1. Introduction

Increasing number of applications and wireless devices has increased demand for radio spectrum. Current static spectrum allocation policy is not optimum for scarcity of the spectrum, which is why we are having the problem now. Recent researches have shown that most of the available spectrum are either underutilized or completely idle which can be seen in a particular case in figure 1. This inefficient use of the spectrum has created a problem of spectrum scarcity for ever increasing spectrum demand for wireless devices and applications.

Federal Communications Commission (FCC) published a report prepared by Spectrum Policy Task Force in November 2002, which reports that [1]:

“In many bands, spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access.”

The term cognitive radio (CR) refers to a radio that is aware of its surrounding environment and can intelligently access the unused spectrum bands thereby increasing the communication capacity and efficiency. Once such empty spaces are found it is possible for secondary users who do not hold license or right to the frequency band. Hence, for the efficient use of spectrum the first step is to sense whether the spectrum is being used by primary users or not. One of the most important cognitive features of the cognitive radio standard is spectrum sensing which senses the white spaces or channels void of primary users in the available frequency spectrum.

Cognitive Radio is an advancement over earlier proposed Software Defined Radio with added functionalities to sense its surrounding environment, and reason, analyze and adapt to the changing operating environment. A CR monitors the spectrum bands and detects the white spaces or spectral holes. Afterwards, it analyzes the characteristics of such detected spectral holes and then determines the operating parameters such as bandwidth, modulation, coding etc. optimum to such spectral holes.

Spectrum sensing has been viewed as a signal detection problem whereby spectrum sensors detect the presence of primary user signals. Most of the spectrum sensing algorithms are based on sample size and sensing time which are predetermined and fixed. In contrast, Wald proposed that a detector based on sequential detection requires less average sensing time in comparison to a fixed sample size detector.

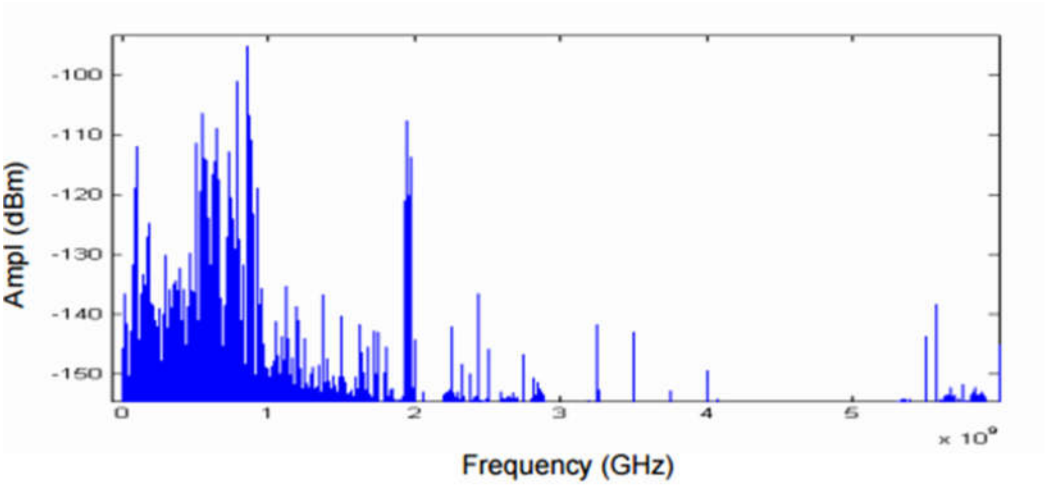


Figure 1: A Snapshot of the spectrum utilization up to 6GHz in an urban area [18]

The case of spectrum underutilization can be improved if a secondary user can access the unused licensed spectrum bands during a certain temporal frame of time in which it is unoccupied. Therefore, Opportunistic Spectrum Access (OSA) has been proposed as a solution for present problem of spectrum scarcity and the new spectrum policy is called Dynamic Spectrum Allocation (DSA) policy, whereby the secondary or non-licensed users can sense the frequency bands and if it is found that the bands are not being used at that particular time, they start communicating using those bands. However, there are many things that must be made sure; primary users still should be able to access the spectrum whenever they want to and then the Quality of Service should not be degraded for the users. These characteristically, are the features of Cognitive Radio that is touted as a revolution in the future of wireless communication which attempts at Dynamic Spectrum Allocation. The name mostly refers to spectrum aware communication systems. It is defined as Software Defined Radio which is aware of its environment, learns from and has the ability to change its parameters according to these changes in its environment and the network requirements [2].

