3.1 Introduction

Radio spectrum is not efficiently used, mainly due to the prevailing rigid frequency allocation policy. Only some bands of the spectrum - such as those bands used by cellular base stations - are heavily used. Many bands are not used at all or are used only part of the time. Radios using cognitive radio technology are aware of their frequency environment. Spectrum licensing offers an effective way to guarantee adequate quality of service (QoS) for license-holders.

Cognitive radio (CR) technologies have been proposed for lower priority secondary systems aiming at improving spectral efficiency by sensing the environment and then filling the discovered gaps of unused licensed spectrum with their own transmissions. The aim of the cognitive radio is very practical and concentrates on the efficient use of natural resources, which include frequency, time, and transmitted energy. Spectrum sensing is a crucial task in a cognitive radio system. The transmissions of licensed users have to be reliably detected and spectrum sensing is thus the first step towards adaptive transmission in unused spectral bands without causing interference to PUs. The secondary system has to be spectrum aware in order to exploit the available spectrum efficiently. The secondary system can obtain the current spectrum use pattern either actively or passively. Spectrum usesa pattern that shows which frequencies are occupied and which frequencies are available for use in a band of interest at a particular geographic location and a particular time[7].

The spectrum awareness is classified into two forms:

1. An opportunistic one, where the secondary system recognizes the spectrum use pattern individually by sensing techniques.

2. The sharing information approach where spectrum knowledge is distributed through beacons or control channels, or by sharing databases of existing users.

3.2 Spectrum Sensing Techniques

An important requirement of the cognitive radio is to sense the spectrum holes. Cognitive radio is designed to be aware of and sensitive to the changes in its surrounding. The spectrum sensing function enables the cognitive radio to adapt to its environment by detecting spectrum holes.

The most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range of a cognitive radio user. In reality, however, it is difficult for a cognitive radio to have a direct measurement of a channel between a primary receiver and a transmitter [13]. Generally, the spectrum sensing techniques can be classified as transmitter detection, cooperative detection, and interference-based detection, as shown in Figure (3.1).

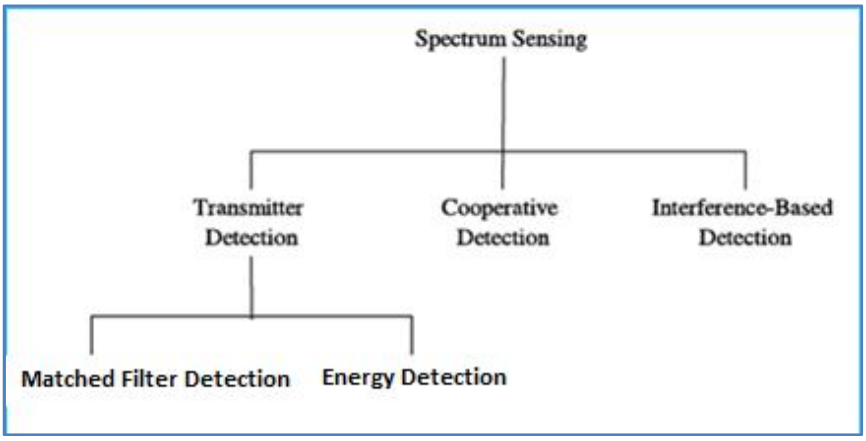

Figure (3.1): Classification of Spectrum Sensing Techniques.

3.2.1 Transmitter Detection

The cognitive radio distinguishes between used and unused spectrum bands. Thus, the cognitive radio hasthe capability to determine if a signal from primary transmitter is locally present in a certain spectrum. Transmitter detection approach is based on the detection of the weak signal from a primary transmitter through the local observations of cognitive radio users.Basic hypothesis model for transmitter detection can be defined as in equation 3.1

$$x(t) = \begin{cases} n(t) H_0 \\ hs(t) + n(t) H_1 \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.1$$

Where$x(t)$is the signal received by the cognitive radio user, $s(t)$is the transmitted signal of the primary user, $n(t)$ isthe AWGN and h is the amplitude gain of the channel.H_0 is a null hypothesis, which states that there isno licensed user signal in a certain spectrum band.On the other hand, H_1 is an alternative hypothesis, which indicates that there exists some licensed user signal[13].

