

CHAPTER 4 SPECTRUM SENSING

Given the limitations of the natural frequency spectrum, it becomes obvious that the current static frequency allocation schemes cannot accommodate the requirements of an increasing number of higher data rate devices. In this chapter, we discuss the basic elements of wireless systems that utilize radio spectrum space in our analysis. The details of the energy detector for single and multiple antennas are described. Finally, we derive the average detection probability and probability of false-alarm for each case.

The radio spectrum the segment of the electromagnetic continuum containing waves in the RF range accommodates countless communications devices today. The tremendous growth in the wireless based systems and the evolution of the radio communication technologies at a much faster rate have put a great pressure on RF spectrum management in order that the spectrum is used in an efficient, economical, rational and equitable manner. Many new technologies are emerging like Broadband, 4G etc. which require spectrum for faster growth. There are growing, conflicting and competing demands on the spectrum by all sectors government, private and telecom service providers. The requirement of spectrum by all sectors has increased manifold for variety of applications. The problem is not a dearth of radio spectrum; it's the way that spectrum is used. In fact, in some locations or at some times of day, 70% of the allocated spectrum may be sitting idle, even though it's officially spoken for.

Investigation of spectrum utilisation suggests that not all the spectrum is in use for all of the time. Meaning thereby there is no shortage of radio spectrum, only a dearth of affordable communications infrastructure. The solution lies with CR, devices that figure out which frequencies are quiet and picks one or more over which to transmit and receive data.

The detection of spectrum opportunities is one major task in the research area of dynamic spectrum allocation. This fact becomes even more important in the context of cognitive radio which is aware of environmental changes and has the ability to act accordingly. A wellknown method for the detection of occupied spectrum is energy detection where a decision on use/no use of spectrum is simply done by judging the strength of the detected signal within a predefined bandwidth. Another possibility is cyclostationary based detection. Here, inherent characteristics of modulated signals are exploited that can additionally be used in the receiver for parameter estimation.

4.1 Power-based Sensing

Power based sensing is general method for signal detection. After selecting the bandwidth of interest, the energy in the signal defined as

$$E = \int_{-T/2}^{T/2} s^2(t) dt \quad (4.1)$$

when, E is the energy of the input signal $s(t)$ at any time over the interval T in the past. The input signal $s(t)$ consists either of noise alone or a signal plus noise. Thus, detection means the test of the following hypothesis:

$$\begin{aligned} \mathcal{H}_0 : y(t) &= n(t) \\ \mathcal{H}_1 : y(t) &= s(t) + n(t) \end{aligned} \quad (4.2)$$

Afterwards, a free or used decision is made. Of course, processing gain can be improved as the observation time is increased. Another benefit of a longer observation time is the fact that the noise level is decreased, thus increasing the signal-to-noise ratio. In spite of these advantages, including a simple implementation [61-67], the power detector owns some drawbacks. Since a power detector is not able to differentiate between thermal noise and modulated signals, there is no possibility to cancel interferers by using signal processing techniques [66]. The performance of the detection algorithm can be summarized with two probabilities the probability of detection, P_d , and probability of false-alarm, P_f , are defined by the probability of detection is the probability to decide \mathcal{H}_1 and \mathcal{H}_1 is true. Thus, the large detection probability is desired. It can be formulated as

$$P_d = \Pr[E > \lambda | \mathcal{H}_1] \quad (4.3)$$

where P_d is the probability of detection and λ as the detection threshold. The false alarm probability that the test incorrectly decides that the probability to decide \mathcal{H}_1 but \mathcal{H}_0 is true and it can be written as

$$P_f = \Pr[E > \lambda | \mathcal{H}_0] \quad (4.4)$$

where, P_f is the false alarm probability. P_f should be kept as small as possible. The decision threshold λ can be selected for finding an optimum balance between P_d and P_f . As shown in Figure 4.1 a smaller probability of false alarm suggest a larger probability of miss detection. Let $P_f = \varepsilon$ and $P_d = 1 - \delta$. However, this requires knowledge of noise and detected signal powers. The noise power can be estimated, but the signal power is difficult to estimate as it changes depending on ongoing transmission characteristics and the distance between the cognitive radio and licensed user.

