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Why Cooperative Spectrum Sensing in Cognitive Radios? A Review on Moving From Local to Cooperative Spectrum Sensing

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ABSTRACT: Cognitive radio, an enabling technology has been flourishing day-by-day that allows number of unlicensed users to operate in licensed spectrum bands compromising not to cause any interference to licensed user. The main challenge in cognitive radio technology is to identify the silent periods of licensed users i.e. the unused spectrum of primary users which is called spectrum sensing. In this paper, we described why cooperative spectrum sensing is considered better than local spectrum sensing. Concentrating mainly in centralized cooperative sensing, we analyzed the elements needed in it which includes spectrum sensing models, hypothesis testing techniques, transmission techniques and different types of cooperation models. Also we have added some of the challenges faced during the implementation of cooperative spectrum sensing model in the real world.

Keywords: Spectral agile radios, centralized cooperative sensing, cooperational models for decision making, transmission techniques, issues in sensing

I. INTRODUCTION

Over the recent past years, there had been a tremendous growth in wireless communication and mobile communication technologies. In our daily life, devices such as TV remote controllers, cellular phones, PDA's and satellite TV receivers are based on wireless communication technologies. The increasing demand for such devices has necessitated the up gradation of wireless communication technologies through several generations. With all the technological advancements along with the simultaneous coexistence of 2G, 2.5G, 3G, 4Gand 5G, many new design scenarios have been developed and the inter-operability has to be considered [1].

Wireless communication systems are built based on the transmission of electromagnetic waves (i.e radio waves) with frequencies in the range 3 Hz to 300 GHz Also as per the study given by Spectrum Policy Task Force (SPTF) of FCC (Federal Communications Commission) [1-2], some frequency bands are heavily used by licensed systems only in some particular locations and at particular times and remaining bands are unoccupied. The major factor of this inefficient usage of spectrum is the spectrum licensing itself i.e. spectrum allocated to licensed users cannot be utilized by unlicensed users and applications. In order to enhance the utilization of the radio frequency spectrum, a new paradigm of designing wireless communication has been evolved i.e., cognitive radio/spectrum agile radio. This new technology came across the minds of the engineers in order to overcome the present scarcity of available spectrum. Nowadays Software Defined Network (SDN) architecture has become a popular architecture for network controlling regardless of the applications and network services used. Authors in [3] reviewed some of the most recent SDN techniques which can improve mobile network. The idea behind cognitive radio is spectrum sharing in which secondary users/ unlicensed users use the licensed band for communication when they are not fully utilizing it [3]. Two main characteristics of cognitive radio are cognitive capability and re-configurability or self adjustment. Cognitive capability is the ability of radio technology to capture or sense the information from its radio environment. Re-configurability refers to the ability of radio to be dynamically programmed according to the radio environment.

1.1 Basic Requirements And Functionalities In Cognitive Radio Environment:

Cognitive radio is an adaptive and intelligent radio network technology that can automatically detect available channels in a wireless environment and adapting to it by changing its transmission parameters. One of the major requirements on CR which distinguishes it from the conventional wireless communication technology is that it has to tackle the coexistence of SU's with PU's. Such coexistence can be identified as three different scenarios i.e. interweave, underlay and overlay [4].

Interweave is essentially a detect and avoid (DAA) technique where the SU analyze the spectrum to detect the PU and if it is present, it looks further for other spectral opportunities both in time and frequency domain according to their own requirements in terms of QoS or maximum tolerable delay. The main drawback is that all available resources are not fully utilized and may prevent the transmission of SU even though PU is not affected at all.

In underlay approach, the cognitive users are allowed to operate on a certain frequency band, either the primary user is occupied or not, provided that the interference caused to PUs remains below a fixed threshold. The interference constraint may be met via wideband signaling to maintain interference below the noise floor (spread spectrum or UWB) and also via multiple antennas and beam forming [4]. The main challenges faced in this approach are the measurement of interference at the primary receivers and some policy issues such as the licensed users don't allow underlay transmission since they have paid some dollars for their spectrum.

In the overlay approach [5], primary users share their information such as signal codebooks and messages with the cognitive users. Rather than vying for spectrum access, the cognitive devices may enhance and assist the non cognitive transmission. The messages collected by the cognitive devices are used either to eliminate the interference effects produced during the primary transmission at the cognitive receiver side or to improve the performance of the primary transmission through relaying the obtained messages to the primary receiver. There should be a careful trade-off between the interference induced on the primary signal and the improvement made in secondary user to maintain a stagnant SNR.

Cognitive radios/spectrum agile radio can be divided into two types: a) Type-1 and b) Type-2 radios [6]. In type-1 agile radio, the radio device uses fixed spectral bandwidth to transmit its data but may exploit the holes in the spectrum by opportunistically hopping on these holes for the absence of primary or secondary radio systems. WLANs that exist today are examples of type-1 agile radios. In this model, WLAN system may hop from one channel to other channel, but the bandwidth of the channel has to be 20 MHz. In type-2 radios, the system may be able to expand or contract its spectral bandwidth. Consider the current WiMedia UWB system. This system uses OFDM and the bandwidth is between 3.1 and 10.6 GHz. It is easier to shape the spectral mask to tune into holes available in the spectrum. If the bands 4-6 GHz are occupied, then this type of agile radio system will switch off the carriers in the range between 4-6 GHz and transmit data in the range of 3-4 GHz and 6-10 GHz.

