# Comparative Study of Spectrum Sensing Techniques in Cognitive Radio Networks

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*Abstract*—**Traditional wireless networks including wireless sensor networks working in an unlicensed spectrum band are suffered from uncontrolled interference, as this unlicensed spectrum band gets crowded day by day. This problem is not because of spectrum band deficiency, rather it is because of the misuse/inefficient usage of the spectrum bands i.e., fixed spectrum assignment policy. Cognitive Radio (CR) is a promising technology to solve this challenging spectrum allocation problem. The CR opportunistically access vacant spectrum bands in a licensed spectrum. When the current band/channel becomes unavailable, the device can switch to another available channel. However, for the realization of the cognitive radio networks, spectrum sensing is the ground work and also regulatory bodies need to adopt flexible and non-fixed policies & techniques. In this paper, we analyze different spectrum sensing techniques to detect the presence of the Primary User (PU). The techniques covered in this paper are fuzzy logic cooperative spectrum sensing, asynchronous cooperative spectrum sensing, cooperative spectrum sensing based on network coding, cooperative spectrum sensing with relay diversity, and distributed cooperative spectrum sensing based network coding.**

***Keywords-component; Cognitive Radio Networks, Cooperative Spectrum Sensing, Distributed Sensing, Fuzzy Logic based Spectrum Sensing, Relay based Spectrum Sensing.***

## I. INTRODUCTION

The current wireless networks are regulated by a fixed spectrum assignment policy, i.e. the spectrum is controlled by government agencies and is allocated to authorized customers or service providers for a long period of time and geographical regions. As it is also a common delusion that the current spectrum is becoming deficient. However, this deficiency is not because of its physical paucity of the spectrum, it is because of the poor management of spectrum allocation. However, an enormous quota of the allocated spectrum is used occasionally as demonstrated in Figure 1, where the signal strength distribution is shown in geographical variations in the utilization of assigned spectrum ranges from 15% to 85% with a high variance in time [1]. Other recent work on the same topic indicated that the average spectrum occupancy from 30 MHz to 3 GHz in 6 cities in USA is 5.2% and only in New York City it is 13.1% [2]. In order to compact with the situation of spectrum deficiency and low utilization, building a cognitive radio network (CRN) can be a promising approach [3].

In cognitive radio networks (CRNs) jargon, the Primary User (PU) is the user who pays for the service and has higher priority to use the spectrum. While, Secondary User (SU) also called Cognitive User, who does not pay for the services it uses and has low priority. SU should make use of the spectrum by causing no harmful interference to PU. Therefore, in CRNs, SU must have CR capabilities, like spectrum sensing, channel handoff, and channel switching. One of the most important constituent of the CR is the ability to quantify, sense, cram, and be aware of the restrictions related to the radio channel characteristics, availability of spectrum and power, operating environment of radio, user and application requirements, available network infrastructure and nodes, local policies and other operating limitations.

A number of spectrum sensing methods have been proposed for detecting the presence of PU signal transmission. For example, energy detection introduced in [4], matched filter detection in [5], cyclostationary feature detection in [6], and eigenvalue based detection in [7]. Each of the proposed techniques has its pros and cons. For example, cyclostationary feature detection techniques and matched filter detection techniques requires priori knowledge about PU, which is unfeasible for certain applications. On the other hand, energy detection and eigenvalue based detection techniques do not need any priori information of the signal, and hence are called blind detection methods. Further, eigenvalue based detection is divided into eigenvalue ratio based (ER) detectors and largest eigenvalue based (LE) detectors. Different Spectrum Sensing techniques are shown in Figure 2.

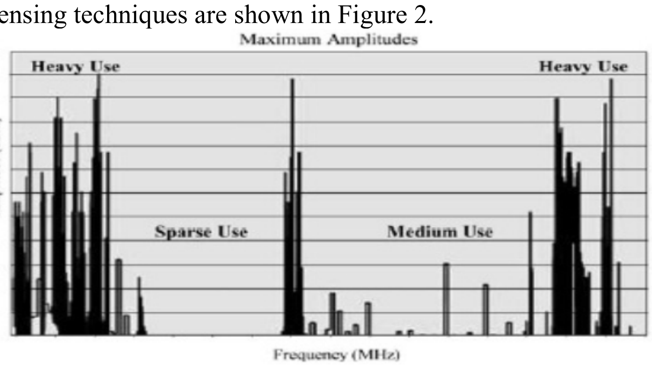


Figure 1. Spectrum Utilization

Cognitive Radio Networks will play the same role in the near future, what computer played in last sixty years, and wireless sensor networks (WSN) in the last two decades. However, WSN are expected to play an important role in the future society. For example, delivering data with guarantee is of great importance in various applications such as health monitoring, industrial monitoring, and house automation etc.

