# Augmented Spectrum Sensing in Cognitive Radio Networks

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**Abstract - Opportunistic unlicensed access to the (temporarily) unused frequency bands across the licensed radio spectrum is currently being investigated as a means to increase the efficiency of spectrum usage. Wireless communication, in which a transmitter and receiver can detect intelligently communicate channels that are in use and those which are not in use are known as Cognitive Radio, and it can move to unused channels. Dynamic spectrum access is a promising approach to make less severe the spectrum scarcity that wireless communications face now. It aims at reusing sparsely occupied frequency bands and does not interfere to the actual licensees. The ability to reliably and autonomously identify unused frequency bands is envisaged as one of the main functionalities of cognitive radios. In this paper, it is proposed that an augmented spectrum sensing algorithm in cognitive radio systems and calculate the optimal value $n_{opt}$ to minimize the error rate in cooperative spectrum sensing.**

**Keywords -** *Cognitive Radio System, Dynamic Spectrum, Spectrum Sensing Algorithm, Cooperative Spectrum Sensing.*

## 1. Introduction

Driven by consumers increasing interest in wireless services, demand for radio spectrum has increased dramatically. Moreover, with the emergence of new wireless devices and applications, and the compelling need for broadband wireless access, this trend is expected to continue in the coming years. The available electromagnetic radio spectrum is a limited natural resource and is getting crowded day by day due to increase in wireless devices and applications. It has been also found that the allocated spectrum is underutilized because of the static allocation of the spectrum. Also, the conventional approach to spectrum management is very inflexible in the sense that each wireless operator is assigned an exclusive license to operate in a certain frequency band. And, with most of the useful radio spectrum already allocated, it is difficult to find vacant bands to either deploy new services or to enhance existing ones. Relatively low utilization of licensed spectrum is largely due to inefficient fixed frequency allocations rather than any physical shortage of spectrum [7, 8]. In order to overcome this situation, we need to come up with a means for improved utilization of the spectrum creating opportunities for dynamic spectrum access [1, 2, 3].

The issue of spectrum underutilization in wireless communication can be solved in a better way using Cognitive radio (CR) technology. Showing support for the cognitive radio idea, the Federal Communications Commission (FCC) allowed for usage of the unused television spectrum by unlicensed users wherever the spectrum is free [4-5]. IEEE has also supported the cognitive radio paradigm by developing the IEEE 802.22 standard for wireless regional area network (WRAN) which works in unused TV channels [6]. Cognitive radios are designed in order to provide highly reliable communication for all users of the network, wherever and whenever needed and to facilitate effective utilization of the radio spectrum.

## 2. Cognitive Radio Network

According to FCC, a cognitive radio can be defined as ”A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets.” Cognitive Radio (CR) is an adaptive, intelligent radio and network technology that can automatically detect available channels in a wireless spectrum and change transmission parameters enabling more communications to run concurrently and also improve radio operating behavior. A cognitive radio system is a ’smart’ network that can observe, learn from, and adjust to changing environment conditions. A network where the spectrum access is allowed only in opportunistic manner and does not have license to operate in a desired band is called Cognitive Radio Network (CRN). Cognitive Radio Networks have been emerged as a promising solution for solving the problem of spectrum scarcity and improving spectrum utilization by opportunistic use of spectrum. Cognitive radio networks utilize the spectrum which is licensed to primary radio users when they are not utilizing it, i.e., when the spectrum is idle. The CRNs can be deployed in network-centric, distributed, adhoc, and mesh architectures, and serve the needs of both licensed and unlicensed applications. The basic components of CRNs are mobile station (MS), base station/access point (BSs/APs) and backbone/core networks.

The main characteristics of cognitive radios are Cognitive Capabilities and Reconfigurability.

- Cognitive Capability - Cognitive capability refers to the ability of radio to sniff or sense information from its environment and perform real time interaction with it. The cognitive capability can be explained with the help of three characteristics; Spectrum Sensing, Spectrum Analysis and Spectrum Decision. The spectrum sensing performs the task of monitoring and detection of spectrum holes. The spectrum analysis will estimate the characteristic of detected spectrum hole. In the spectrum decision, the appropriate spectrum is selected by determining the parameters like data rate, transmission mode etc.