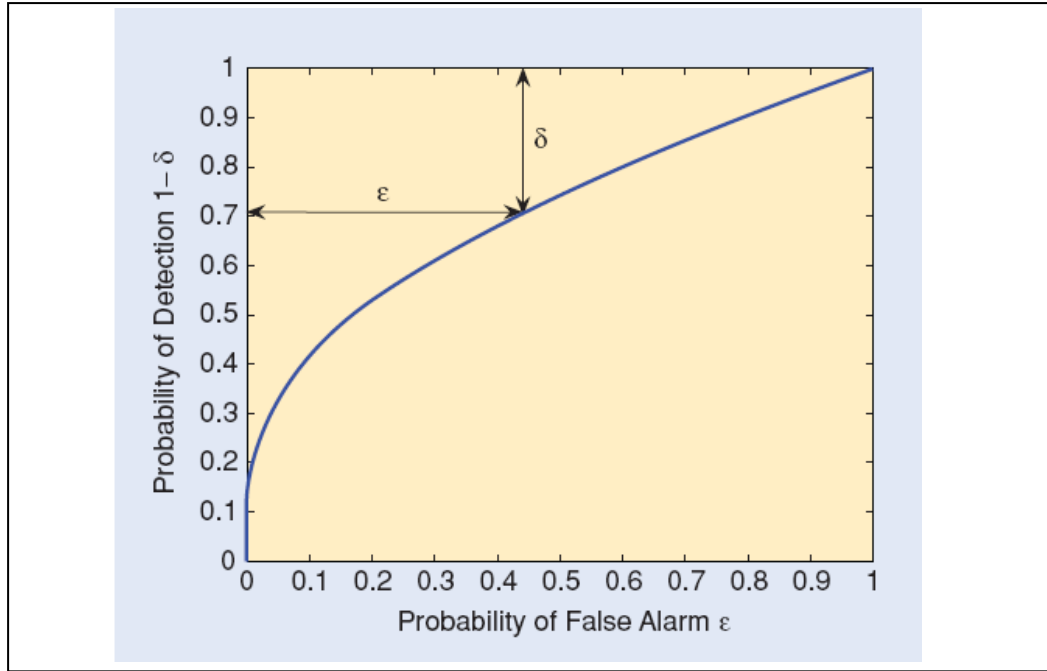


Figure 4.1 Characteristics of detection

4.2 Waveform-based Sensing

Waveform based sensing is a method for detecting primary user transmissions by correlating the received signals [63], [67], [68]-[71]. This means the method is not work to systems without unknown signal patterns. The results presented in [63] show that waveform based sensing requirement time. Furthermore, waveform based sensing has good performance at low signal to noise ratio (SNR). Since many of the modulation techniques employed in wireless communication signals, waveform sensing is closely related to automatic modulation recognition of communication signals. Waveform based sensing is performed in time domain. The waveform sensing can be written as

$$S = \text{Re} \left[\sum_{n=1}^N y(n)s^*(n) \right], \quad (4.5)$$

where N is signal samples. In the absence of the licensed users, the signal pattern becomes

$$S = \text{Re} \left[\sum_{n=1}^N w(n)s^*(n) \right], \quad (4.6)$$

In the signal present, the sensing metric is

$$S = \sum_{n=1}^N |y(n)|^2 + \text{Re} \left[\sum_{n=1}^N w(n)s^*(n) \right]. \quad (4.7)$$

The present signal decision can be used by comparing the decision metric S against a fixed threshold.

The present literature for spectrum sensing is still in its early stages of development. A different methods number are proposed for identifying the presence of signal transmissions. In some approaches, characteristics of the identified transmission are detected for deciding the signal transmission as well as identifying the signal type. In this chapter, some of most common spectrum sensing techniques in the spectrum sensing literature are explained.