Mostly in such applications data is usable only for a short period of time and must be received before it perishes. Taking into considerations a packet caring an abnormal data of a patient should reach the doctor as early as possible. Similarly, in industrial monitoring, a sensor node should perform recognition of smoke or fire. In short, providing real-time services is becoming an important issue of WSN. Building a CRN can be a promising approach for providing data transmissions in a WSN with QoS requirements [3,8]. However, there are many challenges and open research issues to practically build a CRN. Some of the basic issues are efficient sensing, allocating the spectrum, minimum or no interference to the PU etc. Some survey papers regarding these issues are available in literature [8]-[10]. Some other work on quality of service performance can be found in [11]-[13]. Other studies regarding real-time performance in CRNs can be found in [14]-[17].

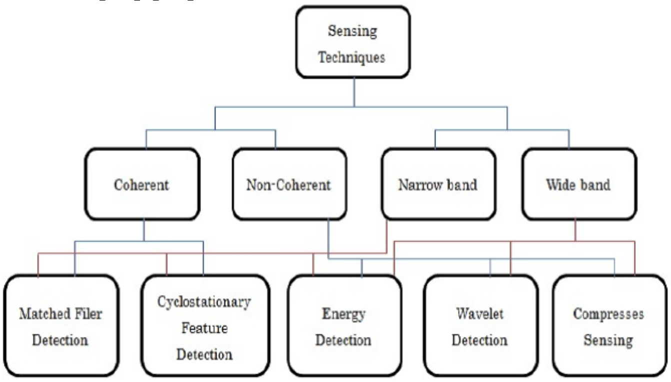

Figure 2. Categorization of Spectrum Sensing Techniques

The rest of the paper is in accordance to the following pattern: White gaps in frequency spectrum is discussed in section 2, research methodology is presented in section 3; collaborative spectrum sensing using fuzzy logic is described in section 4; asynchronous cooperative spectrum sensing is discussed in section 5; cooperative spectrum sensing based on network coding is discussed in section 6; section 7 presents distributed cooperative spectrum sensing; section 8 demonstrates results and analysis and section 9 gives the conclusions.

## II. White Gaps in Frequency Spectrum

The policy of static spectrum allocation caused uneven usage of the overall spectrum. Some of the bands in the spectrum are heavily used while other bands remain unused and go wasted. These unused and unoccupied bands are called white gaps, spectrum holes or white spaces, and can be classified in to three categories [18]:

### *A. Spatial Holes*

These spatial holes are the differences in the usage of a specific frequency band by a PU over a specific geographical area. In urban area a specific band may be highly used while other bands may be underutilized in rural areas. This is because of the differences in the usage and number of users. Figure 3 shows differences in usage of the 3 different frequency bands in 4 different subareas. The data shown here is averaged over time and hence indicates average usage with respect to space.

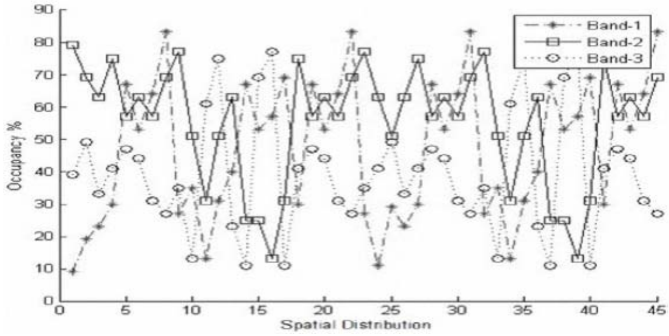

Figure 3. Usage statistics of 3 different frequency bands over different areas

### *B. Temporal Holes*

These holes are the differences in usage of a specific frequency band by a PU over time. There may be period of time during a day when a specific frequency band is highly used like business hours in a trading area, similarly, the period of time when same bands are not efficiently used or even not used at all like night hours or early morning hours in the same area. Figure 4 indicates differences in the usage of a particular band over different times of the day in the same area.

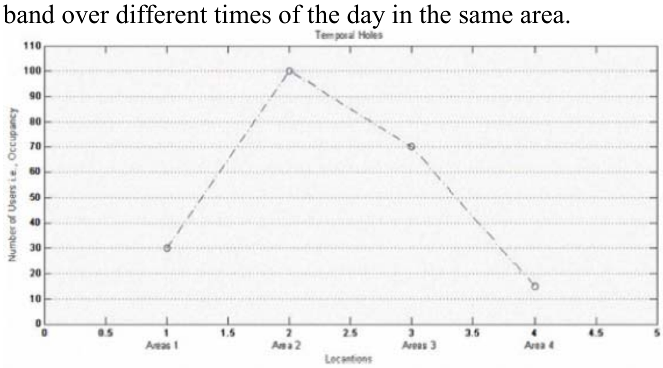

Figure 4. Indicating variation in usage of a particular frequency band over different times of the day at same place

### *C. Spectral Holes*

These holes are the gaps or white spaces in a specific frequency band used by a specific PU. Within a certain band depending upon the encoding and modulation schemes certain frequencies/channels may remain vacant like frequencies on the border regions of the bands or guard bands in CDMA are left unused to avoid interference. Similarly in case of frequency reuse the assigned frequency band is divided into sub bands to be used at different sites to help in avoiding interferences and to ensure better frequency and user management. This leaves a large portion of the band vacant. For example, spectral diversity in cellular technology.