The assumption of the primary transmitter detection is that the locations of the primary receivers are unknown due to the absence of signaling between primary users and the cognitive radio users. Therefore, the cognitive radio relies on only weak primary transmitter signals based on the local observation of the cognitive radio user. However, in most cases, a cognitive radio is physically separated from the primary network so there is no interaction between them. Thus, with the transmitter detection, the cognitive radio user cannot avoid the interference due to the lack of the primary receiver’s information as depicted in Figure (3.2).

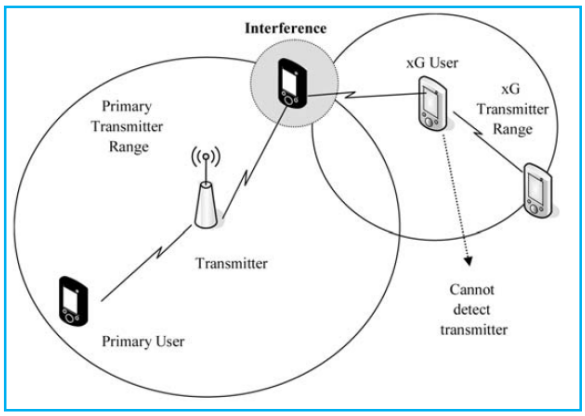

Figure (3.2) Transmitter detection problem: receiver uncertainty.

Moreover, the transmitter detection model cannot prevent the hidden terminal problem. A cognitive radio transmitter can have a good line-of-sight to a receiver, but may not be able to detect the transmitter due to the shadowing problem. Consequently, the sensing information from other users is required for more accurate detection. In the case of non-cooperative detection the cognitive radio users detect the primary transmitter signal independently through their local observations[9].

There are two detection techniquesthat involve the transmitter detection and theses are; Matched Filter Detection and Energy Detection.

1. **Matched Filter**

The matched filter is the linear optimal filter used for coherent signal detection to maximize the signal-to-noise ratio (SNR) in the presence of additive stochastic noise. As shown in Figure (3.3), it is obtained by correlating a known original PU signal s(t) with a received signal r(t) where Ts is the symbol duration of PU signals. Then the output of the matched filter is sampled at the synchronized timing. If the sampled value Y is greater than the threshold λ the spectrum is determined to be occupied by the PU transmission. This detection method is known as an optimal detector in stationary Gaussian noise. It shows

a fast sensing time, which requires O (1/SNR) samples to achieve a given target detection probability. However, the matched filter necessitates not only a priori knowledge of the characteristics of the PU signal but also the synchronization between the PU transmitter and the CR user[7].

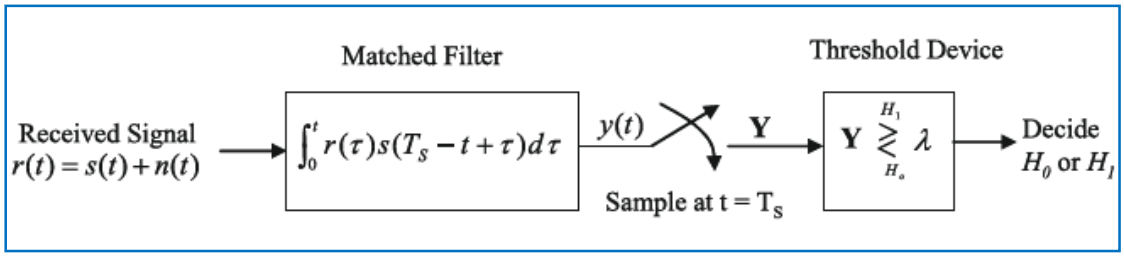

Figure (3.3): Block Diagram of Matched Filter Detection.

If this information is not accurate, then the matched filter performs poorly. Furthermore, CR users need to have different multiple matched filters dedicated to each type of the PU signal, which increases the implementation cost and complexity. For more practical implementation, a pilot signal of PU systems is used for the matched filter detection. In this method, PU transmitters send the pilot signal simultaneously with data, and CR users have its perfect knowledge, which may not still feasible in CRNs. For this reason, energy detection and feature detection are the most commonly used for spectrum sensing [19].