We considered a single and multiple antennas at the receiver side. Let $s(t)$ be the primary user signal that is transmitted over a channel with gain h and additive zero-mean white Gaussian noise $n(t)$. Let W denote the signal bandwidth, and T be the observation time over which signal samples are collected, so chosen that the time-bandwidth product, $\Lambda = TW$, is an integer. The goal is to determine whether a signal is present (hypothesis \mathcal{H}_1) or not (hypothesis \mathcal{H}_0). Under these two hypotheses, the received signal is given by

$$\begin{aligned}\mathcal{H}_0 : y(t) &= n(t) \\ \mathcal{H}_1 : y(t) &= hs(t) + n(t)\end{aligned}\tag{4.8}$$

Let N_0 be the two-sided noise psd. We consider a modified energy detector that differentiates between hypotheses \mathcal{H}_1 and \mathcal{H}_0 based on the normalized quantity, $E = E_r / N_0$, where E_r is the energy of the received signals under the two hypotheses. Under \mathcal{H}_0 ,

$$E = \frac{1}{N_0} \int_0^T n^2(t) dt = \frac{1}{2N_0W} \sum_{i=1}^{2\Lambda} n_i^2,\tag{4.9}$$

where n_i are the samples obtained by sampling $n(t)$ at the Nyquist frequency $2W$. Note that since $n_i \sim \mathcal{N}(0, 2N_0W)$, under \mathcal{H}_0 , E has a central chi-squared distribution with 2Λ degrees of freedom. Similarly, under \mathcal{H}_1 , E has a non-central chi-squared distribution with 2Λ degrees of freedom and non-centrality parameter 2ρ , where ρ is the SNR. Thus,

$$\begin{aligned}\mathcal{H}_0 : E &\sim X_{2\Lambda}^2 \\ \mathcal{H}_1 : E &\sim X_{2\Lambda}^2(2\rho)\end{aligned}\tag{4.10}$$

For the modified energy detector, with η as the detection threshold, the probability of detection, P_d , and probability of false-alarm, P_f , are defined by the probability of detection is the probability to decide \mathcal{H}_1 and \mathcal{H}_1 is true. Thus, the large detection probability is desired. It can be formulated as

$$P_d = \Pr[E > \eta | \mathcal{H}_1]\tag{4.11}$$

where P_d is the probability of detection and η as the detection threshold . The false alarm probability that the test incorrectly decides that the probability to decide \mathcal{H}_1 but \mathcal{H}_0 is true and it can be written as

$$P_f = \Pr[E > \eta | \mathcal{H}_0] \quad (4.12)$$

where, P_f is the false alarm probability. P_f should be kept as small as possible. The decision threshold λ can be selected for finding an optimum balance between P_d and P_f . However, this requires knowledge of noise and detected signal powers. The noise power can be estimated, but the signal power is difficult to estimate as it changes depending on ongoing transmission characteristics and the distance between the cognitive radio and primary user. Then, using (4.10), we can obtain the following closed-form express [57], [72] for (4.12) and (4.13),

$$P_d = Q_\Lambda(\sqrt{2\rho}, \sqrt{\eta}), \quad (4.12)$$

$$P_f = \Gamma(\Lambda, \eta/2)/\Gamma(\Lambda), \quad (4.13)$$

where $\Gamma(.,.)$ is the incomplete Gamma function, defined by $\Gamma(a, b) = \int_b^\infty e^{-t} t^{a-1} dt (\text{Re}(a) > 0)$, and $\Gamma(a, 0) = \Gamma(a) \cdot Q_\Lambda(a, b)$ is the generalized Marcum-Q function defined by

$$Q_\Lambda(a, b) = \frac{1}{a^{\Lambda-1}} \int_b^\infty x^\Lambda e^{-\frac{x^2+a^2}{2}} I_{\Lambda-1}(dx) dx, \quad (4.14)$$

where $I(.)$ is the modified Bessel's function of the first kind.