- Reconfigurability - A CR can be programmed to transmit and receive on a variety of frequencies, and use different access technologies supported by its hardware design [9].Through this capability, the best spectrum band and the most appropriate operating parameters can be selected and reconfigured.

The ultimate objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and reconfigurability. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as illustrated in Fig. 1. The cognitive radio enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space [10]. If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference as shown in Fig. 1.

Cognitive radio dynamically selects the frequency of operation and also dynamically adjusts its transmitter parameters.

A common assumption in cognitive radio network is that the licensed users which own the spectrum rights are unaware of the presence of secondary users. Hence the burden of interference management relies mainly on the secondary system. In particular, either (i) there is a maximum interference level that the primary system is willing to tolerate, and the secondary powers/activity are to be adjusted within this constraint, hence both primary and secondary users transmit in the same band, or (ii) secondary users are allowed to opportunistically access the spectrum on the basis of no-interference to the primary (licensed) users. These two paradigms fit into what is commonly known as hierarchical-access schemes, referring to the fact that secondary users need to fulfill the constraints imposed by the primary user (Fig. 2).

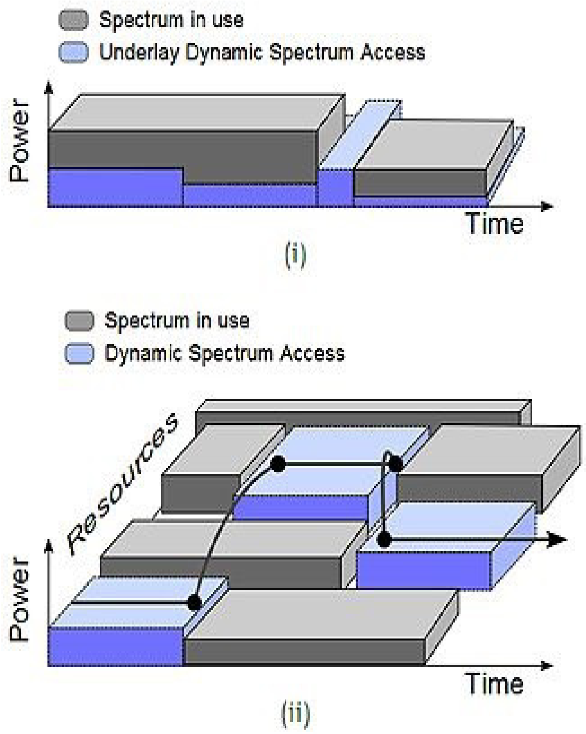


Fig 1 Hierarchical-access paradigms: (i) Underlay dynamic spectrum access, (ii) Overlay dynamic spectrum

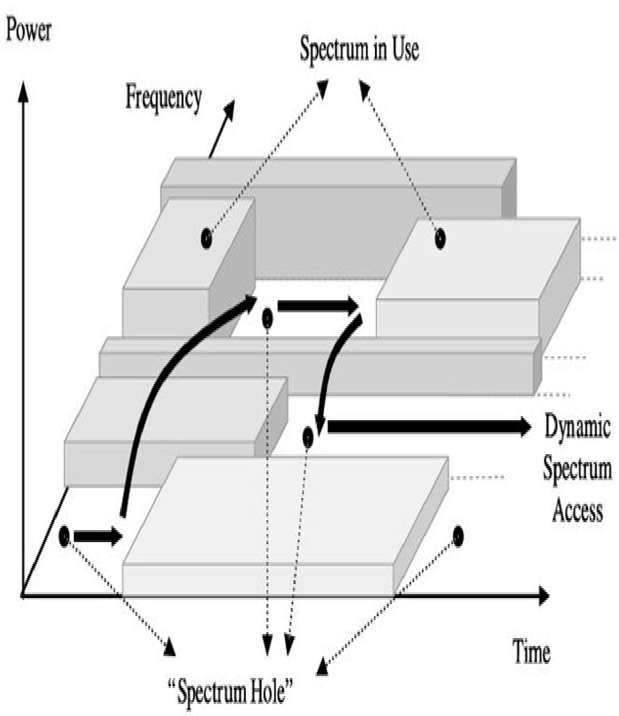


Fig 2 Spectrum hole concept

## 3. Related Work

The main component of cognitive radios is their ability to dynamically manage the spectrum. Spectrum management allows the optimal sharing between the primary, licensed users and the secondary users to reduce the waste of underutilized frequency bands. Alkyidiz [11] details the four primary steps of the spectrum management framework:

1. Spectrum sensing: The ability to detect the available spectrum bands and determine available frequency holes.
2. Spectrum decision: The policies in which the available spectrum will be allocated.
3. Spectrum sharing: The coordination among multiple cognitive radio users to prevent interference.
4. Spectrum mobility: The capability to move frequency bands if the primary user has current control of a particular spectrum.