2. Energy Detections

Energy detection is a spectrum sensing method that detects the presence/absence of a signal just by measuring the received signal power. Energy Detection (ED) is the most popular sensing technique in cooperative sensing. The block diagram for the energy detection technique is shown in the figure (3.4)

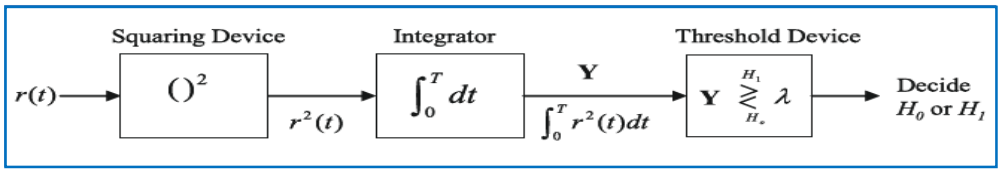

Figure (3.4): Energy Detector Block Diagram

The measured signal r(t) is squared and integrated over the observation interval (T) the signal square to convert voltage to energy and the integration in the period from 0 to T in order to determine the energy in the whole observation interval. Finally, the output of the integrator is compared with a threshold λ to decide if a PU is present.

The threshold value can be set to be fixed or variable based on the channel conditions. Energy detection technique are also called BLIND SIGNAL DETECTION because it ignores the structure of the signal and estimates the presence of the signal by comparing the energy received with a known threshold derived from the statistics of the noise [2]. Signal detection is reduced to a simple identification problem, as a hypothesis test,

$$H0: \ y(n) = w(n)$$

$$H1: \ y(n) = x(n) + w(n)$$

Where:

Y (n) is a received signal.

X (n) is a PU signal.

W (n) is an Additive white Gaussian noise (AWGN).

While the energy detector is easy to implement, it has several shortcomings. Disadvantages associated to ED[2]:

i) High sensing time taken to achieve a given probability.

ii) Detection performance is subject to the uncertainty of noise power.

iii) Using Energy Detection technique it is difficult to distinguish primary signals from the CR user signals.

iv) CR users need to be tightly synchronized and refrained from the transmissions during an interval called Quiet Period in cooperative sensing.

v) ED is not suitable to detect spread spectrum signals.

3.2.2 Cooperative Detection

Cooperative detection refers to spectrum sensing methods where information from multiple cognitive radio users is incorporated for primary user detection. Cooperative detection can be implemented either in a centralized or in a distributed manner. In the centralized method, the cognitive radio base-station plays a role to gather all sensing information from the cognitive radio users and detect the spectrum holes. On the other hand, distributed solutions require exchange of observations among cognitive radio users[13].

The critical challenging issue in spectrum sensing is the hidden terminal problem, which occurs when the CR is shadowed or in severe multipath fading. Figure (3.5) shows that CR 3 is shadowed by a high building over the sensing channel. In this case the CR cannot sense the presence of the primary user, and thus it is allowed to access the channel while the PU is still in operation. To address this issue, multiple CRs can be designed to collaborate in spectrum sensing [9]. Recent work has shown that cooperative spectrum sensing can greatly increase the probability of detection in fading channels [5]. In general, cooperative spectrum sensing can be performed as shown in figure (3.5), CR 1 is shadowed over the reporting channel and CR 3 is shadowed over the sensing channel.

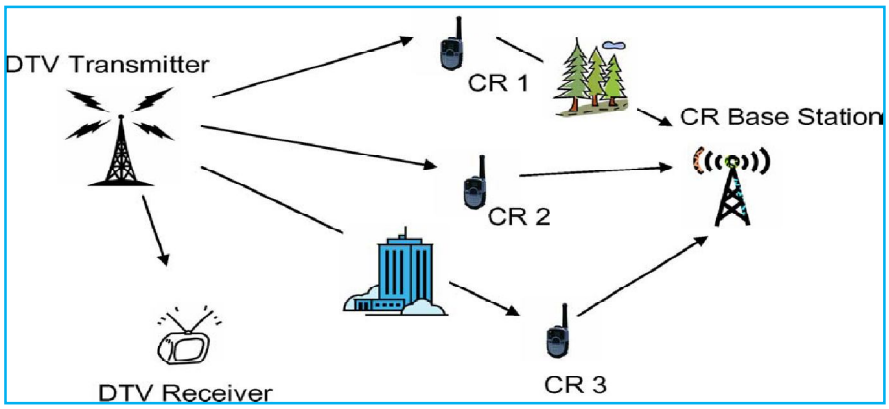

Figure (3.5) Cooperative spectrum sensing.