4.3 Detection Performance

We now consider a Rayleigh fading channel, i.e. h follows a Rayleigh distribution. Under this scenario, with ρ being the average SNR, the SNR ρ has the pdf

$$f(\rho) = \frac{1}{\rho} e^{-\frac{\rho}{\rho}}, \rho \geq 0 \quad (4.15)$$

The detection probability, $\bar{P}_{d,SA}$ is then obtained by averaging (4.12) over the fading realizations (4.15) and is given by

$$\bar{P}_{d,SA} = \int_0^\infty Q_\Lambda(\sqrt{2\rho}, \sqrt{\eta}) \frac{1}{\rho} e^{-\frac{\rho}{\rho}} d\rho$$

Observe that P_f in (4.12) is independent of the SNR ρ , and hence this expression remains unchanged under fading considerations. We now consider two receivers

processing schemes and obtain the expressions for the probabilities of detection and false-alarm in each case for Rayleigh fading wireless channels. Our approach will be to first derive the probabilities of detection and false-alarm for an AWGN channel, and then use these expressions to derive the corresponding expressions under Rayleigh fading. The idea in this technique is to linearly combine signals coherently. That is, with h_i being the channel gain, the output $y(t)$ is given by

$$\rho_{MRC} = \sum_{i=1}^M \rho_i \quad (4.16)$$

Note that, under \mathcal{H}_1 , E is a sum of M i.i.d. non-central chi-squared distributed variables, with 2Λ degrees of freedom and non-centrality parameter $2\rho_i$, and hence has a non-central χ^2 distribution with $2M\Lambda$ degrees of freedom and non-centrality parameter $2\sum_{i=1}^M \rho_i = 2\rho_{MRC}$. Then, in the case of an AWGN channel, using the arguments on above, it is easy to see that

$$P_d = Q_{M\Lambda}(\sqrt{2\rho_{MRC}}, \sqrt{\eta}) \quad (4.17)$$

It is well known that the pdf of ρ_{MRC} is given by [10, eq.9.5]

$$f_{MRC}(\rho) = \frac{1}{(M-1)!} \frac{\rho^{M-1}}{\rho^{-M}} e^{-\frac{\rho}{\rho}} \quad (4.18)$$

The expression for the resulting detection probability with Rayleigh fading is derived by averaging (4.17) over the fading realizations distributed according to (4.18),

$$\bar{P}_{d,MRC} = \int_0^\infty Q_{M\Lambda}(\sqrt{2\rho}, \sqrt{\eta}) \frac{1}{(M-1)!} \frac{\rho^{M-1}}{\rho^{-M}} e^{-\frac{\rho}{\rho}} d\rho$$

Given that n_{ik} are i.i.d. and have distribution $\mathcal{N}(0, 2N_0W)$, the random variable

$\sum_{i=1}^M h_i^* n_{ik} \sim \mathcal{N}(0, 2N_0W\alpha_h^2)$, where the pdf of E is then given by

$$f_E(y) = \frac{1}{\alpha_h^{2\Lambda} 2^\Lambda \Gamma(\Lambda)} y^{\Lambda-1} e^{-\frac{y}{2\alpha_h^2}}, y \geq 0, \quad (4.19)$$

and the cdf of E is given by

$$F_E(y) = \int_0^y \frac{1}{\alpha_h^{2\Lambda} 2^\Lambda \Gamma(\Lambda)} u^{\Lambda-1} e^{-\frac{u}{2\alpha_h^2}} du = 1 - \frac{\Gamma(\Lambda, y/(2\alpha_h^2))}{\Gamma(\Lambda)} \quad (4.20)$$

As a result, the probability of false-alarm for the AWGN channel is given by

$$P_f = 1 - F_E(\eta) = \frac{\Gamma(\Lambda, \eta / (2\alpha_h^2))}{\Gamma(\Lambda)} \quad (4.21)$$

Given that the square of the absolute value of a Rayleigh distributed random variable has exponential distribution, α_h^2 has a Gamma distribution given by

$$f_{\alpha_h^2}(\alpha) = \frac{\alpha^{M-1} e^{-\alpha}}{\Gamma(M)} \quad (4.22)$$