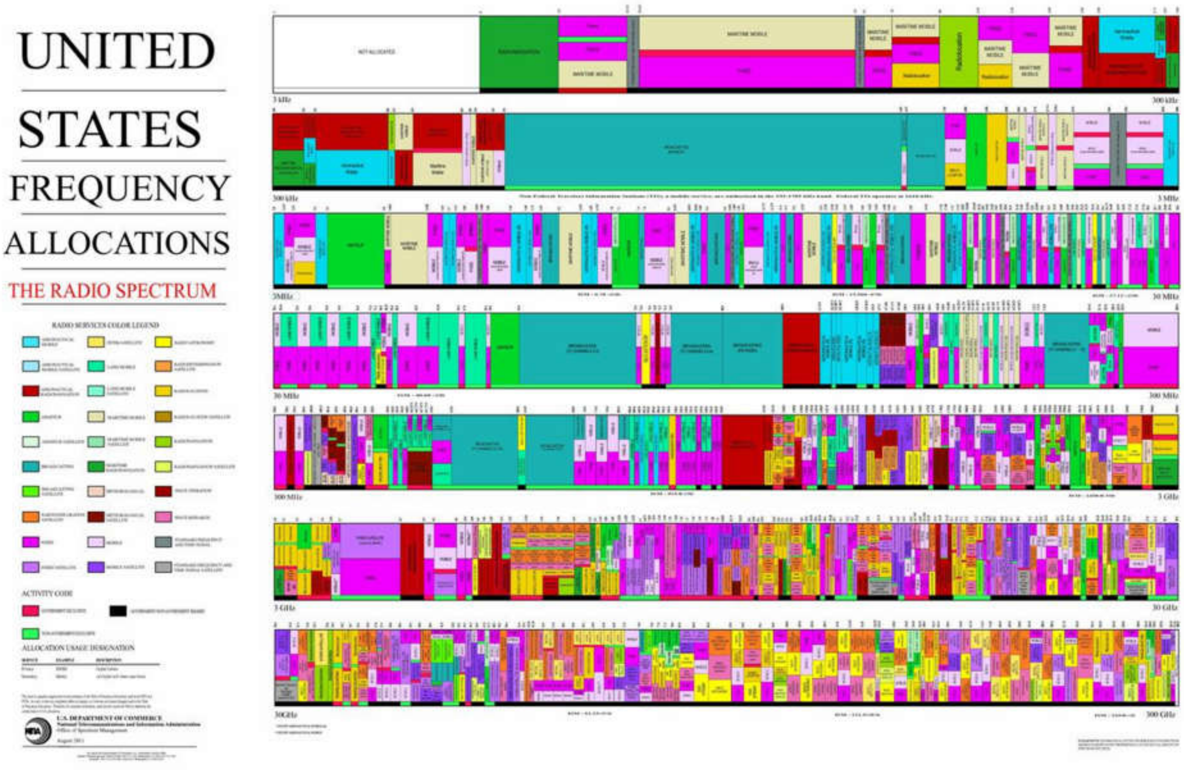


Figure 2: Spectrum Allocations in United States

Cognitive radio [10] can be further defined as [2], *“Building on the spectrum holes detected by the radio scene analyzer and the output of transmit-power controller, select a modulation strategy that adapts to the time-varying conditions of the radio environment, all the time assuring reliable communication across the channel.”*

The main functions of a cognitive radio can be addressed as follows [3]:

- Spectrum sensing is the process of a cognitive Radio sensing the channel and determining if a primary user is present, detecting the spectrum holes.