1.2 Channel Capacity Of Spectrum Agile Radios

To determine the channel capacity of a spectral agile radio two parameters are required. One is spectral utilization factor and the other blocking time. The spectral utilization factor of a cognitive radio network can be measured by the total amount of channel accessing for transmission. The blocking time for an agile radio network is defined as time interval during which a secondary network has no spectral opportunity to utilize for its transmission.

In the presence of an Additive White Gaussian Noise (AWGN), Shannon's channel capacity can be defined as [1]

$$C = B\log_2(1+\frac{S}{N_o B}) \tag{1}$$

Equation (1) is modified to include the extra utilization factor that can be obtained by an agile radio network of type 1 as

$$C_{agile} = U_{agile} B\log_2(1+\frac{S}{N_0 B}) \tag{2}$$

where U_{agile} is the utilization factor of agile radio network.

The basic functionalities of a cognitive radio are classified as radio scene analysis, identification of channel characteristics, power controlling in transmission and dynamic spectrum management. In radio scene analysis, the cognitive radio senses the environment in order to detect unused bands i.e. spectrum holes.. Channel identification includes the channel state information estimation and the determination of the channel capacity. It determines the best available unused bands for transmission so that QoS of a cognitive radio should be met. In order to cater QoS challenges, C-RAN (Cloud Radio Access Network) in introduced as illustrated in literature [7]. After obtaining the channel information as desired by unlicensed secondary users (SUs), an effective transmission power control mechanism should be performed in order to avoid interference to licensed primary users (PUs). To avoid excessive interference caused by channel uncertainty, some power control methods are proposed to deal with channel gain fluctuations by modeling it as a combination of deterministic and uncertain components.

Different spectrum sensing methods that are being used are local spectrum sensing, cooperative spectrum sensing and interference based sensing. In local sensing, each cognitive node individually senses the available spectrum whereas in cooperative spectrum sensing, the cognitive node cooperatively senses the available spectrum. The interference based sensing depends on the interference temperature of the primary users.

This type of sensing is little bit difficult to implement because of the unavailability of sufficient information about the interference temperature.

In this paper, Section II describes different types of local spectrum sensing techniques and its challenges and how far cooperative sensing can overcome these challenges. This work mainly concentrates in centralized cooperative sensing strategies. Hence section III describes the elements in centralized cooperative sensing such as cooperative techniques, spectrum sensing techniques, hypothesis testing, cooperation models and transmission techniques in cooperative spectrum sensing. Section IV describes some of the issues in cooperative spectrum sensing.

II. SPECTRUM SENSING IN COGNTIVE RADIO

Due to the time varying nature of wireless channels and multipath fading effects such as large scale fading and small scale fading spectrum sensing is considered a little bit tough task. Small scale fading models include the well-known Rayleigh, Rice and Nakagami-m distributions [22]. For large scale scale fading effects, log-normal distributions are used for the modeling purposes. Rayleigh and Nakagami distributions are used to model dense scatters, while Rician distribution models fading with a stronger line of sight. Nakagami distributions can be reduced to Rayleigh distributions, but give more control over the extent of the fading.

1.3 Local Spectrum Sensing

To determine the presence or absence of the PU transmission, different local spectrum sensing techniques have been used. The detectors used in this category of spectrum sensing can be broadly classified as single band detectors and multiband spectrum sensing detectors. The most frequently used single band spectrum sensing techniques includes matched filtering, energy detectors and feature detectors [9-10]. The feature detection can be exploited using methods such as cyclo-stationary based sensing [11], second order moments [12] and covariance matrix based sensing techniques [13-14]. In case of multiband scenario, there are techniques such as serial spectrum sensing [15-16], parallel spectrum sensing [17], wavelet sensing [18], compressed sensing [19], angle based sensing [20], blind sensing [21] and other algorithms as shown in fig.1.

