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Analysis of Spectrum Sensing Techniques for Cognitive Radio Networks (CRN): A Boon for Wireless Communication

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***Abstract*— Increasing demand of multimedia services requiring use of higher data rates and the overcrowding of the fixed spectrum has led to the concept of spectrum holes. The white spaces can be exploited by Cognitive Radio (CR) by introducing the concept of Dynamic Spectrum access (DSA) with the aim of enhancing the spectrum efficiency and reducing spectral congestion. Spectrum Sensing Techniques that are considered as the heart of Cognitive Radio are used to sense the spectrum and allowing secondary users to utilize the vacant band at a particular time and geographical area. A comprehensive literature review is done for different types of spectrum sensing techniques and their comparative analysis is being done in this paper.**
***Keywords*— Cognitive Radio, Spectrum Sensing Techniques, Energy Detection, Matched filter detection, Cyclostationary Feature Detection, Cooperative Sensing, Opportunistic usage, Spectrum hole**

I. INTRODUCTION

The need of flexible and robust wireless communication has increased in the recent years but as the radio frequency spectrum is a scarce and expensive resource which is licensed by the government for its use (except ISM band) [1], it becomes the bottleneck in satisfying the ever increasing demand of customers for the services. Other factor burdening the frequency spectrum is the need of higher data rates for the multimedia services [2]. During any operation, some portion of the spectrum is used heavily while the other part of the spectrum remains underutilized. To address this problem of spectrum scarcity i.e. under-utilization, 'cognitive radio' (CR) is a tempting solution. The term 'cognitive radio' was coined by Joe Mitola [3]. It can be considered as an intelligent wireless communication system, as it is aware of the radio frequency environment. The user having the license or legal rights to use a specific frequency band is termed as the primary user and all other users are called secondary users. Interconnected CRs form cognitive radio network (CRN).

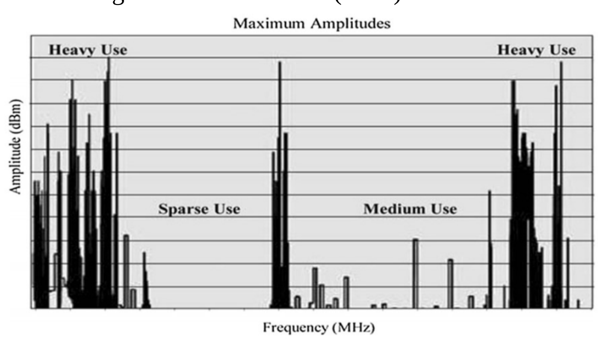

Fig. 1 Fixed Spectrum Utilization [9]

CR provides opportunistic access to the spectrum by identifying the spectrum holes or white spaces and allows the secondary users to use the free bands in the absence of primary users [2]. A spectrum hole is defined as the range of frequencies assigned to a primary user but that is not being utilized by that user at a particular time and geographical area [3]. The main function of CR is spectrum sensing i.e. sensing the presence of primary users continuously and, if not present, allowing secondary users to access the channels while avoiding interference to licensed users by the condition that the SU has to vacate the band in case PU transmission is detected [1]. Even after entering into the transmission, the bands must be continuously checked for any primary user ready to transmit in the range. Hence, CR is defined as a wireless communication device which detects the communication channel intelligently and adopts its parameters according to the statistical variation of the environment and providing efficient utilization of the spectrum [3]. It enables a smooth and interactive way of using the spectrum. Imperfect sensing lead to false detection (P_{fa}) and misdetection (P_m) thereby increases interference to primary users [4].

The definition of cognitive radio adopted by Federal communications commission (FCC): *"Cognitive Radio: A radio or system*

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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" [2].

Currently, the communication is carried out using static or fixed spectrum access (FSA) which does not have any provision of sharing while cognitive radio uses Dynamic spectrum access (DSA) in which unlicensed users are allowed to use the licensed band by changing its parameters dynamically [5] in the absence of licensed ones improving the usage of the channel.