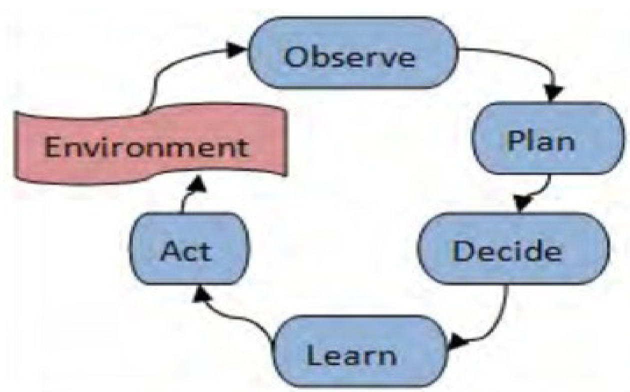


Fig 3 Cognitive Cycle

The radio takes information about its operating Environment through direct or through signal observation inspection, in practice the techniques of spectrum sensing (Observe), that detects these Spectrum holes. For that, Cognitive Radio devices are also known as White Space Devices (WSD). This information is then pre-processed and evaluated to determine the priority. Based on these evaluations, the radio will consider the alternatives (Plan) and chooses one by allocating the necessary resources in the right way (Decide). If the priority is normal, from the Plan status we go on to Decide and then to Act.

This process is known as Cognitive Cycle. After all these steps, the cycle begins alternating with periods of rest, known as sleep, in which the radio is in standby.

### 3.1 Classification of Techniques

The main challenge to the Cognitive radios is spectrum sensing. In spectrum sensing there is a need to find spectrum holes in the radio environment for CR users. However it is difficult for CR to have a direct measure of channel between primary transmitter and receiver [11].
A CR cannot transmit and detect the radio environment simultaneously, thus, we need such spectrum sensing techniques that take less time for sensing the radio environment. In literature the spectrum sensing techniques have been classified into following two categories [11].

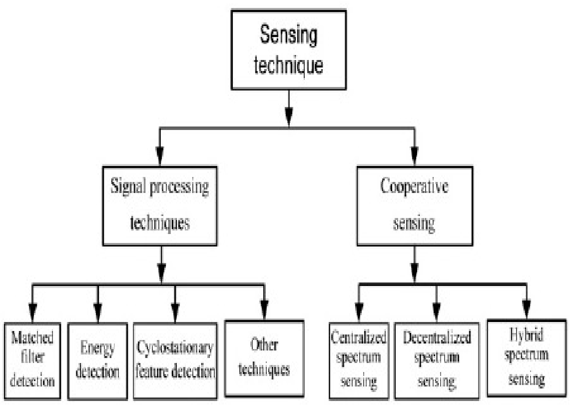


Fig 4 Classification of Spectrum Sensing Techniques

### 3.2 Matched Filter Detection

Matched-filtering sensing is the optimal detector when the primary transmitted signal is known to the receiver. The receiver correlates the received signal to a complex, conjugate, time reversed version of it and maximizes the SNR. This requires perfect receiver knowledge of the bandwidth, operating frequency, modulation type, pulse shaping, and frame format. The matched-filter performs poorly when information about the transmitted signal is not accurate, which could decrease the accuracy in widely varying systems [13]. If the receiver has perfect knowledge, then this method outperforms the others in terms of accuracy and requires a short time to achieve a particular probability of detection. However, perfect knowledge is typically not feasible in most practical applications, which restricts the robustness of matched filtering sensing.

Jiang et al. in [14] computed the theoretical probability of detection and verified the calculations with simulations. The probability of detection for various SNR values and probability of false alarms is calculated. Based on the results, matched-filter detection performs very well at low SNRs, as well as at providing a low probability of false alarms. This improvement in detection comes with an increased complexity. Due to demodulation, the receiver has to synchronize with the primary carrier and possibly perform channel equalization. However, since the receiver has significant knowledge about the primary signal, only O (1/SNR) samples are needed to meet a particular probability of detection (15).