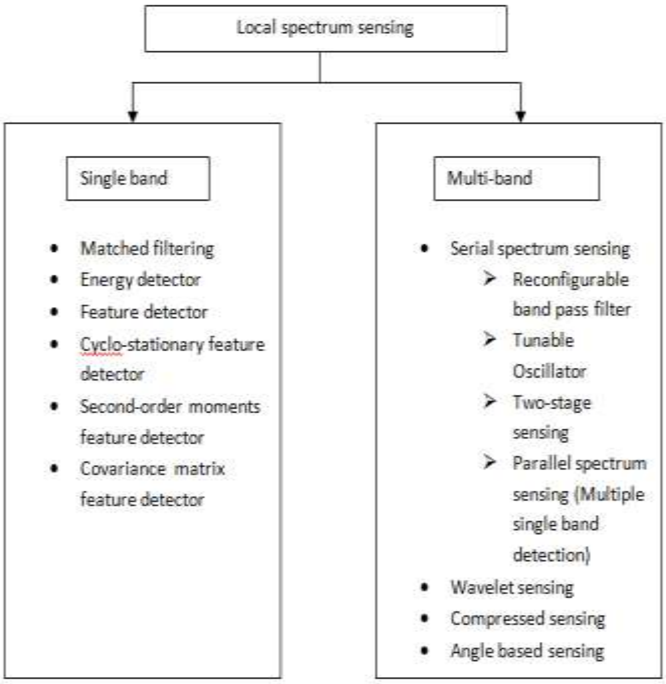

Figure1: Local spectrum sensing

In addition to time varying nature of wireless channels, there are other factors such as shadowing, hidden primary user problem i.e, receiver uncertainty which degrades the detection performance of local spectrum sensing. As shown in figure 2, CR1 and CR2 are located inside the transmission range of primary transmitter (PU TX) while CR3 is outside the range. Due to multiple attenuated copies of the PU signal and the blocking of a house, CR2 experiences multipath and shadow fading such that the PU's signal may not be correctly detected. CR3 experiences receiver uncertainty problem because of its unawareness of the PU's transmission and the existence of primary receiver (PU RX). Thus the transmission from CR3 is interfered with the reception at PU RX [23].

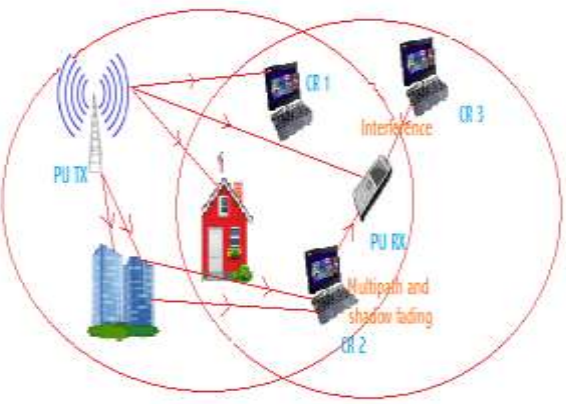

Figure 2: Receiver uncertainty and multipath/shadow fading

1.4 Local Sensing Challenges

The performance of spectrum sensing is subjected to certain regulatory constraints to protect the primary systems from harmful interference. Some of the constraints are given below [8]:

Sensing periodicity:

During the transmission phase of a secondary user, when a primary user starts to transmit, the secondary user should continue to periodically sense the band. The sensing period is the maximum time during which the secondary user will be unaware of a primary user and may cause interference to primary user. Hence sensing interleaved with data transmission is more beneficial.

Detection sensitivity:

The maximum distance from a primary receiver at which the incurred interference is considered harmful is said to be the interference range of a secondary transmitter. Let R be the maximum length of a point-to-point microwave link or the coverage radius of a TV station as shown in fig.3. The interference range of the secondary user, D, is then determined by the following condition:

$$\frac{P_p L(R)}{P_s L(D) + P_b} = \Gamma \tag{3}$$

where P_b is the power of background interference at the primary receiver, L(D) denotes the total path loss at a distance D from the transmitter. Let P_p and P_s denote the transmitted power of the primary and secondary users respectively. Since path loss varies with frequency, terrain characteristics and antenna heights, these parameters should be taken into account in the evaluation of D. The detection sensitivity, $\gamma_{\min}$ is the minimum SNR at which the primary signal may still be accurately detected by the cognitive radio; this requirement may be expressed as

$$\gamma_{\min} = \frac{P_p L(D+R)}{N} \tag{4}$$

where N is the noise power. Thus the detection sensitivity is strongly related to its maximum power it is allowed to transmit in a certain licensed band. Therefore to manage the spectrum, a spectrum management scheme should be placed according to the network's detection sensitivity.

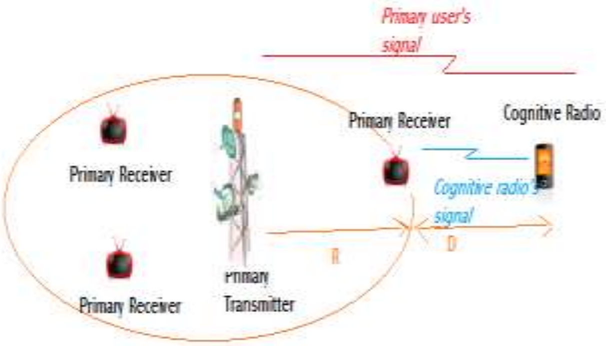

Figure 3: Interference range of a cognitive radio

Hidden node problem

The power of a transmitted signal decreases with distance from the transmitter. Hence if the signal travels a long distance then it will be very low in power. However, because radio signals can suffer from fading on the journey from the transmitter to the receiver it is possible for a cognitive radio to be near a transmitted signal and not detect its presence.

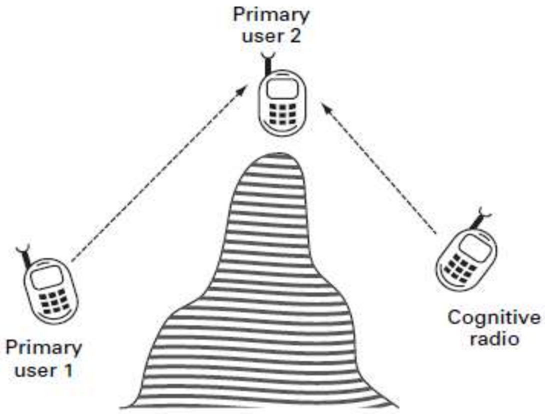

Figure 4: Hidden node problem

Consider the scenario shown in fig.4, primary user 1 is transmitting to primary user 2 on frequency F1. User 2 is on a hilltop and has good line-of-sight with user1. The cognitive radio, however, cannot detect the transmission as the cognitive radio is positioned in the shadow of a large building complex. The cognitive radio therefore decides that F1 is free for use. The cognitive radio transmits on F1 and in doing so causes interference to primary user2. Hence the hidden node problem leads the secondary user to incorrectly conclude that spectrum is unoccupied, when in fact it is not [2].