The average probability of false-alarm can then be obtained by integrating P_f in (15) over the pdf above. Although an elegant closed-form expression appears to be difficult to obtain, the value of the threshold parameter η that needs to be set to achieve a certain P_f can be obtained using numerical integration. For the selection processing technique, the receiver branch with the highest SNR is chosen, and processed further. Under this case, the resultant SNR, ρ_{SP} , is simply ρ_{\max} . It is well known that the pdf of ρ_{\max} (or ρ_{SP} ,) is given by [59, eq. 9.326]

$$f_{SP}(\rho) = \frac{M}{\rho} e^{-\frac{\rho}{\rho}} (1 - e^{-\frac{\rho}{\rho}})^{M-1} = M \sum_{i=0}^{M-1} C_i^{M-1} \frac{(-1)^i}{i+1} \frac{1}{\rho/(i+1)} e^{-\frac{\rho}{\rho/(i+1)}} \quad (4.23)$$

Here C_k^n denotes the binomial coefficient, $C_k^n = \frac{n!}{(n-k)!k!}$. The detection probability

$\bar{P}_{d,SP}$ is then obtained by averaging (4.12) over the pdf in (4.23). The resulting detection probability $\bar{P}_{d,SP}$ in this case can be written as

$$\bar{P}_{d,SP} = M \sum_{i=0}^{M-1} C_i^{M-1} \frac{(-1)^i}{i+1} J(\Lambda, \frac{\bar{\rho}}{i+1}, 1, \eta) \quad (4.24)$$

To obtain the probability of false-alarm, first note that the cdf of E under \mathcal{H}_0 can be derived from (4.10) and is given by

$$F_E(x) = 1 - \frac{\Gamma(\Lambda, x/2)}{\Gamma(\Lambda)} \quad (4.25)$$

Under selection processing, the cdf of E under \mathcal{H}_0 is then given by

$$F_{E,SP}(x) = \left[1 - \frac{\Gamma(\Lambda, x/2)}{\Gamma(\Lambda)} \right]^M \quad (4.26)$$

4.3 Numerical Examples

We illustrate the efficacy of the multiple antenna processing techniques through the detection probability for a pre-specified probability of false-alarm, P_f , at given SNR. We considered a four-antenna system ($M = 2$) with the processing techniques described earlier in Section 2, and the single antenna system in Section II. For a fixed value of the time-bandwidth product, $\Lambda = 6$, we considered two cases corresponding to different P_f : (a) $P_f = 0.01$, and (b) $P_f = 0.001$. We then compared the achieved P_d as SNR was varied from 0 dB to 30 dB, for given P_f and Λ . Figure 4.2 and Figure 4.3 shows comparisons of the achieved detection probability with varying SNR for the single antenna against the two multiple antenna processing techniques described: maximum ratio processing and selection processing. The improvement in detection achieved through the diversity gains offered by multiple antennas processing in energy detection is evident. There is more than an order of magnitude improvement in detection performance with the use of maximum ratio antenna processing and selection processing.