### 3.3 Energy Detector based Sensing

The energy detector based sensing approach detects the primary users signal by comparing the output of an energy detector to a fixed threshold. The fixed threshold is a design choice that depends on the variance of the noise. The simplified signal that the CR receives is modeled as [12].

$$y(i) = s(i) + n(i) \qquad (1)$$

where y(i) is the received signal, s(i) is the primary users transmitted signal, and n(i) is the noise, which is assumed to be additive white Gaussian noise (AWGN). The index I denotes the sample. If the primary user is not transmitting, then s(i) = 0, and the received signal contains only the noise component. In order to make a decision about the availability of a frequency band, the receiver for the traditional energy detector (TED) compares the threshold to a decision metric.

$$N = \sum |y(i)|^2 \qquad (2)$$

where N is the total number of received samples. Therefore, if the energy of the received signal is greater than a threshold (λ), then this particular frequency band is detected as being in use. In [16] the authors proposed the energy detector as shown in Figure 7. The input band pass filter selects the center frequency (f) and bandwidth of interest (W). The filter is followed by a squaring device to measure the received energy then the integrator determines the observation interval, T. Finally the output of the integrator, Y is compared with a threshold, to decide whether primary user is present or not. A common challenge with energy detector based sensing is choosing a threshold that will allow for accurate and reliable detection. Since the received signal is the transmitted signal plus noise, or only the noise component, the threshold depends on the noise. If the receiver has a noise estimation error, this could provide a threshold that is too high or low, which produces false positives or negatives.

### 3.4 Cyclostationary based Sensing

Cyclostationarity refers to the built-in periodicity in the mean and autocorrelation of the transmitted modulated signal. Cyclostationarity arises from sine wave carriers, pulse trains, cyclic prefixes, and various other sources [13]. Cyclostationarity based sensing exploits the cyclostationarity features of the received signal by using the cyclic correlation function to detect primary user's signals. The cyclic spectral density functions as defined in [12].

$$S(f,a) = \sum_{T = -\inf}^{\inf} R_y^{\alpha}(\tau)\, e^{-j2\Pi f\tau} \quad (3)$$

Where $R_y^{\alpha}$ is the autocorrelation function and is the cyclic frequency. The function outputs peak values when the cyclic frequency is equal to the transmitted signals fundamental frequency.

### 3.5 Coherent Waveform based Sensing

Coherent based sensing, or waveform sensing, is performed by correlating a received signal with itself. This sensing method requires that the transmitted signal contain a known pattern, such as a preamble, midamble, or pilot sequence. Using the same received signal as in (i), the decision metric now becomes

$$M = Re[\sum_{i=1}^{N} y(i)\, s^*(i)] \quad (4)$$

Similar to the previous method, the decision metric is compared to a fixed threshold to determine if a transmitted signal is detected. When the primary user is transmitting, the decision metric becomes

$$M = \sum_{i=1}^{N} |s(i)|^2 + Re[\sum_{i=1}^{N} n(i)\, s^*(i)] \quad (5)$$

Coherent based sensing offers improved reliability and requires fewer samples to converge to a decision metric when compared to energy detector sensing. However, the primary restriction is that the receiver requires the transmitted signal to contain a known pattern. In practice, the exact positions of the pattern may not be known, which would require position estimation. This increases the implementation complexity of coherent based sensing.

### 3.6 Cooperative vs. Non-Cooperative Sensing

The detection behavior can be categorized into two main branches, Non cooperative and cooperative. In non-cooperative detection behavior cognitive radio user can detect the signal of primary transmitter by its own observation and analysis independent of the other cognitive radio users. While in Cooperative detection behavior the information from many cognitive radio users are combined to detect the primary user. Moreover, Cooperative behavior helps to overcome the multi path fading and shadowing effect that will increase its usability. There are two ways for the implementation of cooperative detection, centralized and distributed. In Centralized Cooperative detection mechanism the base station is responsible for gathering all information from other cognitive radio users to detect the primary user. While in distributed mechanism, cognitive radio exchange messages among each other to get the desired objective. With comparison to non-cooperative mechanism cooperative detection provides more accurate performance at the expense of additional operations and overheads but it still lacks about location of the primary receive.