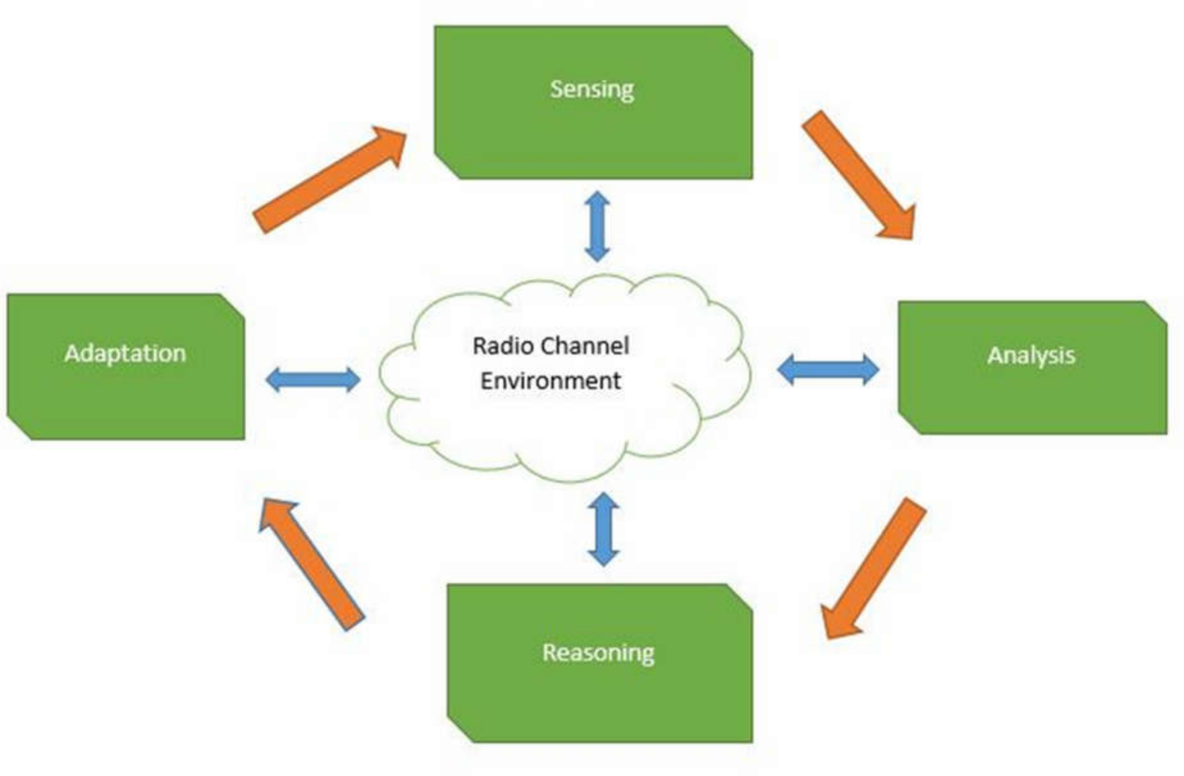
- Spectrum management is selecting the best available channel for a cognitive user over the available channels.

- Spectrum sharing is the allocation of available frequencies between the cognitive users.

- Spectrum mobility is the case of when a secondary user rapidly allocates the channel to the primary user when a primary user wants to retransmit.

However, spectrum sensing is the one which has driven most interest.

Figure 3: Cognitive Cycle



1.1 Dynamic Spectrum Access

Dynamic Spectrum Access is the opposite of the current static spectrum management policy. However, the word has a broad meaning and consists of various access strategies. To make the concept clear, we can look at the figure and see how the strategies are categorized. Dynamic Spectrum Access is classified into three main classes:

Dynamic Exclusive Use Model:

This model is further categorized into two approaches: Spectrum Property Rights and dynamic spectrum allocation. In the first approach, licensees are allowed to sell the spectrum to other users. In the second approach, spectrum is assigned dynamically among the users with a view to improve the spectrum efficiency. However, the assignment gives the exclusive right to the users.

Open Sharing Model:

Also known as spectrum commons, it enables the open spectrum sharing between users. The success of ISM band supports the implementation of this model.

Hierarchical Spectrum Model:

This model is further categorized depending on how the primary and secondary users coexist while sharing the same spectrum band. In the spectrum underlay, secondary users are allowed to communicate all the time while keeping the interference to the primary users below a predetermined noise floor level. In the spectrum overlay, secondary users are allowed to transmit or communicate only when the primary users are not active.