### *D. Opportunities*

A combination of any two or all of the above postulated holes or gaps offer opportunities to be used by the SU/CR users. These opportunities are flexible, and depend on band, time and space but definable to a fair degree. Figure 5 is the represents the combination of Spatial Holes and Spectral Holes in unison.

Figure 5 shows opportunities as white spaces representing frequency usage over various areas.

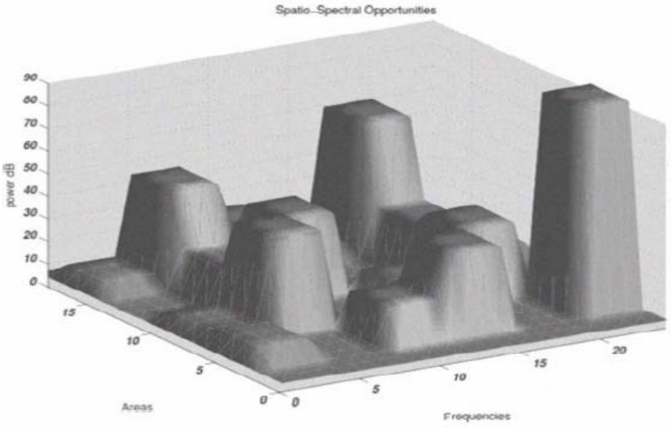


Figure 5. Spatio-spectral diversity/Frequency usage in different areas

## III. RESEARCH METHODOLOGY

In this section we discuss a methodology used by cooperative spectrum sensing methods. The groundwork of spectrum sensing is the detection of PU; here we demonstrate the problem of the PU detection in cooperative spectrum sensing and also discuss types of cooperative spectrum sensing techniques.

### A. Primary User Detection

The phenomena of cooperative sensing start with local sensing, i.e., spectrum sensing performed by individual CR/SU user. Normally, local sensing function for the detection of PU is formulated as a binary hypothesis test between the following two hypotheses [18]:

$$r_i(t) = \begin{cases} n(t) & H_0 \text{ (PU not detected)} \\ h(t).s(t) + n(t) & H_1 \text{ (PU detected)} \end{cases} \quad (1)$$

where $r(t)$ represents the signal received by a SU, $s(t)$ is signal of PU, channel gain is represented by $h(t)$, and $n(t)$ represents the zero-mean Additive White Gaussian Noise (AWGN), $H_1$ and $H_0$ represents the hypothesis test of the existence and the non-existence o PU, respectively.

### B. Spectrum Sensing Techniques

For the simplicity of cooperative spectrum sensing analysis, the cooperative spectrum sensing techniques are divided into three types, depends on how CR/SU users share the sensing data is shown in the Figure 6, (a) centralized, (b) distributed, and (c) relay-assisted.

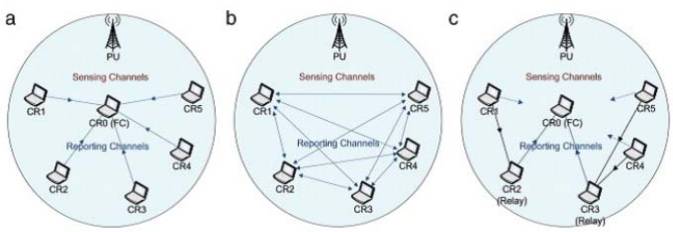


Figure 6. Spectrum Sensing Techniques

Local sensing at each SU node can be performed by using any of the spectrum sensing methods such as energy detection, matched filter detection, or cyclostationary feature detection. However, as discussed above simple sensing method is energy detection. Energy detection method is the most popular method which does not require any prior knowledge; it simply detects PU based on sensed energy of the received signal. The pictorial representation of energy detection method to perform spectrum sensing is shown in Figure 7. As SU senses the signal $r(t)$ of PU, it applies a filter of bandwidth W followed by a square law device and an accumulator. The output of the accumulator $R$ is compared to a thresh hold $K$ and a local decision is made, $H_1$ if $R > K$, i.e., PU is present and $H_0$ if $R < K$, i.e., PU is absent.

The test statistic of energy detector for $jth$ SU is given by

$$r_i(t) = \begin{cases} \sum_{i=1}^{M} |n(t)|^2 & H_0 \text{ (PU not detected)} \\ \sum_{i=1}^{M} |h(t).s(t) + n(t)|^2 & H_1 \text{ (PU detected)} \end{cases} \quad (2)$$

where $ri$ is the $ith$ received signal sample and $M = 2TW$, where $T$ is detection time and $W$ is the bandwidth in Hz.

