Synchronization
- Suitable geographical spread of cooperating nodes.

f) Classification of cooperative sensing:

Cooperative sensing can be classified into three categories based on how cooperating CR users share the sensing data in the network: centralized, distributed, and relay-assisted. These three types of cooperative sensing are illustrated in Fig. 10 [17].

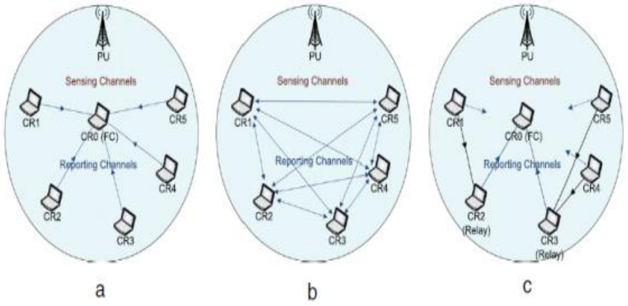

Figure 10. Classification of cooperative sensing: (a) centralized, (b) distributed, and (c) relay-assisted

In centralized cooperative sensing, a central identity called fusion center (FC) controls the three-step process of cooperative sensing. First, the FC selects a channel or a frequency band of interest for sensing and instructs all cooperating CR users to individually perform local sensing. Second, all cooperating CR users report their sensing results via the control channel. Then the FC combines the received local sensing information, determines the presence of PUs, and diffuses the decision back to cooperating CR users. As shown in Fig. 10 (a), CR0 is the FC and CR1– CR5 are cooperating CR users performing local sensing and reporting the results back to CR0. For local sensing, all CR users are tuned to the selected licensed channel or frequency band where a physical point-to-point link between the PU transmitter and each cooperating CR user for observing the primary signal is called a sensing channel. For data reporting, all CR users are tuned to a control channel where a physical point-to-point link between each cooperating CR user and the FC for sending the sensing results is called a reporting channel. Note that centralized cooperative sensing can occur in either centralized or distributed CR networks. In centralized CR networks, a CR base station (BS) is naturally the FC. Alternatively, in CR ad hoc networks (CRAHNs) where a CR BS is not present, any CR user can act as a FC to coordinate cooperative sensing and combine the sensing information from the cooperating neighbors [17].

Unlike centralized cooperative sensing, distributed cooperative sensing does not rely on a FC for making the cooperative decision. In this case, CR users communicate among themselves and converge to a unified decision on the presence or absence of PUs by iterations. Fig. 10 (b) illustrates the cooperation in the distributed manner. After local sensing, CR1–CR5 shares the local sensing results with other users within their transmission range. Based on a distributed algorithm, each CR user sends its own sensing data to other users, combines its data with the received sensing data, and decides whether or not the PU is present by using a local criterion. If the criterion is not satisfied, CR users send their combined results to other users again and repeat this process until the algorithm is converged and a decision is reached. In this manner, this distributed scheme may take several iterations to reach the unanimous cooperative decision.

In addition to centralized and distributed cooperative sensing, the third scheme is relay-assisted cooperative sensing. Since both sensing channel and report channel are not perfect, a CR user observing a weak sensing channel and a strong report channel and a CR user with a strong sensing channel and a weak report channel, for example, can complement and cooperate with each other to improve the performance of cooperative sensing. In Fig. 10 (c), CR1, CR4, and CR5, who observe strong PU signals, may suffer from a weak report channel. CR2 and CR3, who have a strong report channel, can serve as relays to assist in forwarding the sensing results from CR1, CR4, and CR5 to the FC. In this case, the report channels from CR2 and CR3 to the FC can also be called relay channels. Note that although Fig. 10 (c) shows a centralized structure, the relay-assisted cooperative sensing can exist in distributed scheme. In fact, when the sensing results need to be forwarded by multiple hops to reach the intended receive node, all the intermediate hops are relays. Thus, if both centralized and distributed structures are one-hop cooperative sensing, the relay-assisted structure can be considered as multi-hop cooperative sensing. In addition, the relay for cooperative sensing here serves a different purpose from the relays in cooperative communications, where the CR relays are used for forwarding the PU traffic.

IV. CONCLUSION

Cognitive radio is the promising technique for utilizing the available spectrum optimally. The important aspect of cognitive radio is spectrum sensing and from that identifying the opportunistic spectrum for secondary user communication. In this paper, various spectrum sensing techniques are reviewed and collaborative sensing is considered as a solution to some common problems in spectrum sensing.

Cooperative sensing is an effective technique to improve detection performance by exploring spatial diversity at the expense of cooperation overhead. In this paper, we dissect the cooperative sensing problem into its fundamental elements and investigate in detail how each element plays an important role in cooperative sensing.

We further identify the research challenges and unresolved issues in spectrum sensing and cooperative sensing that may be used as the starting point for future research.

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