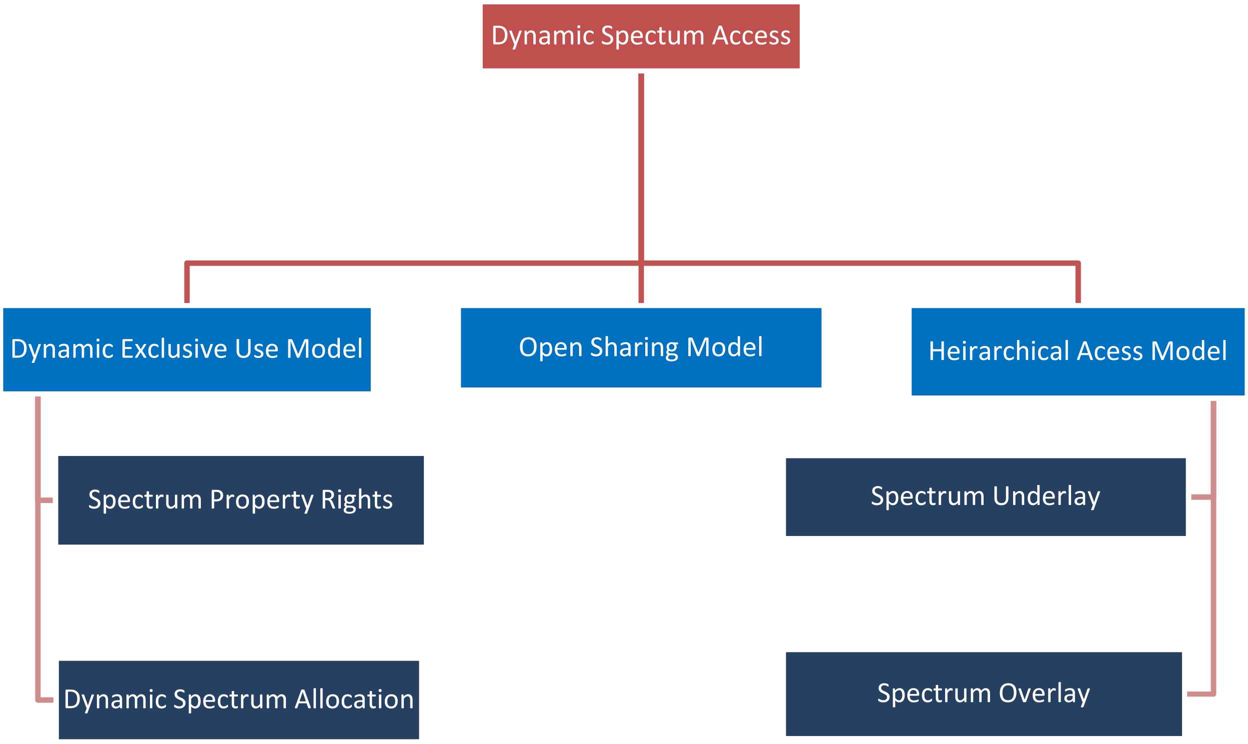


Figure 4: Dynamic Spectrum Access

1.2 Signal Representation

We develop mathematical representations of primary user signals in two different forms to analyze the systems in time domain.

Complex Baseband Representation

In this thesis, we assume that the channel is wireless and the primary user signal is a carrier modulated bandpass signal. The signal can be modeled as

$$\boldsymbol{x_c(t) = x_A(t)cos(2\pi f_c t + \theta(t))} \quad 1.1$$

where$x_A(t)$ is amplitude that varies with time, $\theta(t)$ is phase which also varies with time and f_c is the carrier frequency which is used to modulate the base band signal.

If we rearrange the term we get

$$x_c(t) = x_A(t)(\cos(2\pi f_c t)\cos(\theta(t)) - \sin(2\pi f_c t)\sin(\theta(t)) \quad 1.2$$

We can further define $x_A(t)\cos(\theta(t))$ as $x_I(t)$ and $x_A(t)\sin(\theta(t))$ as$x_Q(t)$.