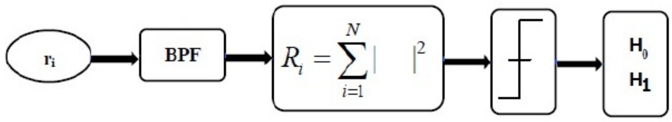


Figure 7. Block Diagram of Energy Detection Techniques

### C. Sensing time of a Cognitive Radio Node

We consider that all channels have the same statistical activities, i.e., all channels have the same distribution for their channel availability and channel unavailability. For all nodes, probability of detection ($P_D$) is same, as low Signal-to-Noise-Ratio (SNR) node requires more time for sensing the energy of the signals in a particular band compared to high SNR node. We can say that there is a relation among and sensing time to obtain $P_D$ as well as probability of false alarm ($P_F$). In order to find the $PD$ in a fixed band the required SNR is directly proportional to $1/\sqrt{p}$, shown below, where $P$ represents sensing period [20].

$$SNR = k(\frac{1}{\sqrt{P}}) \quad (3)$$

## IV. COLLABORATIVE SPECTRUM SENSING BASED ON FUZZY LOGIC

This section demonstrates cooperative spectrum sensing technique using fuzzy logic. Figure 8 depicts the network model for collaborative spectrum sensing using fuzzy logic. Figure 8 shows that there is a PU, AP and $N$ SUs in the network. In this technique decisions of SUs are sending to Access point (AP) where AP multiplies credibility $Cr$ of each SU with the received decisions, and makes a combined decision about the absence or presence of PU. This technique is modeled in three stages i.e. the learning, the decision, and the fuzzy combination [19].

### A. Learning stage

At learning stage, we need to find the $C_r$ of every SU. We use fuzzy model which has three sets. These sets are probability set (PS), estimation set (ES) and fuzzy combination set used to find the $C_{rj}$ of $j^{th}$ SU. The PS ={$P_D$, $P_M$, $P_F$} and weights are assigned to them are WPS={5/10, 3/10, 2/10}. The estimation set is ES ={Very High, High, Medium, Low, Very Low} and weights are assigned to them are WES= {10/10, 8/10, 6/10, 4/10, 2/10}. Let's the result of *m* rounds is a single PS matrix with order of 3x5 for each SU.

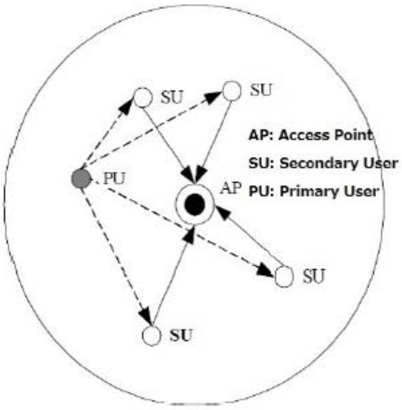


Figure 8. Collaborative Spectrum Sensing Model using fuzzy Logic

$$SPS = \left(\frac{A_{ij}}{m}\right) \quad (4)$$

where $A_{ij} = count(PS_i, ES_j)$, $i = 1,2,3$ and $j = 1,2,3,4,5$. At this stage, every row of the matrix shows one of the PS elements whereas every each column shows one element of the ES. $C_r$ of each SU is computed using equation 5.

$$C_i = (WPS_i \circ SPS_i) \times WES \quad (5)$$

where $i$ is the number of SU, and its values are from 1 to $N$. The pictorial representation of this stage is show in Figure 9 below.

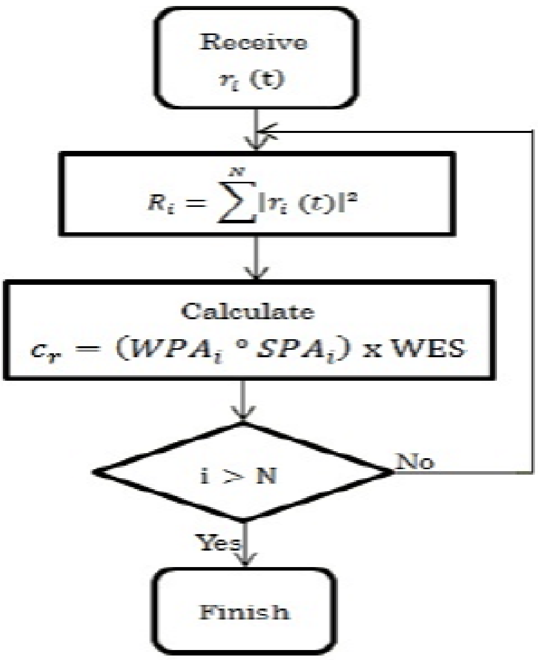


Figure 9 . Learning Stage of a Secondary User

*B. Decision Phase*

Energy detection method is used for detecting PU. Based on the sensed values of $r_i(t)$ shown in equation 1, each SU decides whether the PU is present or not. The sensing metric and its details are shown in equation 2. Each SU decides on the output of energy detector and sends this result to AP for combined decision. Figure 10 shows the decision phase of collaborative spectrum sensing techniques using fuzzy logic.