### 3.7 Reactive vs. Proactive Sensing

Spectrum sensing schemes may be broadly categorized as reactive and proactive, depending on the way they search for white spaces. Reactive schemes operate on an on-demand basis where a cognitive user starts to sense the spectrum only when it has some data to transmit. Proactive schemes, on the other hand, aim at minimizing the delay incurred by cognitive user(s) in finding an idle band by maintaining a list of one or more licensed bands currently available for opportunistic access through periodic sensing of the spectrum. Of course, the enhanced responsiveness toward data transmission requests comes at the cost of increased sensing overhead. Therefore, choosing the appropriate sensing mode involves a trade-off between the periodic sensing overhead and the on-demand sensing overhead. Intuitively, delay-sensitive applications favor proactive sensing as the delay associated with reactively finding an idle band may be significant (e.g., when searching over a crowded region of the spectrum with a relatively small number of white spaces available). On the other hand, energy efficiency concerns along with the delay tolerance of the application may warrant the selection of reactive sensing. As such, to maintain optimum performance, a cognitive radio has to adapt its sensing mode to the varying spectrum usage, available resources, and application characteristics.

As soon as a cognitive radio starts to utilize a white space, it no longer has a choice regarding the sensing mode and has to sense the band proactively at periodic intervals. As discussed before, this will ensure timely detection of any primary users trying to reclaim the band as mandated by the regulatory bodies.

## 4. Problem with Spectrum Sensing

Spectrum sensing in cognitive radio networks is challenged by several sources of uncertainty ranging from channel randomness to device level and network-level uncertainties. Since spectrum sensing should perform robustly even under worst case conditions, such uncertainties usually have implications in terms of the required detection sensitivity, as discussed below.

### 4.1 Channel Uncertainty

Under channel fading or shadowing, a low received signal strength does not necessarily imply that the primary system is located out of the secondary users interference range, as the primary signal may be experiencing a deep fade or being heavily shadowed by obstacles. Therefore, spectrum sensing is challenged by such channel uncertainty since cognitive radios have to be more sensitive to distinguish a faded or shadowed primary signal from a white space. Any uncertainty in the received power of the primary signal translates into a higher detection sensitivity requirement. Under severe fading, a single cognitive radio relying on local sensing may be unable to achieve this increased sensitivity since the required sensing time may exceed the sensing period, Tp.

This issue may be tackled by having a group of cognitive radios share their local measurements and collectively decide on the occupancy state of a licensed band.

### 4.2 Noise Uncertainty

In order to calculate the required detection sensitivity, the noise power has to be known. Such a priori knowledge, however, is not available in practice, and Noise power has to be estimated by the receiver. Unfortunately, calibration errors as well as changes in thermal noise caused by temperature variations limit the accuracy with which noise power can be estimated. Since a cognitive radio may violate the sensitivity requirement due to an underestimate of noise power, detection sensitivity should be calculated with the worst case noise assumption, thereby necessitating a more sensitive detector.

Spectrum sensing is further challenged by noise uncertainty when energy detection is used as the underlying sensing technique. More specifically, a very weak primary signal will be indistinguishable from noise if its SNR falls below a certain threshold determined by the level of noise uncertainty. Feature detectors, on the other hand, are not susceptible to this limitation due to their ability to differentiate between signal and noise.

### 4.3 Aggregate Interference Uncertainty

With widespread deployment of secondary systems in the future, there will be increased possibility of multiple cognitive radio networks operating over the same licensed band. As a result, spectrum sensing will be complicated by uncertainty in aggregate interference (e.g., due to the unknown number of secondary systems and their locations). In particular, even though a primary system may be out of any secondary systems interference range, the aggregate interference may turn out to be harmful. This uncertainty calls for more sensitive detectors as a secondary system may harmfully interfere with primary systems located beyond its interference range, and hence should be able to detect them. Energy detection sensing method performs very well in detecting free bands but performs poorly at low signal to noise (SNR) ratio due to noise sensitivity. Cyclostationary sensing method can detect spectrum holes in low SNR accurately but are computationally expensive.

Computational complexity and estimation time are two important factors in spectrum sensing. In this paper we formulate an enhanced sensing technique which uses energy detection and cyclostationary sensing method as both these methods are complimentary to each other.