III. COOPERATIVE SPECTRUM SENSING

In order to deal with the above challenges, cooperative spectrum sensing is seen as a potential solution by the communication engineers. The idea behind cooperative spectrum sensing in a RF sensor network is the collaboration of nodes in deciding the spectrum band used by the primary transmitters emitting the signal of interest [23]. Cooperative nodes send either their test repots or local decisions, comprising of information about the presence of signal of interest to another node, which acts as a decision maker. Through cooperation, the unwanted effects of fading, shadowing and noise can be minimized.

As the number of collaborating nodes increases, the probability of missed detection for all nodes decreases. Let us consider there are N numbers of users sensing the PU. Each CR user makes its own local decisions regarding the presence or absence of primary user and forwards the binary decision (1 or 0) to the decision maker. The PU is located far away from all CRs. Each CR user tends to form a cluster such that the distance between any two CRs is considered negligible compared to the distance from the PU to a CR. All the

CR users receive the primary signal with same local mean signal power. Assume that the noise, fading reports and average SNR are same and also consider that the channels between CRs and FC are ideal channels

In independent decisions making, the fusion problem where k out of N CR [24] users can be described by binomial distribution based on Bernoulli trials where each trial represents the decision of each CR user. With a hard decision counting rule, the fusion center implements an n-out-of-M rule that decides on the signal present hypothesis whenever at least k out of the N CR user decisions indicate. Assuming uncorrelated decisions, the probability of detection at the fusion center is given by

$$P_d = \sum_{l=k}^{N} \binom{N}{l} P_{d,i}^{l} \left(1 - P_{d,i}\right)^{N-l} \tag{5}$$

where $P_{d,i}$ is the probability of detection for each individual CR user.

1.5 Cooperative techniques

One of the major issues in cooperative sensing is how to cooperate between multiple CR users [25]. In general, cooperative techniques can be classified into 3 levels: Centralized coordinated, decentralized coordinated and decentralized uncoordinated. In centralized coordinated, a perfect infrastructure is deployed in which a CR informs a CR controller about the presence of a primary transmitter or receiver. The operation may be a partially cooperative or totally cooperative (fig. 5). It is partially cooperative because it cooperates only during sensing and totally cooperative when CRs cooperates in relaying each other's information in addition to sensing. In decentralized coordinated, there is no CR controller rather it needs a dedicated control channel or an UWB channel. These cognitive users are gathered into clusters and automatically coordinate themselves. De-centralized uncoordinated coordination could be done in sensor networks which are placed externally to CR i.e., external sensing. In this section we mainly focus on centralized cooperative sensing.

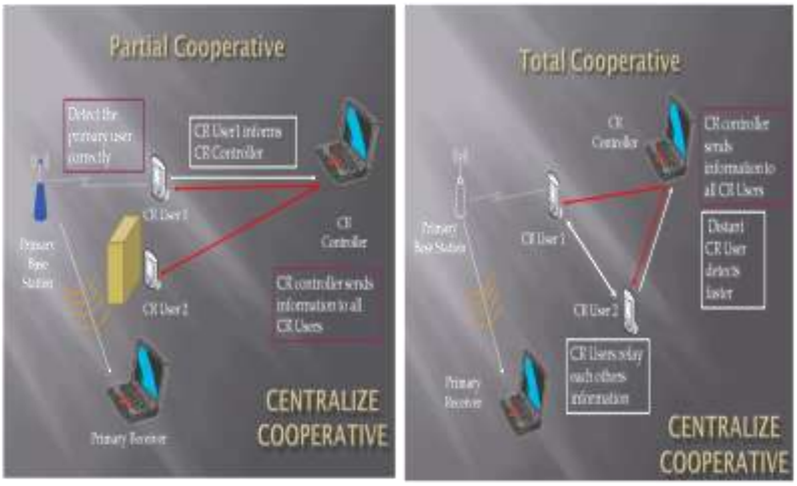

Figure 5: Centralized cooperative system

1.6 Centralized Cooperative spectrum sensing

In centralized cooperative spectrum sensing, a central unit collects hard or soft sensing information from cognitive radios, identifies the available spectrum, and broadcasts this information to other cognitive radios or directly controls the cognitive radio traffic. Data fusion technique is applied to combine the local detection data [26]. Techniques that include the detection of primary transmitter (PT) were fuzzy logic collaborative sensing [27], asynchronous cooperative sensing [28], weighted cooperative sensing [30] etc. Transmitter based detection techniques have to rely on the detection of weak signals received from the licensed user. The performance of these techniques is highly degraded in shadowing and fading environments. In this situation, sensing information is more helpful for accurate primary transmitter detection referred to as cooperative detection. Spectrum sensing is performed in two steps i.e. Local spectrum sensing at each CR and collective decision at Decision center. Each CR user performs its spectrum sensing individually, which can be formulated as a binary hypothesis test shown in below equation [41]:

$$s_i(t) = \begin{cases} n(t) & \mathrm{H_0}\ \text{(CR user absent),} \\ hm(t)+n(t) & \mathrm{H_1}\ \text{(CR user present)} \end{cases} \tag{6}$$

where $s_i(t)$ is the signal received by the i^{th} CR user, m(t) is primary transmitter signal, n(t) is the additive white Gaussian noise(AWGN) and h(t) is the impulse response of the channel.