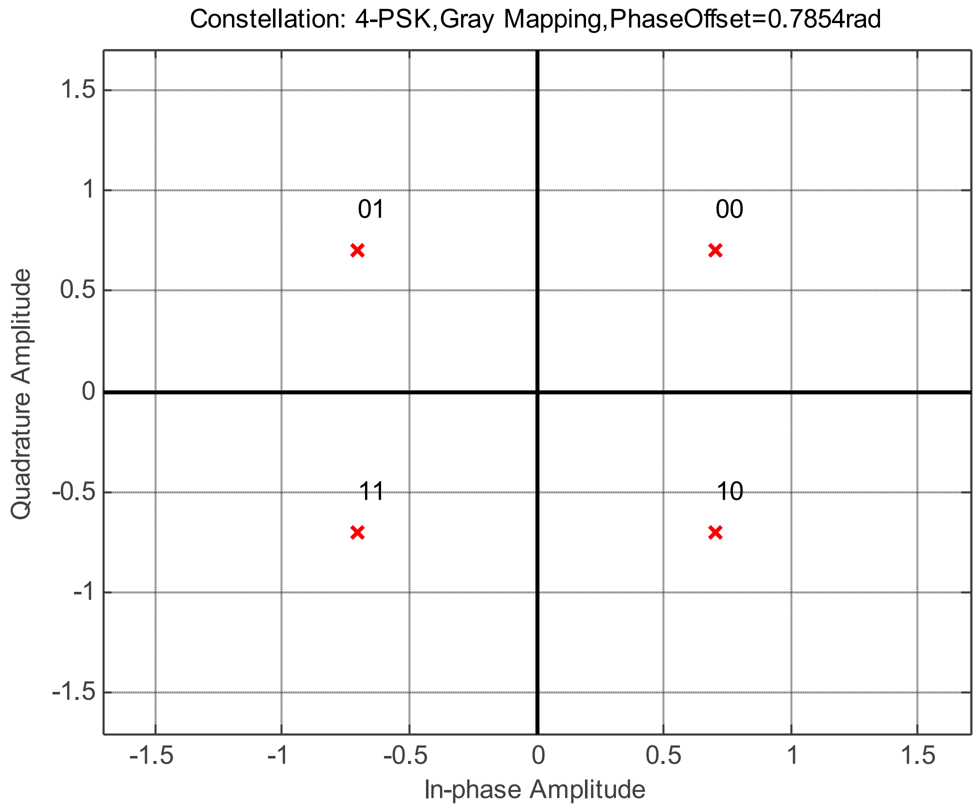


Figure 5: QPSK signal constellation

Hence, rearranging the terms and taking in consideration that the carrier signal is often in cosine term we get

$$x_c(t) = x_I(t)\cos(2\pi f_c t) - x_Q(t)\sin(2\pi f_c t) \quad 1.3$$

Where $x_I(t)$ is in-phase with the carrier and therefore it is called as in-phase bandpass component of the signal and $x_Q(t)$ is 90 degree out of phase with the carrier signal and hence called the quadrature component of the bandpass signal.

To make the notation compact we further define a complex signal

$$x_Z(t) = x_I(t) + jx_Q(t) \qquad 1.4$$

The original bandpass signal is given by the complex envelope as

$$x_c(t) = \sqrt{2}\Re[x_Z(t)e(j2\pi f_c t)] \qquad 1.5$$

This allows us to represent bandpass signals as complex baseband signals and hence simulate detection systems at baseband.