- **Cooperative Spectrum Sensing:**

1) Every CR performs its own local spectrum sensing measurements independently and then makes a binary decision on whether the PU is present or not.

2) All of the CRs forward their decisions to a common receiver.

3) The common receiver fuses the CR decisions and makes a final decision to infer the absence or presence of the PU.

Generally the data transmission and sensing function are collocated in a single cognitive radio user device. However, this architecture can result in suboptimal spectrum decision due to possible conflicts between data transmission and sensing. In order to solve this problem, two distinct networks are deployed separately, i.e., the sensor network for cooperative spectrum sensing and the operational network for data transmission. The sensor network is deployed in the desired target area and senses the spectrum. A central controller processes the spectrum information collected from sensors and makes the spectrum occupancy map for the operational network. The operational network uses this information to determine the available spectrum[9].

While cooperative approaches provide more accurate sensing performance, they cause adverse effects on resource-constrained networks due to the additional operations and overhead traffic.

3.2.3Interference-based Detection

Interference is typically regulated in a transmitter-centric way, which means interference can be controlled at the transmitter through the radiated power, the out-of-band emissions and location of individual transmitters. However, interference actually takes place at the receivers.

Therefore recently, a new model for measuring interference, referred to as interference temperature shown in Figure (3.6)has been introduced by the FCC. The model shows the signal of a radio station designed to operate in a range at which the received power approaches the level of the noise floor. As additional interfering signals appear, the noise floor increases at various points within the service area, as indicated by the peaks above the original noise floor. Unlike the traditional transmitter-centric approach, the interference temperature model manages interference at the receiver through the interference temperature limit, which is represented by the amount of new interference that the receiver could tolerate. In other words, the interference temperature model accounts for the cumulative RFenergy from multiple transmissions and sets a maximum cap on their aggregate level. As long as cognitive radio users do not exceed this limit by their transmissions, they can use this spectrum band[7].

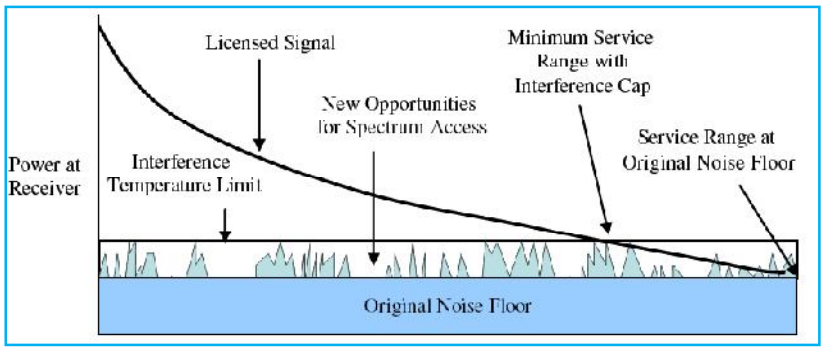

Figure (3.6): Interference Temperature Model

However, there exist some limitations in measuring the interference temperature. The interference is defined as the expected fraction of primary users with service disrupted by the cognitive radio operations. This method considers factors such as the type of unlicensed signal modulation, antennas, ability to detect active licensed channels, power control, and activity levels of the licensed and unlicensed users.

However, this model describes the interference disrupted by a single cognitive radio user and does not consider the effect of multiple cognitive radio users. In addition, if cognitive radio users are unaware of the location of the nearby primary users, the actual interference cannot be measured using this method. A direct receiver detection method is presented, where the local oscillator (LO) leakage power emitted by the RF front-end of the primary receiver is exploited for the detection of primary receivers. In order to detect the LO leakage power, low-cost sensor nodes can be mounted close to the primary receivers. The sensor nodes detect the leakage LO power to determine the channel used by the primary receiver and this information is used by the unlicensed users to determine the operation spectrum [12].