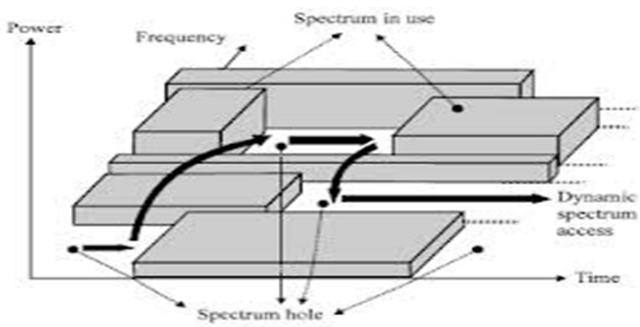

Fig. 2 Spectrum holes and spectrum in use [8]

II. COGNITIVE RADIO

The CR senses the environment and adopt according to it. The steps performed to adapt to the surroundings are collectively termed as cognitive cycle [3].

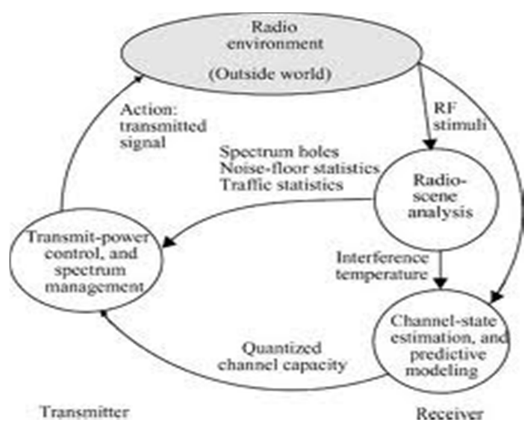

Fig. 3 Basic cognitive cycle [3]

A. Basic Cognitive Tasks

1) *Spectrum Sensing*: It is the most important component of CR and is performed by receiver. At this stage, radio scene analysis takes place which includes
   a) Detection of the white spaces
   b) Calculation of the interference temperature of the radio channel which is a parameter used to specify maximum limit of acceptable RF interference.
2) *Spectrum Analysis*: Spectrum Analysis is based on spectrum sensing. This stage includes:
   a) Channel state estimation and predictive modeling.
   b) Calculation of various parameters such as error rate, throughput for each spectrum hole that were detected by sensing and finding optimal one accordingly.
3) *Spectrum Decision Making:* It is based on the channel state information (CSI) obtained during spectrum analysis. It includes:
   a) Transmit power control performed by transmitter.
   b) Spectrum management by selecting best possible hole for detection.

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The transmitter and receiver should be synchronized and to maintain it, feedback channel is provided between transmitter and receiver to transmit the performance information of the forward link to the transmitter. Therefore, CR is an example of feedback communication system [3].

B. Cognitive Radio Characteristics

1) Cognitive capability: It enables the CR to sense the environment for the white spaces and choose the best available one to maximize several utility functions such as throughput without causing any interference to primary users. It encompasses all the steps of the cognitive cycle.

2) Re-configurability: It is the property which enables the CR to adapt to the surroundings by changing its parameters dynamically and allows SUs to use the band. It is implemented by using Software Defined Radio (SDR) [1].

III.SPECTRUM SENSING TECHNIQUES

Spectrum sensing techniques can be classified into two broad categories:

A. Non Cooperative techniques : Transmitter Detection

1) Energy detection

2) Matched filter detection

3) Cyclostationary feature detection

B. Cooperative techniques

1) Centralized sensing

2) Distributed sensing

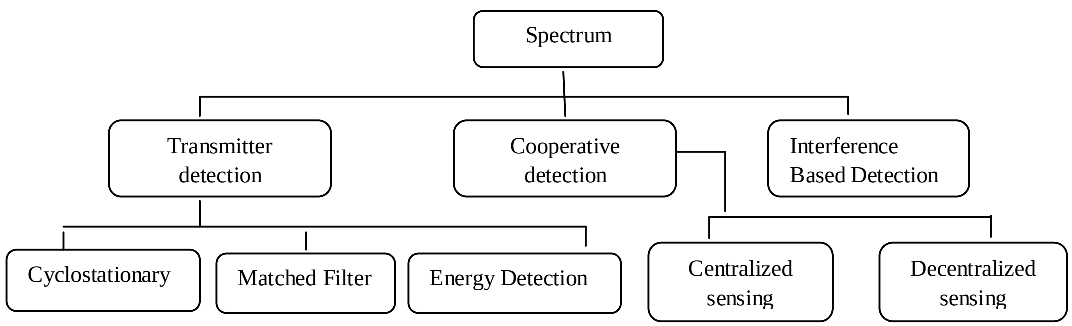

Fig.4 Spectrum Sensing Techniques Classification [8]

A. Non Cooperative Sensing Techniques

1) Energy Detection: Energy detection is the most popular and simplest technique. It is based on the binary hypothesis detection test:

$$y(n) = s(n) \qquad : H0$$

$$y(n) = s(n) * h(n) + w(n) \qquad : H1$$

Where y(n),s(n),w(n) denotes the received signal at the cognitive user, transmitted signal from licensed user, additive white Gaussian noise with zero mean and σ^2 variance respectively .

H0: free band means absence of licensed terminal

H1: occupied band means the presence of licensed terminal

Energy detection is dependent on the predefined detection threshold λ which represents the energy of the noise content in the channel hence depends on the noise floor for the detection of the PU signal. It is also dependent on the SNR. The signal is detected by computing the energy collected in a time interval which then serves as the Decision metric denoted by T [6],[7]. It is also used for comparison.

$$T = \sum_{n=1}^{N} [Y(n)]^2 , \qquad T > \lambda :\ H1$$

$$T < \lambda :\ H0$$

The following parameters are considered to evaluate the performance of the detector by plotting a curve between P_d and P_{fa} called ROC (Receiver Operating Characteristics) [6], [9].

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- Probability of detection (P_d): Channel is vacant and declared as vacant. It should be as high as possible.

$$Pd = P(decision\ of\ H1/H1) = P(\prod(y) > \lambda/H1)$$

- Probability of false alarm (P_{fa}): Channel is vacant and declared as occupied. It should be as low as possible. When signal is absent (H0): The received signal is equal to noise present in the channel.

i.e. y(n)=w(n)

$$Pfa = P(decision\ of\ H1/H0) = P(\prod(y) > \lambda/H0)$$

- Probability of misdetection (P_m): Channel is occupied and declared as vacant [6], [7].

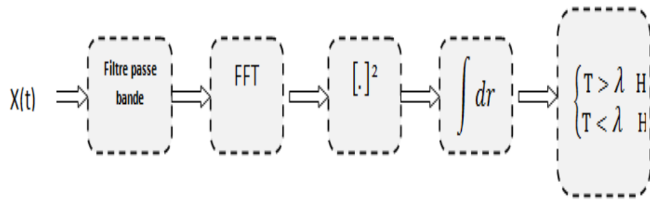

Fig. 5: Energy detection model [6]

The input signal is passed through band pass filter of bandwidth W. In further steps, its energy is calculated in a specified time interval and frequency. The output of the detector is compared with the predefined threshold to detect the presence of primary signal. If the energy is greater than the threshold, the primary user is declared to be present.
In the absence of the primary user H0, the statistical decision T follows a central chi-squared distribution $\chi 2$ with N degrees of freedom[6],[7]:

$$T \sim N(N\sigma^2{}_w, 2N\sigma^4{}_w)$$

In the presence of the primary user H1, the statistical decision T follows a non-central chi-squared distribution $\chi 2$ with N degree of freedom, but according to the central limit theorem, if N> 100, the distribution $\chi 2$ can be approximated by a normal distribution.

$$T \sim N(N\sigma^2_w + \sigma^2{}_x, 2N\sigma^2_w + \sigma^2_x\ )^2$$

Energy detection is a blind sensing method since that it doesn't require any prior information of the transmitted signal. This is one of the important advantages of energy detection. Other advantages include simplest implementation and short sensing time. But it is not efficient under low SNR and noise uncertainty and is unable to differentiate the user and the noise present in the channel. Threshold estimation is also required for energy sensing [7].