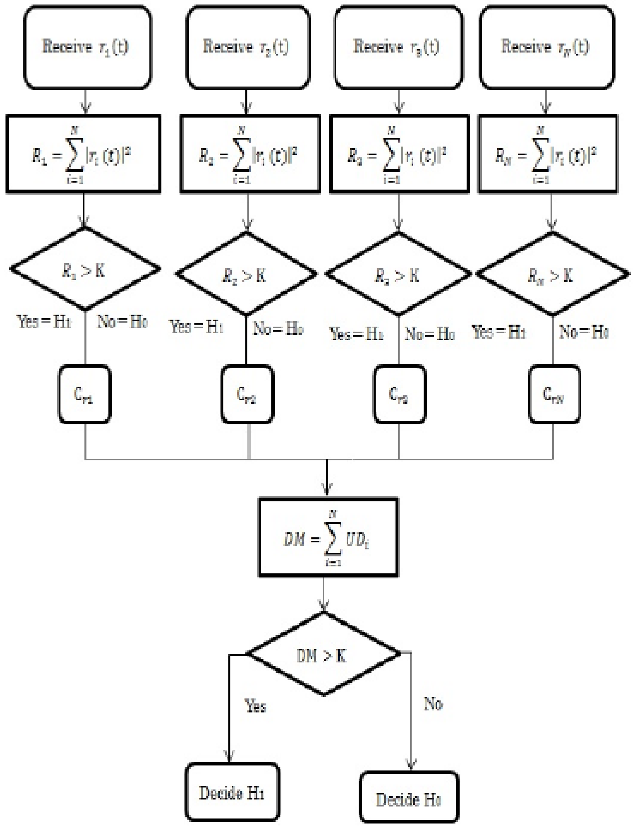


Figure 10. Pictorial representation of the decision phase

*C. Fuzzy Combination*

In the last stage AP receives the local sensing results of each SU denoted by $D_i$ where *i* is the number of SU, and its values starting from 1 to *N*. $UD_i = C_i D_i$ is used to calculate the result of each SU including the Cr. After this, the AP calculates a decision metric (DM) as follow;

$$DM = \sum_{i=1}^{N} UD_i \quad (6)$$

where $C_{ri}$ represents the $ith$ user credibility calculated in learning stage. Finally, AP compares the decision with a predefined threshold and announces the presence or absence of PU.

## V. Asynchronous Cooperative Spectrum Sensing

Most of the spectrum sensing techniques needs long time for sensing/observation to ensure the presence or absence of PU accurately. The theme of this method is to quickly sense the PU and minimize the detection time of PU, so that SU may not interfere PU communication by evacuating the bands in question as soon as PU arrives. This is two phase technique: the sensing phase and the reporting phase [20]. Figure 11 shows the network model of this technique, where one is more SU are shadowed. Each SU performs its spectrum sensing individually and sends the results shown in equation 1 to the Fusion Center, and based on the first received result from any SU, the Fusion Center decides the presence or absence of PU.

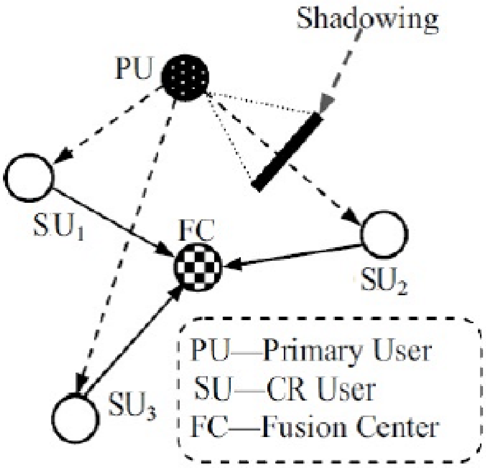


Figure 11. Asynchronous Cooperative Spectrum Sensing Model

*A. Sensing Phase*

In this phase every SU senses the spectrum and decides locally about the presence or absence of PU. The required sensing time T, to detect the PU in a specific band by the SU is relied on the SNR of PU signal. Detection method used in this scheme is energy detector.

*B. Reporting Phase*

As the required sensing time for a SU with higher SNR is smaller than the user with lower SNR. In this method the SU with high SNR transmits the result of local sensing to the Fusion Center (FC) earlier compare to other nodes, i.e., users with lower SNR. Figure 12 depicts the idea of asynchronous spectrum sensing technique. There are n sensing time periods for each SU $T_1$, $T_2$ ... $T_n$ and their corresponding different SNR values $S_1$, $S_2$ ... $S_n$. For every pair of sensing time period T and SNR S, n thresholds $K_1$, $K_2$ ... $K_n$ are obtained by fixing PF. After a particular interval, the FC gets sensing results from a SU and compares with a predefined threshold K, then makes a decision for that interval and select either $H_0$ (absence of PU or $H_1$ (presence of PU). If FC selects $H_0$, then waits for another interval, otherwise, it announces the presence of PU.