1.6.1 Energy detector spectrum sensing[34,41]:

The local decision at each node can be taken by applying any of the transmitter based technique like match filter, cyclo-stationary and energy detection. Under the same probability of detection the sensing node with lower SNR requires more observation time as compared to higher SNR. Hence there is a trade-off between SNR and observation interval to have specific probability of detection and false alarm. For a constant bandwidth the SNR required to achieve a desired detection probability is inversely proportional to $\sqrt{T}$, where T is the observation interval [41].

$$SNR \approx K\left(\frac{1}{\sqrt{T}}\right) \tag{7}$$

For local nodes, energy detection is a simple and efficient method. It accumulates energy in a certain range of frequency. When the energy exceeds a certain threshold value V_T, it can be concluded that signal from primary user exists. After nyquist sampling, received signal energy can be expressed as [41]:

$$V = \sum_{i=1}^{N} \left|y_i\right|^2 \tag{8}$$

The signal with duration of T and bandwidth of W can be represented by N sampling points, while N=2TW is two times product of duration and bandwidth. If output sampling points are approximately regarded as independent Gaussian variables, output energy meets chi square distribution. On the condition of H_o and H_1 output statistics are subject to central and non-central chi square distribution with freedom degree of N respectively. When N stands at a certain large value, detection statistics can approximately be regarded in accordance with Gaussian distribution [41]:

$$\begin{cases} H_1: & \mathrm{V} - \mathrm{N}\left(\mathrm{N}\left(\sigma_{\mathrm{n}}^2 + \sigma_x^2\right), 2N\left(\sigma_n^2 + \sigma_x^2\right)^2\right) \\ H_o: & \mathrm{V} - \mathrm{N}\left(\mathrm{N}\sigma_n^2, 2N\sigma_n^4\right) \end{cases} \tag{9}$$

where σ_n^2 represents noise variance and σ_x^2 represents signal average power [34].

1.6.2 Collaborative sensing using Fuzzy logic

Here, the local decisions are made by CR user which sends its decision to DC (Decision Center). DC multiplies the decision with the credibility of CR user, which takes a collaborative decision regarding presence of PT. This spectrum sensing technique comprises of two phases. First is learning phase and second is decision phase [41-42].

Learning phase:

In learning phase decision center have three sets for each CR user i.e. Quality attributes set, Estimation set and Fuzzy transformation set to calculate the credibility of each CR user. The Quality attributes are QA= {Detection probability, Misdetection probability, false alarm probability} and weight assigned to these quality attributes is WQA= {0.5, 0.3, 0.2}. The Estimation set is ES= {Very Good, Good, Medium, Bad, Very bad} and weight assigned to the estimation set is WES= {1, 0.8, 0.6, 0.4, 0.2}. Consider m tests are performed in this phase and the resultant is single quality attribute matrix with order of 3x5 for each CR user [41-42].

$$\mathrm{SQA} = \left[\frac{A_{ij}}{m}\right] \tag{10}$$

where A_{ij}=count(QA_i,ES_j), i=1,2,3 and j=1,2,3,4,5.

Now each row of matrix represents one of the qualities attribute where as each column represents one of the estimation sets. Credibility of each CR user is computed from the following equation [42]

$$C_i = (WQA_i \text{ o } SQA_i) \text{ x } WES \tag{11}$$

where i=1, 2, 3 …N which are the CR users.

Decision phase:

In this phase decision center obtains the local decisions of each CR user denoted by D_i where i=1, 2, 3 …..N and N is the number of CR users. $UD_i=C_iD_i$ is used to compute the decision of each CR user including the credibility. Now decision center computes a decision metric based on following formula, which is denoted by DM [42].

$$DM = \sum_{i=1}^{N} UD_i \tag{12}$$

where C_i is the credibility of i^{th} user computed during learning phase. Finally, decision center compares the DM with a predetermined threshold and declares that a primary transmitter is present or absent.

1.6.3 Asynchronous cooperative sensing:

The major aim of asynchronous cooperative spectrum sensing technique is to reduce the detection time of primary transmitter so that CR user communicating on a particular band can evacuate this band as soon as primary transmitter is detected. This technique is divided into 2 phases: sensing phase and reporting phase [41-43].

Sensing phase:

Each CR user performs spectrum sensing locally and makes the decision whether the primary transmitter is present or not. The observation time T required for sensing at a particular CR user is dependent on the SNR of received signal from primary transmitter.