## 5. System Model

H0: y[n] = w[n] ) => Primary User absent
H1: y[n] = x[n] + w[n] ) => Primary User present
n = 0, 1, …. (N - 1) (N - Sample observation window of received signal)

x[n] = transmitted signal

w[n] = noise (zero - mean AWGN with variance $\sigma_w^2$ )

y[n] = transmitted signal

$H_1$ and $H_0$ denote the binary hypothesis that a primary user is present and absent, respectively. The binary hypotheses( $H_0$,$H_1$)are defined in a way such that, under hypothesis H1 and n Є [1,.., N], the $n^{th}$ collected sample, y(n) , is composed of a primary user signal sample x(n) that follows a normal distribution of zero mean and variance $\sigma_w^2$ affected by the channel coefficient, plus an additive Gaussian noise sample, w(n).

### 5.1 Augmented Spectrum Sensing Algorithm

It is assumed that $N_0$ is constant in time. Let $X_i$ be the energy of the N received samples during an observation time T after the $i^{th}$ iteration, $\xi$ a variable threshold that is first initialized at infinity. At the beginning of the sensing, the energy detector calculates the energy X of the received samples after an observation time T, then if X falls inside the interval [0, $\xi$], the energy detector cannot make a direct decision of type signal present or signal absent. In that case, the adaptation stage presented will call the cyclostationary block to make the decision. After the decision of the cyclic test is taken, if it is of the type signal present (resp. signal absent), the calculated value X is then saved in a buffer called $buffer_2$ of size $N_2$ (resp. $buffer_1$ of size $N_1$). The algorithm continues in the same way except when $buffer_2$ is full. In this case, the adaptation stage starts to modify the value of the threshold $\xi$ according to the average of $buffer_2$ and then the oldest value in the buffer will be replaced by the new calculated one ($X_i$ after the $i^{th}$ iteration). At any time, if the calculated value X is greater than $\xi$ the adaptation stage will take automatic decision of type signal present avoiding the use of the cyclic test.

When $buffer_1$ is full, its mean 1 will be calculated. Then, the enhanced sensing algorithm will use the following equation to estimate $N_0$ using $N_0=\mu_1/BT$ (since the distribution of X under $H_0$ follows a Gaussian law with mean $\mu_1 = N_0 . B.T$), then using $\hat{N}_0$ we can estimate $\xi$ that guarantees the desired false alarm $P_{fa,des}$ from the equation, $\hat{\xi} = f(P_{fa,des})\,\hat{N}_0$. It should be noted that $N_1$ is big enough (bigger than $N_2$) in order to make a good estimation of $N_0$.