## VI. Cooperative Spectrum Sensing Based on Network & Space-time Coding

This technique ensures originality of the sensing information of CR user at the Base Station (BS). This technique uses network coding for checking either the sensing information exchanged is correct or not. Figure 13 shows the network model of this scheme, which consists of a PU, two CR users, BS which performs fusion, and a relay node. This technique is a two-step process, i.e., Relay Selection and Sensing based on Network & Space-time coding [21].

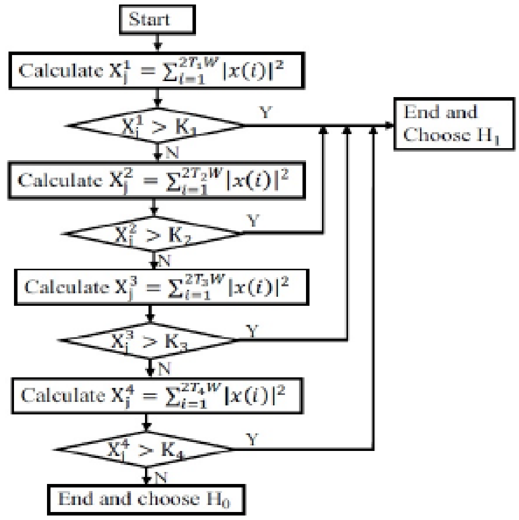


Figure 12. Pictorial representation of the Reporting Phase

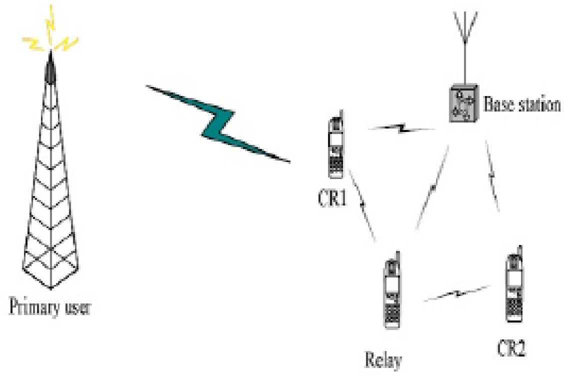


Figure 13. Network Model: Sensing based on Network & Space-time Coding

*A. Relay Selection*

The basis for the cooperative spectrum sensing based on network coding is the relay selection. Therefore, a set of relay must be established first, and after that the best relay should be selected. A relay node could be any node with cognitive capabilities and should not be a reporting user or BS. The job of relay node is to improve the reliability of the exchange decision results. For example, bit error rate (BER) among the CR users is $Pe_0$, and the BER among the two CR users & the relay are $Pe_1$ and $Pe_2$. Then the BER of the exchange result through the network decoding are given as follow;

$$P'e_1 = Pe_R(1 - Pe_2) + Pe_2(1 - Pe_R) \tag{7}$$

$$P'e_2 = Pe_R(1 - Pe_1) + Pe_1(1 - Pe_R) \tag{8}$$

Where

$$Pe_R = Pe_1(1 - Pe_2) + Pe_2(1 - Pe_1) \tag{9}$$

To achieve good performance of exchange information, the relay selection must meet the following condition.

$$\max\{P'e_1, P'e_2\} < Pe_0 \tag{10}$$

The rule is to choose the least $\max\{P'e_1, P'e_2\} < Pe_0$

among the relay set.

*B. Sensing based on Network & Space-time Coding*

The employment of relay is necessary to enhance the reliability of the sensing information exchange. There are three possible methods to decrease the reporting error:

1) Direct received from the CR user,
2) Decoded the network coding information from the relay and
3) Decoded the space-time coding information from the CR users.

Figure 14 shows the phenomenon used by this technique.