Vector Representation

Detection theory is based on the principle of probability and random process theory which is based on finite sequence of random variables. However, the received primary user signal are carrier modulated and continuous bandpass signals. To obtain the vector of the random variable from the continuous time signal we can use the orthogonal representation of the signal. In a digital modulation technique which uses M-ary schemes based on quadrature multiplexing, a block of sequence of data bits are mapped into a signal $x_i(t)$ form a signal space of M finite energy signals$\{x_i(t)\}$.

$$x_i(t) = \sum_{j}^{N} x_{ij}(t)\,\Phi_j(\mathrm{t}), \quad \begin{cases} 0 \le t \le T \\ i = 1, 2, \dots\dots M \end{cases} \qquad 1.6$$

Where $x_{ij}(t)$ is given by

$$x_{ij}(t) = \int_0^T x_i(t)\,\Phi_j(\mathrm{t}), \qquad \begin{cases} i = 1, 2, \dots\dots . M \\ j = 1, 2, \dots\dots . . N \end{cases} \qquad 1.7$$

Function $\Phi_j(\mathrm{t})$othonormal basis function which is given as

$$\int_0^T \Phi_i(\mathrm{t})\Phi_j(\mathrm{t})dt = \delta_{ij} = \begin{cases} 1\ if\ i = j \\ 0\ if\ i \neq j \end{cases} \qquad 1.8$$

1.3 AWGN Channel

An appropriate model to represent the physical channel between transmitter and receiver is a crucial requirement in the design of a communication systems. We must consider various propagation issues for cognitive radio in the physical channel. Basic principle of a cognitive radio is to detect the presence of other radios in its vicinity using the same spectrum and then to devise appropriate transmission and reception strategies to start communication [16]. For the design, analysis and implementation of such strategies is must to understand the required propagation channels.

AWGN channel is assumed to corrupt the signal by the addition of white Gaussian noise, $n(t)$, which denotes a sample function of the additive white Gaussian noise process with zero-mean and two-sided power spectral density given by

$$\Phi_n(f) = \frac{1}{2}N_0 \quad W/Hz \tag{1.9}$$

whereN_0 is the noise power spectral density.

1.4 Hypothesis

We propose a detector which is based on Sequential probability Ratio Test (SPRT) and uses combined energy as well as cyclostationary feature detector. Sequential analysis will decrease the sensing time which carries a huge significance in spectrum sensing. Energy detector as a non-coherent detection method, does not require any prior knowledge of a PU's waveform and so is easy to implement, however it is highly affected by interference and noise uncertainties [4]. Therefore, cyclostationary feature detector is applied for a reliable sensing accuracy in low SNR as the researches have shown that cyclostationary feature detection is more suitable than the energy detection when the noise uncertainties are unknown [5]. In general, test statistic is calculated using SPRT for energy detector, terminated after the sample number for the test reaches certain predetermined value and further analyzed using cyclostationary feature detector to perform the task of sensing presence of primary user signals. Combined spectrum sensing technique of ED and CFD has been used to obtain better results with less mean detection time [7].

Decision whether a channel is free or not is based on the result of a binary hypothesis testing experiment [5].

In signal detection, the task is to decide whether observation were generated under null or alternative hypothesis [6].This binary hypothesis testing problem in spectrum sensing is formulated as a decision between two hypotheses H_0 andH_1, where $H_0$is the null hypothesis and H_1 is the alternative hypothesis. The result of the hypothesis testing is the decision between two hypotheses. If the decision is H_0 hypothesis then it means the absence of primary user signal. However, H_1 decision means the presence of primary user signal in the spectrum.

Hypotheses can be formulated as:

$H_0: y[n] = w[n]$,presence of white Gaussian noise only

$H_1: y[n] = hx[n] + w[n]$,presence of white Gaussian noise plus signal from primary users

where$h$ is the channel gain, $x[n]$ is the primary signal and $w[n]$ is the additive noise.

The detector collects the received samples, builds a test statistic and compares it against predefined thresholds.

1.5 Detection Problem

- Probability of False Alarm (P_{FA}): The decision is made on presence of primary user signal when the spectrum band is actually unoccupied.

$$P_{FA} = P(\Upsilon > \lambda | H_0) = P(u = 1 | H_0) \qquad 1.10$$

- Probability of Miss Detection (P_{MD}): the decision is made on absence or primary user signal when the frequency band is actually occupied.

$$P_{MD} = P(\Upsilon < \lambda | \mathcal{H}_1) = P(u = 0 | H_1) \qquad 1.11$$

- Probability of Detection (P_D): The decision is made on presence of primary user signal when the frequency band is actually occupied.