Reporting phase:

The observation interval for a CR user with higher SNR is smaller as compared to a user with lower SNR. As a result, user with higher SNR sends its local decision to the decision center earlier than with lower SNR. Three novel selective reporting strategies are used to reduce the duration of the reporting phase while maintaining an acceptable level of performance. In the first strategy, the Dual-Threshold Cooperative Spectrum Sensing (DTCSS), network terminals whose local energy estimates fall within a preset “no decision” region are not allowed to report to the FC. However, this does not reduce the duration of reporting process since the identity of the silent terminals cannot be known a priori. To overcome this, the Maximum Cooperative Spectrum Sensing (MCSS) and the Maximum Minimum Cooperative Spectrum Sensing (MMCSS) strategies are proposed [41-43].

1.6.4 Cooperative sequential sensing [44]:

As the number of cooperating user grows, the energy consumption of the cognitive radio network increases, but the performance generally saturates. It is one of the energy efficient cooperative spectrum sensing. In classical sequential detection, the basic idea is to minimize the sensing energy by minimizing the average sensing time, subject to constraints on the probability of false alarm and missed detection i.e, $P_{FA} \le \alpha$ and $P_{MD} \le \beta$. These two constrains are important in a cognitive radio system, since P_{FA} is related to the throughput of the cognitive radio system, whereas P_{MD} is related to the interference to the primary system. Under i.i.d observations, this leads to so called sequential probability ratio test (SPRT)[45], in which sensing is continued as long as the likelihood ratio Λ satisfies $\eta_1 \le \Lambda \le \eta_2$ and a decision is made otherwise, with $\eta_1 = \beta / 1-\alpha$ and $\eta_2 = (1-\beta) / \alpha$.

1.6.5 Multi-threshold detection methods of local nodes[34]:

Noise uncertainty will lead to energy fluctuation. When the fluctuation goes up to a certain level, just a threshold value would not be enough to judge primary users accurately, since regular fluctuation can also lead to excessive uncertainty around the threshold. To overcome the above issues, an adaptive multi-threshold detection method is exploited at local nodes to adjust to different SNR.

When the SNR is relatively small, if the noise fluctuation during a detection time appears to be large, it will raise probability of false-alarm or probability of miss detection [34]:

$$V = \sigma_n^2 > V_T$$

Or

$$V = \sigma_n^2 + \sigma_x^2 < V_T \tag{13}$$

Thus, this algorithm enables every CR user to utilize energy detection methods of two thresholds (TH2) or four thresholds (TH4) that corresponds to relatively large or small SNR respectively. The two thresholds of the former one are named as T1 and T2 and the detected energy is divided into three ranges, while the four thresholds of the later one are named as T1, Tn2, Tn1 and Th and the detected energy is divided into five ranges.

In four-threshold detection method of low SNR, the credibility of energy range 001 and 011 is relatively higher than that of the other three. 001 tends to represent that primary users do not exist while 011 represents the existence of primary users. When the SNR is high, two threshold detection methods should be used. In this situation, 101 and 1111 have higher credibility than 110.

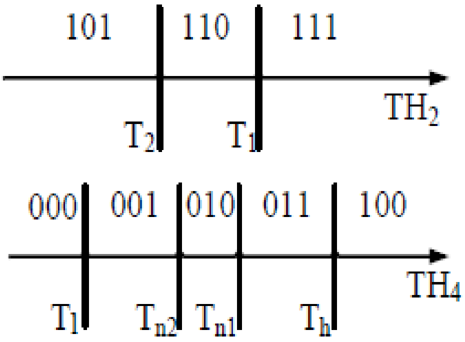

Figure 6: Multiple thresholds based energy detection

Reliability indicates how accurately the spectrum sensing technique has detected the presence of primary transmitter. Observation interval is the time taken to decide the existence of primary transmitter. Complexity is the number of computation involved in the observation interval. To improve the reliability of sensing decision the credibility of each CR user should be considered. On the other hand, in order to decrease the sensing time the diversity of SNR should be taken into account. For a densely populated licensed spectrum band asynchronous energy detection scheme is most suitable because it requires less time to switch CR user from one band to another band. On the other hand, for a non crowded license spectrum band fuzzy collaborative spectrum is the better option [41].

1.7 Hypothesis testing models in Cooperative spectrum sensing

Signal detection problems are traditionally viewed as statistical hypothesis testing [23, 30]. In absence of the a priori probabilities, such as in radar, the Neyman-Pearson criterion [31, 32] is used where a certain false alarm probability is set, and the probability of detection is maximized. Signal detection is usually viewed as a decision theoretic problem, and commonly modeled to have four components: a source that generates outputs (called hypothesis), a probabilistic mechanism, an observation space and a decision rule. The probabilistic mechanism transforms each output of the source into a point in the observation space which is the only thing accessible to a tester.

Let us consider an observation vector r of N values generated by the probability density functions (PDF) $p_r|Ho\ (R|H_0)$ and $p_r|H_1\ (R|H_1)$, where R is a random variable. Here H_0 and H_1 are the hypothesis that the primary signal is absent and present, respectively. Based on r, the test must choose either H_0 or H_1 corresponding to the decision region Z_0 and Z_1. So, for the whole observation space is represented as $Z = Z_0 \cup Z_1$. There are four possibilities in making the decision:

H_0 is true; H_0 is chosen; (acquisition)

H_0 is true; H_1 is chosen; (false alarm)

H_1 is true; H_1 is chosen; (detection)

H_1 is true; H_0 is chosen; (miss-detection)

where the first and third are correct, the second and fourth are wrong [31].