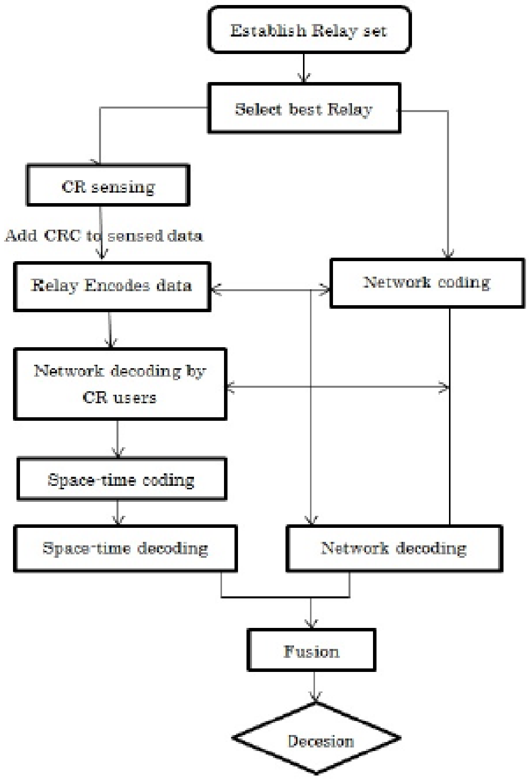


Figure 14. Pictorial Representation of Cooperative Sensing

A relay is selected from the defined set, CR user add cyclic redundancy check (CRC) code to the sensed information and send it to relay. The relay encodes the received information using Network Coding and broadcast it. Each CR user decodes the received information from Relay using network code, and checks its integrity, if not altered, decode it using space time coding and sent it to the BS. The BS decodes Network Code from Relay and Space time code from CR users, check their integrity using CRC, correct of either is fused and decision is made.

## VII. Distributed Cooperative Spectrum Sensing based Network Coding

In distributed cooperative spectrum sensing, SUs share sensing information with each other for PU detection, as a result huge data has to be transferred, which needs high bandwidth. This technique is an attempt to minimize the bandwidth need in CRs. Figure 15 shows the network model of the scheme, consisting of a PU, and N SUs. This technique is a two-step process, i.e., distributed sensing based on network code and data combining rule [22].

*A. Distributed Sensing based on Network Code*

This technique assumes that all the SUs sense the same frequency band. There are $C$ channels to be sensed. Figure 16 shows the pictorial representation of the scheme:

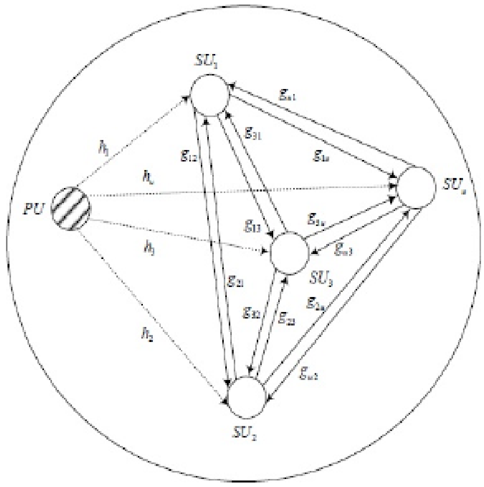


Figure 15. Distributed Sensing Network Model

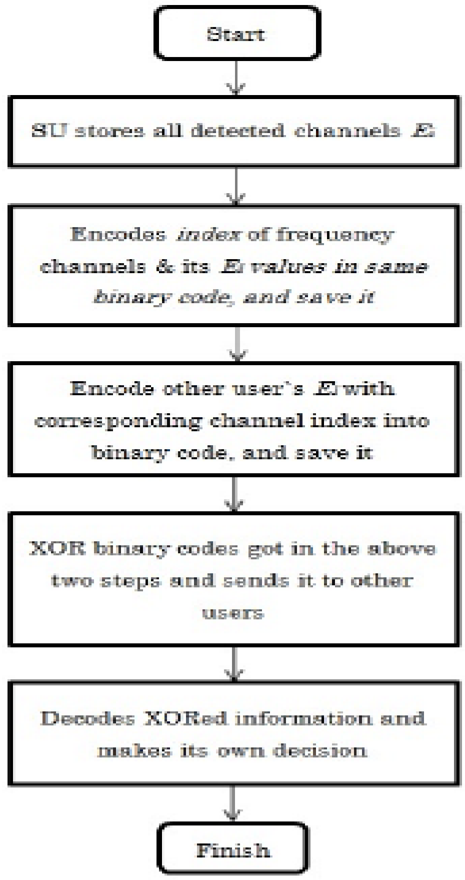


Figure 16. Pictorial Representation of Distributed Sensing

Every SU detects $C$ channels and saves the value as $E_i$, shown in equation 11, where $i= 1,2,..., C^c$ in the frequency table. Now, every SU encodes the frequency channel index and $E_i$ into the same binary code, save them. After encoding its own value, all SU encodes $E_i$ with corresponding channel index of other SUs into binary code, save them also. Each SU XOR the two binary codes, i.e., its own code and other users code. Sends XOR-ed information to other SU. Upon receiving every SU decodes the XOR-ed information and obtain result of other SU, and decides the presence or absence of PU by itself.

*B. Data Combination Rule*

The test statistic of the *uth* SU using energy detection method is shown in equation 11

$$E_i = \sum_{n=1}^{Q} |x_j(n)|^2 \quad (11)$$

For a non-cooperative spectrum sensing technique, the decision rule at each SU is shown in equation 1.

Secondary users interchange information with each other, the *jth* SU sense signal of $N$-1 other SUs, as total number of SUs are $N$;

$$y_{ij} = g_{ij}.E_i + v_{ij} \quad i = 1, ..., N \ \& \ i \neq j \quad (12)$$

where $g_{ij}$ are the SU channel gain, $v_{ij}$ are AWGN.