$$P_D = 1 - P_{MD} = P(u = 1 | H_1) \qquad 1.12$$

1.6 Reason for Choosing the Topic

Spectrum sensing should be fast, accurate and less complex [5]. We have chosen to use combined sequential energy detector and cyclostationary feature detector to improve on mean detection time or to decrease the average number of samples required to achieve a certain performance level and also to provide robustness against noise uncertainties in the low SNR level. One of the main advantage of this method is that it is aenergy based sensing is a blind sensing algorithm and hence we do not need to know about the primary signal beforehand. Also, cyclostationary feature detector can differentiate between primary signal and noise as well as modulation scheme of the primary signal. Hence, it is a good area of research in spectrum sensing with lot of potential.

1.7 Literature Review

In paper [7], authors propose an intelligent spectrum sensing scheme which improves the utilization efficiency of the radio spectrum by increasing detection reliability and decreasing sensing time. The scheme chooses either the combined energy and cyclostationary detector or the matched filter detection depending upon the suitability. In the combined energy and cyclostationary detectors, an energy detector with a bi-threshold is used, and the cyclostationary detector is applied only if the energy of the signal lies between two thresholds.

In paper [11], authors maintain that cyclostationary feature detector is a good method for PU detection in cognitive radio systems but long detection time leads to inefficient spectrum utilization. They propose to apply sequential analysis to the cyclostationary feature detector to improve on sensing delay. In sequential detection, the detection time is not a fixed but rather a random variable which outperforms the fixed-time detection by a very wide margin requiring just one-half to one-third.

In paper [12], authors propose an energy detector based on sequential probability ratio test to reduce the average required sample number and sensing time for spectrum sensing in low-signal-to-noise ratio regime. Data samples are grouped into blocks and the sequential probability ratio test uses energy of the block as test statistic. The results are shown in which the proposed detector significantly reduces Average Sample Number (ASN) and sensing time while retaining a comparable detection performance compared with Sequential Shifted Chi-Square Test (SSCT) and Energy Detector (ED).

In [21], authors propose a two-stage spectrum sensing where coarse sensing is performed by energy detector and fine sensing is performed by cyclostationary feature detector. Threshold parameters are derived in such a way as to maximize the probability of detection under constraints on probability of false alarm.

First one of the two primary purposes for proposing a new detector is to achieve better performance (higherP_D) and the second one is to reduce the sensing time [14]. In a fixed block energy detection system, one of two possible decisions is made after a fixed number of samples N. However, in a sequential system, the number of samples needed to make a decision is no longer a fixed value. It is a random variable because a sequential detector stops testing whenever the received sample provides sufficient information to accept or reject a hypothesis at a given performance level.

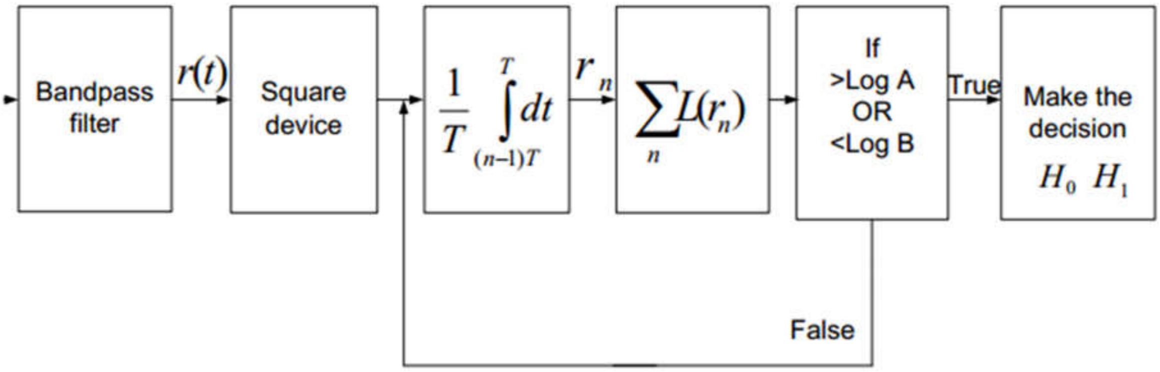


Figure 6: Block diagram of Sequential Energy Detector [14]