1.7.1 Composite hypothesis testing:

A composite hypothesis testing approach for cooperative spectrum sensing is proposed which involves a combination of an optimal likelihood ratio test (LRT) statistic based on the Neyman-Pearson (NP) criterion at the fusion center for both hard (one-bit) and quantized (multi-bit) local decisions. The LRT statistic depends on the modulation type, second and fourth order statistics of the primary signal. Due to the unavailability of such side information some testing methods such as Rao test are applied which does not require any prior knowledge about the primary signal. In this method, the locally most powerful (LMP) detectors at the fusion center are used for both cases of hard and quantized local decisions [33].

1.7.2 A 3-state hypothesis test model for cognitive radio systems:

This model makes ternary decisions about channel status: vacant, underutilized, or congested. A simple autoregressive model is also used to rank channels taking channel into considerations. The set of ranked channels is stored in a look-up table. An opportunistic user seeking a channel for its transmission uses the lookup table to access a vacant channel or share the best underutilized channel.

1.8 Transmission Techniques in Cooperative spectrum sensing [35]:

In the absence of PUs, the CRN uses the vacant channels as if they were the PUs. This means that any communication technique can be used, including multiple antenna techniques, relaying techniques, coordinated multipoint techniques, etc. However, as, some of these techniques cannot be used in certain situations, the network terminals need to make intelligent decisions about the deployed transmission techniques. The transmission techniques used in cooperative spectrum sensing are Chase combining Hybrid Automatic Repeat Request (HARQ), Fixed Relaying (FR), Selective Relaying (SR), Incremental Relaying (IR), and Selective Incremental Relaying (SIR).

1.8.1 Chase Combining HARQ [35-36]:

ARQ is an error control protocol that enhances the communication reliability by using acknowledged transmissions. According to this protocol, the transmitting terminal expects a reception acknowledgement for every transmitted packet. If this Acknowledgement (ACK) is not received during a preset timeout, the packet is retransmitted. This process is repeated until an ACK is received or until a maximum number of retransmissions are reached. A combination of an error correction code and ARQ is referred to as HARQ protocol. In HARQ, the receiver sends an ACK if the channel is good and a Negative ACK (NACK) if the channel is bad. When the retransmitted signals contain the same amount of information; the receiver can use Maximum Ratio Combining (MRC) to combine the replicas. This allows the receiver to maximize the SNR. This type of HARQ is referred to as Chase Combining HARQ [35-36].

1.8.2 Cooperative Diversity [35]:

This family of protocols allows single antenna terminals o experience the virtues of space-time diversity through relaying. In general, cooperative diversity protocols can be classified based on the underlying relaying protocol into transparent protocols, e.g., Amplify and Forward (AF), and regenerative protocols, e.g., Decode and Forward (DF). They can also be classified based on the number of hops into dual-hop protocols and multi-hop protocols [37]. For CCI (Co-Channel Interference) environment, a group of researchers have exploited the abundance of relay terminals to propose relay selection strategies that account for CCI effect. Some of the relaying techniques are given below:

Fixed Relaying (FR):

This primitive protocol allows the destination to enjoy spatial diversity at the cost of halving the throughput. A source terminal, S, communicates with a destination terminal, D, through the assistance of an intermediate relay terminal, R. Every transmission consumes two consecutive time slots. In the first slot, S broadcasts the signal to R and to D, while in the second slot; R forwards a generated replica of this signal. Consequently, D combines the two replicas and achieves a better performance.

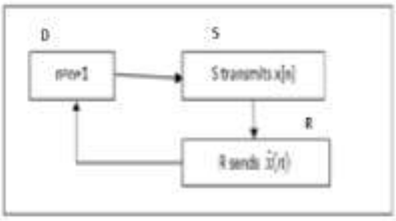

Figure 7: Flow diagram of FR

This relaying protocol suffers from error propagation and throughput reduction. Error propagation results from the fact that R has to regenerate the signal before forwarding it [35].

Incremental Relaying:

In this case, D is likely to successfully decode the signal, and hence, assistance is not needed. Similar to the SR, IR measures the quality of the S-D channel by comparing the instantaneously received SNR/SINR to a preset threshold λ_d. When this threshold is met or exceeded, D sends an ACK asking for a new transmission. Otherwise, it sends a NACK asking R for assistance.

1.9 Cooperation models for decision making

There are three forms of cooperation in spectrum sensing: hard decision (also known as decision fusion), soft decision (also known as data fusion) and quantized decision. The difference between these forms is the type of information sent to the decision maker.

1.9.1 Hard Decision [31]:

In the hard decision fusion scheme, local decisions of the nodes are sent to the decision maker. The main advantage is that it needs limited bandwidth [38]. Every node first performs local spectrum sensing and makes a binary decision on whether a signal of interest is present or not by comparing the sensed energy with a threshold. All the nodes send their one-bit decision result to the decision maker. Then a final decision on the presence of the signal of interest is made by the decision maker.