To find the presence or absence of PU, the *jth* SU combine the signals it detect with the signals obtained from SUs, as

$$y_{cj} = \sum_{i=1}^{N} w_j y_{ij} \quad i = 1, ..., N. \quad (13)$$

After getting information from all the users, each SU decide on its own for $H_0$ or $H_1$.

## VIII. Analysis and Results

This section describes the analysis and results of this study. Evaluations of all the above discussed methods are presented in Table I. The comparison metric for this paper are reliability of the method, sensing time taken by a SU to detect a PU, security provided by the technique, complexity of the technique, and the energy consumption of nodes using a technique. The reliability column in Table I shows that how precisely the SU has sensed the presence or absence of PU. In other words, reliability is the $P_D$, $P_M$, and $P_F$ of a PU. The time column presents the decision time which is made about the existence of PU, or otherwise. When using reliability and sensing time columns for comparison we assume that all the techniques use the same hypotheses i.e., $H_1$ and $H_0$. Security column shows if some alteration has been done to the decision made by each SU locally and it reaches the common receiver/other secondary user, correctly or some changes do occurs during transmission. In other words, local decision $H_1$ changes to $H_0$ and $H_0$ changes to $H_1$ or not. Complexity column shows the number of calculations involved in the detecting of primary user. The energy column shows the total consumption of battery power or node energy at the end of decision session.

Table I shows that every technique has its own merits and demerits. Such as Relay based cooperative spectrum sensing is the best from reliability & security point of view with medium sensing time, complexity, and energy consumption. Similarly, fuzzy Logic based collaboration sensing technique is reliable but it takes long sensing time with high complexity and high energy consumption. Distributed cooperative sensing techniques is reliable and have medium complexity. Although this technique consumes low energy but provides low security and sensing takes time. The asynchronous cooperation scheme is best in terms of sensing time and complexity but provide no security and one cannot rely upon it, although, it energy consumption is very good. The non-cooperative local sensing is not reliable with any security considerations but best in complexity, sensing time, and energy consumption. Figure 17 shows the graphical comparison of cooperative spectrum sensing techniques.

TABLE I COMPARISON OF COOPERATIVE SPECTRUM SENSING TECHNIQUES

| Techniques | Comparison Metric | | | | |
|---|---|---|---|---|---|
| | ***Reliability*** | ***Sensing Time*** | ***Security*** | ***Complexity*** | ***Energy*** |
| Fuzzy Collaboration | High | High | Medium | High | High |
| Asynchronous Cooperation | Medium | Low | Low | Low | Low |
| Relay based Cooperation | High | Medium | High | Medium | Medium |
| Distributed Cooperation | High | Medium | Low | Medium | Low |
| Non Cooperative Sensing | Medium | Low | Low | Medium | Low |

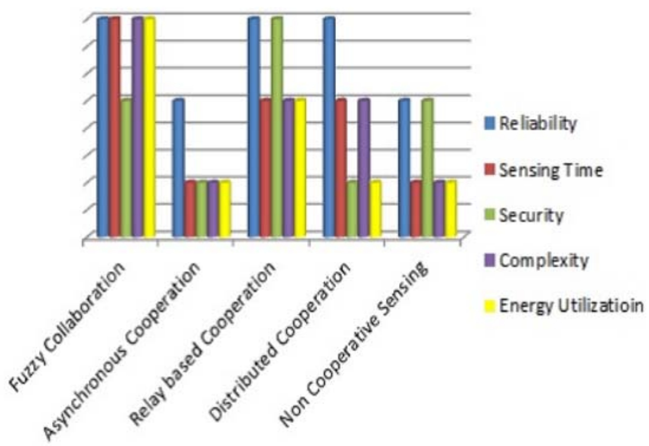


Figure 17. Comparison of Cooperative Spectrum Sensing Techniques

## IX. Conclusion

The reason for spectrum scarcity is its nominal use. As the primary user network does not use all the channels at one time, and some channel are unoccupied all the time. To efficiently utilize these unoccupied channels, effective and reliable sensing of the spectrum is needed. In other words, more than 99% correct decision about the presence or absence of PU should be made. To get better reliability of spectrum sensing techniques, the local sensing decision of each SU user should be considered. Although, considering local decision of each SU in distributed and cooperative spectrum sensing techniques need more sensing time and consumes more energy as depicted in in Figure 17 and Table I. However, distributed and cooperative spectrum sensing increases reliability and security. On the other hand, in order to minimize the spectrum sensing time, the diversity of Signal-to-Noise-Ratio should be considered. Distributed cooperative spectrum sensing techniques and asynchronous energy detection technique is more appropriate for a crowded licensed spectrum band as they need less time to switch a SU from one channel to the other. Whereas, for a less dense populated licensed spectrum fuzzy collaborative spectrum and relay based cooperation are better options.

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