2) *Matched Filter Detection:* Matched filter detection is the optimal detection method only when prior information of the PU signal is available such as bandwidth, modulation, frequency. It is based on the principle of correlation as the received unknown signal is convolved with the impulse response of the matched filter which is the known PU signal (reference signal).

$$Y(n) = \sum_{k=-\infty}^{\infty} h(n-k)x(k)$$

Where 'x' is the unknown signal which is convolved with the 'h' which is impulse response of the matched filter that is matched to the reference signal [20]. Matched filter maximizes the SNR under AWGN. It takes comparatively shorter time to achieve required probability of false alarm or probability of misdetection [2]. The decision statistic is D(r):

$$D(r) = \frac{1}{N}\sum_{n=0}^{N-1} y(n) \times s(n)$$

Where s (n): known PU signal
D(r): test statistic [9]

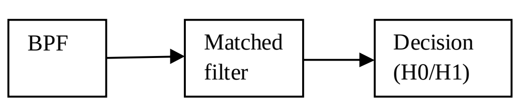

Fig. 6: Matched Filter Detection [20]

As there is need of the prior known PU signal, synchronization is necessary between PU and CU which requires extra hardware. It requires a dedicated receiver for every PU leading to high implementation complexity [9], [10].

3) Cyclostationary Feature Detection: Signals having periodic mean and autocorrelation functions are known as cyclostationary signals. Periodicity occurs due to modulation, coding or pilot data used for synchronization, spreading code or cyclic prefixes which have inbuilt periodicity. Modulated signals are hence cyclostationary in nature whereas noise is a wide sense, stationary signal having no periodicity properties. Hence, any spectral correlation function can be used to differentiate noise from the modulated signal. The presence of the PU signal is detected by analyzing hidden periodicities of the spectrum which reveal information about the PU signal.

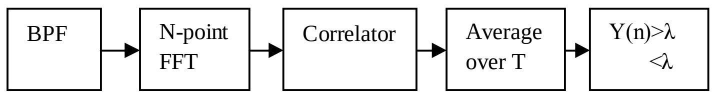

Fig. 7: Cyclostationary feature detector [11]

The input signal is fed to the band pass filter to calculate the energy of the band in use. Now FFT of the received signal is computed and passed to the correlator and then to the integrator. Its output is then compared with the threshold λ which decides about the presence or absence of the primary user [11].

It enjoys the advantage of better ability to differentiate the PU signal and the noise and detection of weak signals in noise. It is more robust in low SNR. It is an optimized technique. But larger observation time and high computational complexity are the main drawbacks [8], [9], [11], [12].

TABLE I COMPARATIVE ANALYSIS OF NON- COOPERATIVE SPECTRUM SENSING TECHNIQUES

Parameters	**Energy detection**	**Matched filter detection**	**Cyclo-stationary feature detection**	**References**
Complexity	Simplest	High Implementation complexity	High computation complexity	[2],[6], [9],[11]
Cost	Least	High	High	[2],[8], [11]
Sensing time	Less	Less	High	[6],[8], [11],[12]
Prior information of PU	Not Required	Required, thus, synchronization needed	Periodicity of signal required	[6]-[12]
SNR	Poor under low SNR	Good under low SNR and Maximizes SNR	Good under low SNR	[6]-[12]
Performance in noise	Can't differentiate PU signal and noise.	Poorly differentiate	Easily differentiate signal and noise based on cyclo-stationarity	[6]-[12]
Threshold	Required	Used after threshold test	PU signal is compared with threshold	[7],[11], [12],[14] [19]
Coherence	Non coherent	Coherent	_	[6],[8], [11],[19]