The detection probability P_d, miss detection P_m and false alarm probability P_f over AWGN channels can be expressed in following way [39].

$$P_{d,k} = Q_m\left(\sqrt{2y}, \sqrt{\lambda}\right) \tag{14}$$

$$P_{m,k} = 1 - P_{d,k} \tag{15}$$

$$P_{f,k} = \frac{\Gamma\left(m, \lambda/2\right)}{\Gamma(m)} \tag{16}$$

where y is the signal to noise ratio (SNR), m=TW is the time bandwidth product, $Q_m(-,-)$ is the generalized Marcum Q-function, $\Gamma(.)$ and $\Gamma(.,.)$ are complete and incomplete gamma functions respectively.

Three of the rules used by the decision maker for a final decision are logical-OR rule, logical-AND rule and majority rule.

Logical-OR rule

In this rule, if any one of the local decisions sent to the decision maker is a logical one (i.e., any one of the nodes decides that the signal of interest is present), the final decision made by the decision maker is one (i.e. decision maker decides that the signal of interest is present) [40].

Logical-AND rule

In this rule, if all of the local decisions sent to the decision maker are one (i.e., all of the nodes decide that the signal of interest is present), the final decision made by the decision maker is one (i.e. decision maker decides that the signal of interest is present) [40].

Majority Rule:

In this rule, if half or more of the local decisions sent to the decision maker are one (i.e., half or more of the nodes decide that the signal of interest is present), the final decision made by the decision maker is one (i.e., decision maker decides that the signal of interest is present) [40].

1.9.2 Soft Combination: [31]

In this scheme, nodes send their sensing information directly to the decision maker without making any decisions. This provides better performance than hard combination, but it requires a wider bandwidth for the control channel. It also requires more overhead than the hard combination scheme. Three major rules used in soft combination are Equal Gain Combining (EGC), Maximal Ratio Combining (MRC) and Optimal Combining (OC).

Equal gain combining:

In this technique, each signal branch weighted with the same factor, irrespective of the signal amplitude. However, co-phasing of all signals is needed to avoid signal cancellation. EGC is simpler to implement than MRC [46].

Maximal Ratio Combining (MRC):

The signals from all the branches are weighted as per their individual signal voltage to noise power ratios and then added with each other. The individual signals must be co-phased before the summing process. Thus MRC produces an output SNR which is sum of individual SNRs of each branch. This provides advantage of having an output with an acceptable SNR even when no individual branch has required SNR [47].

Optimal Combining (OC):

In following technique the signals received by antennas are weighted and combined to maximize the output signal to interference plus noise ratio (SNIR). Thus besides considering the noise power as in MRC, in OC the power of interfering signal is also taken into account.

Quantized fusion:

Instead of sensing the received energy values, the CRs quantize their observations according to their received signal energy and the quantization boundaries. Then, the quantized level is forwarded to the fusion center, which sums up the entire received quantum it re-creates and compares to the fusion threshold [31].

IV. ISSUES IN COOPERATIVE SPECTRUM SENSING

One of the major issues in cooperative spectrum sensing is the introduction of additional overhead referred as cooperative overhead. This overhead includes sensing time and delay, channel impairments, energy efficiency, cooperation sensing efficiency, and security [23].

1.10 Sensing time and delay:

Sensing time is proportional to number of samples taken by the signal detector and sensing delay mainly depends on the sensing technique being used. Sensing efficiency is reduced due to the hardware limitation that a single RF transceiver equipped in each CR cannot simultaneously perform sensing and transmission. Hence throughput performance can be improved by jointly optimizing the sensing time and the number of CR users determining the PUs. The sensing throughput trade-off analysis [48] shows that in addition to sensing delay and CR throughput, the report delay and the delay for synchronization or asynchronous reporting should also be considered.

1.11 Channel impairments:

Channel impairments refer to the phenomena that cause the attenuation and variations of signals propagated through the wireless channels. These phenomena including path loss, multipath fading, shadowing, and interference can inevitably compromise the accuracy of PU detection in spectrum sensing.

1.12 Energy efficiency:

In cooperative sensing, those CR users involved in activity such as local sensing and data reporting consumes additional energy. The energy consumption overhead can be significant if the number of cooperating CR users or the amount of sensing results for report is large. Energy consumption can be reduced by two approaches namely censoring [49] (reducing the amount of reporting data), and by optimization methods [50].

1.13 Sensing efficiency:

Sensing efficiency indicates how often cooperative sensing should be scheduled to sense an appropriate number of channels/bands within a time constraint. It is also a challenge to consider the scheduling of narrowband and wideband sensing in addition to fast and fine sensing to further improve the cooperation efficiency.

1.14 Security:

During cooperation, malfunctioning CR users may unintentionally send unreliable data to the FC. Malicious users may obtain spectrum access by falsely reporting the presence of PUs. Data falsification [51] occurs when detection performance is affected by the falsified sensing data, which is one of the major issues in cooperative transmission. In addition to data falsification problem, there are a variety of security attacks such as PU emulation attack, control channel jamming attack, and node capture attack.

V. CONCLUSION

In this paper, we described the problems faced in non-cooperative type of spectrum sensing and how to overcome those problems using cooperative technique. Also, we have reviewed some of the recent techniques (from 1990-2017) used in solving cooperative spectrum sensing and decision problems. Even though, engineers were striving to solve the problems in cognitive radio, which can be a great boon to mobile technology, some of the throughput tradeoffs restricted this technology to stand behind. We envision that the topic of cooperative spectrum sensing in cognitive radio is a fruitful research area.

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