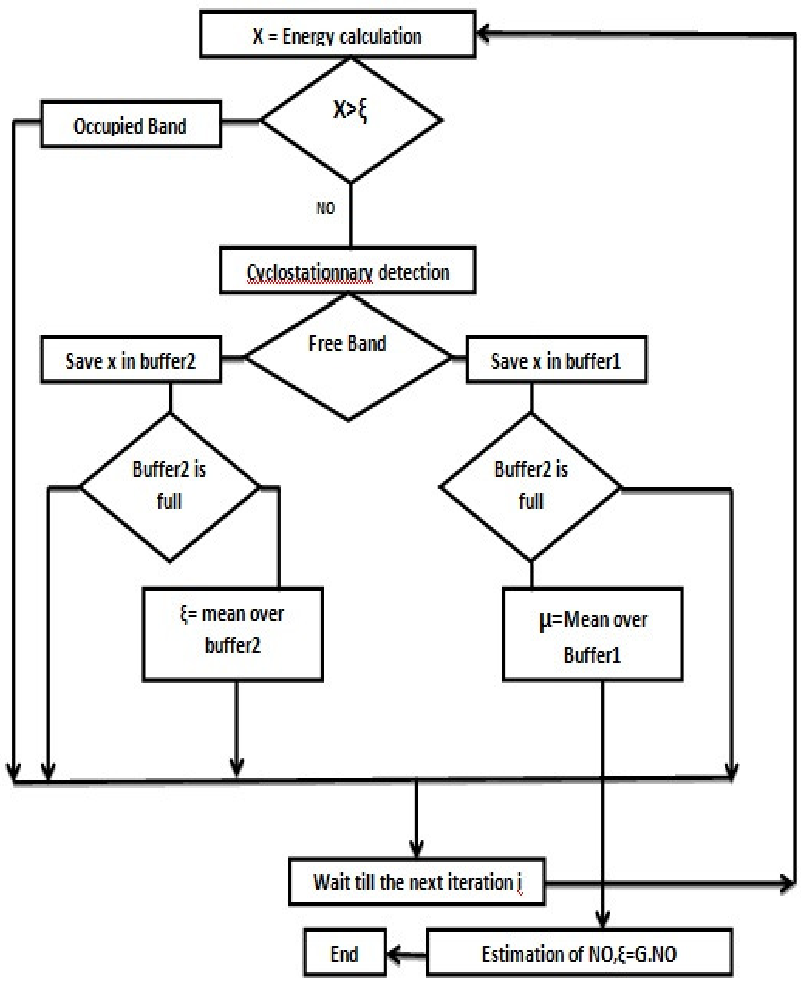


Fig 5 Augmented Spectrum Sensing

## 6. Simulation Model

We consider cognitive network with K number of CR's, one primary user and one fusion centre (i.e. common receiver). The spectrum sensing is done by each CR independently. The decisions taken by CR are sent to the fusion centre then fusion centre will decide that primary user is present or absent. We consider two hypotheses:
$H_0$: The primary user is absent.
$H_1$: The primary user is in operation.

The cooperative spectrum sensing, where number of CR's takes binary decision based on local observation and forwards a bit decision Di to the common receiver. These decisions are summed at common receiver and it will decide whether the PU is absent or in operation.

$$Y = \sum_{i=1}^{K} D_i \begin{Bmatrix} \geq n, H_1 \\ \leq n, H_0 \end{Bmatrix} \quad (6)$$

Here, n is the threshold representing "n-out-of-K" rule. If the number of CR is one, i.e. n=1 then it corresponds to OR rule and if n = K then it corresponds to AND rule.
The false alarm probability of cooperative spectrum sensing is given by

$$Q_f = \text{Prob}\{H_1 \mid H_0\} = \sum_{i=n}^{K} \binom{K}{l} P_f^{l} \ (1 - P_f)^{K-1} \quad (7)$$

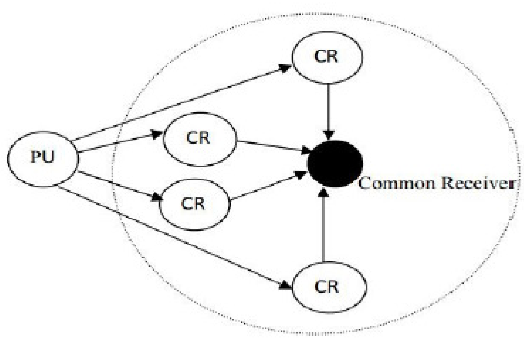


Fig 6 Cooperative Spectrum Sensing

The missed detection probability of cooperative spectrum sensing is given by

$$Q_m = \text{Prob}\{ H_0 \mid H_1\} = 1 - \sum_{l=n}^{K} \binom{K}{l} P_d^{l} \ (1 - P_d)^{K-1} \quad (8)$$

Let, K is fixed then what will be optimal value of n so that we get minimum error rate ($Q_f + Q_m$), this is the optimal voting rule and optimal value of n is called as $n_{opt}$. We have plotted graph for n=1 to n=10. For each n, for different threshold values, we calculated error rate. For small threshold value, we get more error rate and optimal rule AND rule (i.e. n =10). For large threshold value, optimal rule is OR rule. But when n = 5, we get more error rate for medium threshold values.

Statement: To find $n_{opt}$ value for minimum error rate we proposed solution as follows:

$$n_{opt} = \min\left(K, \left\lceil \frac{K}{1+\alpha} \right\rceil\right) \quad (9)$$

Where $\alpha = \dfrac{\ln \frac{P_f}{1-P_m}}{\ln \frac{P_m}{1-P_f}}$

and [.] denotes the ceiling function.

## 7. Conclusion

As spectrum sensing in cognitive radio is subject to time constraints, we have proposed a low complexity architecture, which combines two systems. This architecture benefits from the advantages of both systems, the first one is a low complexity detector, but needs a good estimation of the noise level $N_0$ as for the second, it is a more complex system based on cyclostationary detection, but is less sensitive to a poor estimation of $N_0$.
The hidden terminal problem in cooperative spectrum sensing need to be solved and result will be simulated in MATLAB.

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