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B. Cooperative Spectrum Sensing

Cooperative detection is an important detection method in CR to remove the problems encountered in non-cooperative detection, such as hidden nodes, shadow fades which results in uncertain SNR at the receiver input hampering the correct detection of the PU. Cooperative sensing uses multiple CRs for the detection. Spatial diversity makes it unlikely that all the CRs undergo same amount of fading, shadowing and uncertainty and hence improved results are obtained even in shadowed environment [13]. When energy detection is used, all the secondary nodes transmits their sensing results to the fusion center where the final decision about the presence of the PU is obtained using fusion techniques [2],[14]. Cooperative sensing provides reliable detection. It increases Pd and decreases Pfa and Pm. It also reduces sensing time.

1) Centralized Sensing: In centralized sensing, a central unit acts as the spectrum manager as it performs spectrum sensing and allocates resources to the CRs according to the sensing information obtained for efficient spectrum utilization and to avoid overlapped spectrum usage. The Central Unit decides whether the PU is present and broadcasts it to other SUs. It reduces the complexity [2], [21].

2) Distributed Sensing: In distributed sensing, each SU senses the separately and make their own decisions about the part of the spectrum to be used and the information is shared among the CRs. It can use both centralized and distributed sensing [21]. Distributed sensing is more advantageous as compared to centralized sensing as it eliminates the need of backbone network and hence provides reduced cost [2], [15].

3) Fusion Methods: These are of two types:

a) Data Fusion: The signal received from the PU is amplified by CU and forwarded to the fusion center where different techniques can be used such as Square law combining(SLC), Maximal ratio combining(MRC) to decide the presence of PU [14].

b) Decision Fusion: Each SU makes a decision on the PU activity, and the individual decisions are reported to the fusion center over a reporting channel. Fusion rules used can be classified as Soft and Hard rules.
Hard fusion rules are AND, OR, M out of N rule [18].

i. AND: It decides H1 when all results are H1

$$P_d = 1 - \prod_{i=1}^{M} (1 - P_{d,i})$$

$$P_{fa} = 1 - \prod_{i=1}^{M} (1 - P_{fa,i})$$

ii. OR: It decides H1 if any of received decision plus own is H1

$$P_d = \prod_{i=1}^{M} P_{d,i}$$

$$P_{fa} = \prod_{i=1}^{M} P_{fa,i}$$

iii. M out of N rule: It decides H1 when number of H1 decisions is equal to or larger than M.

$$P_d = \sum_{i=0}^{M-K} \binom{M}{K+i} (1 - P_{d,i})^{M-K-i} \times (1 - P_{d,i})^{K+i}$$

$$P_{fa} = \sum_{i=0}^{M-K} \binom{M}{K+i} (1 - P_{fa,i})^{M-K-i} \times (1 - P_{fa,i})^{K+i}$$

TABLE III
COMPARISON OF FUSION METHODS FOR COOPERATIVE SENSING

Character-istics	**Data Fusion**	**Decision Fusion**	**Reference s**
Bandwidth of the Reporting channel	At least equal to BW of sensed channel	Can be of narrow bandwidth	[2],[13], [14],[15]
Complexity	Less	High	[2],[13], [14],[15]

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IV. CONCLUSION

Spectrum utilization through opportunistic usage has become an exciting concept. The most important task to accomplish this is to sense the spectrum availability. Cognitive Radio has proven to be a promising approach. It utilizes dynamic spectrum sharing to fully utilize the scarce spectrum resources. In this spectrum management paradigm, licensed users can share their spectrum with unlicensed users without interfering licensed users. The drawbacks of this non cooperative scenario are removed by using multiple CRs and sensing decisions are taken cooperatively using different methods. CR enjoys the advantages of increasing the efficiency of spectrum utilization and reducing the problem of spectral congestion, hence improves the quality of the wireless communication.

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