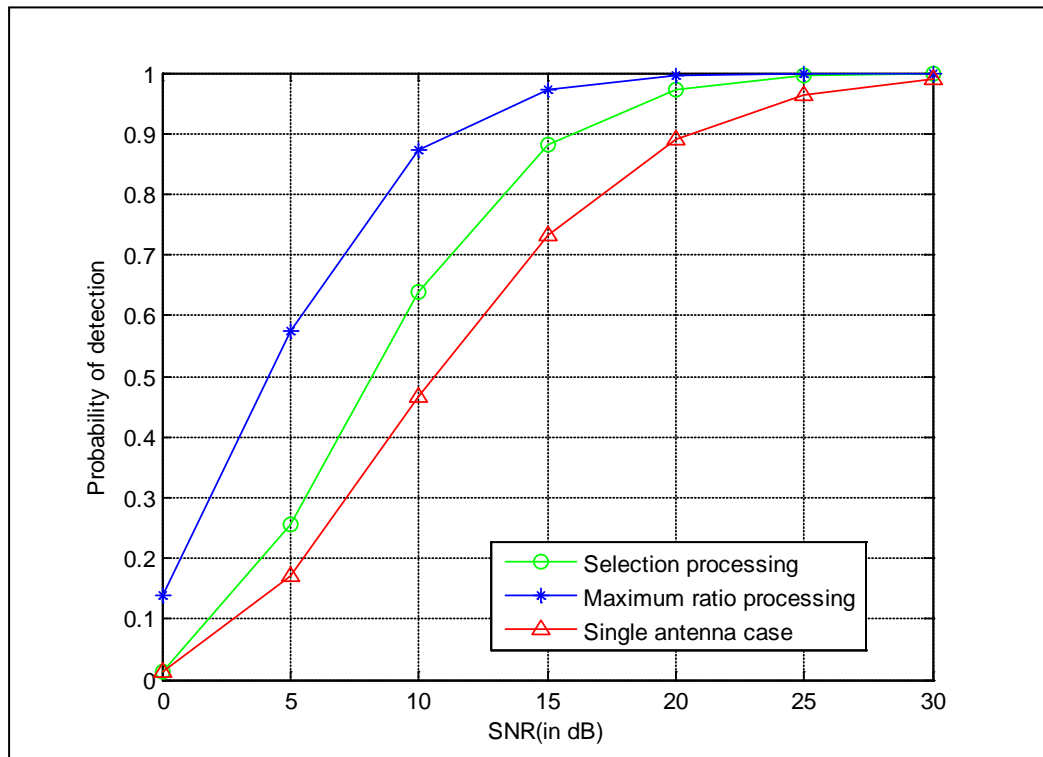


Figure 4.2 Detection performances with multiple antenna processing $P_f = 0.01$

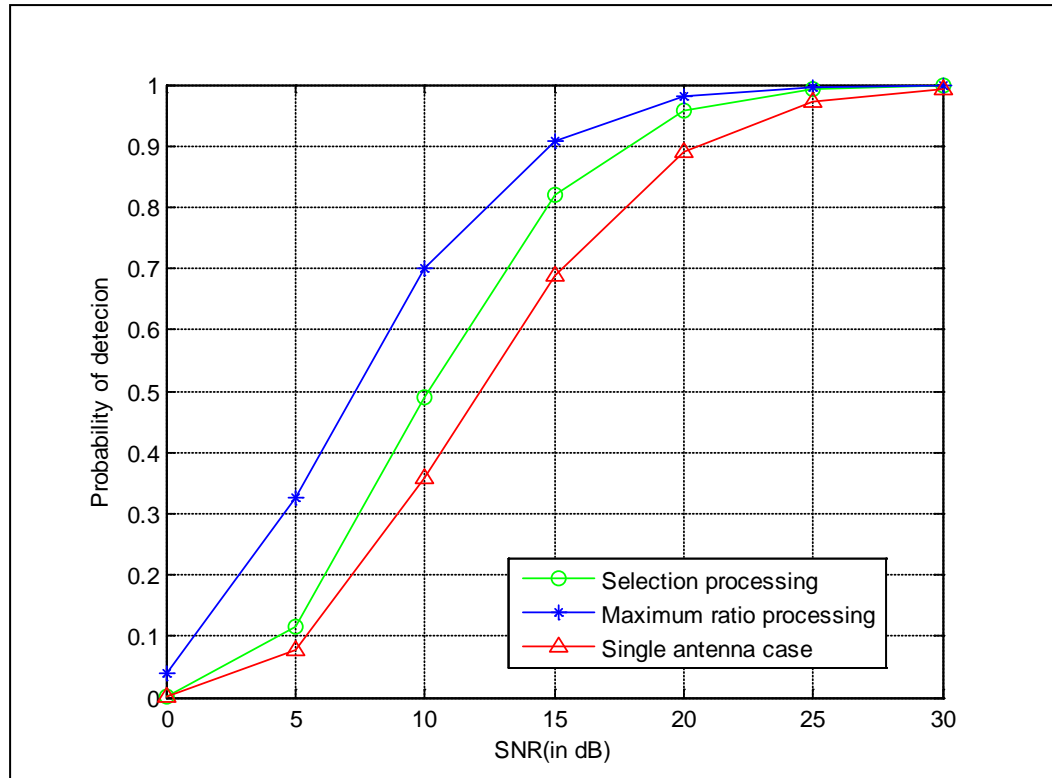


Figure 4.3 Detection performances with multiple antenna processing $P_f = 0.001$

Spectrum is a very valuable resource in wireless communications [34], and it has been an important point for research and development efforts over the last several decades. The situation is especially severe in lower frequencies where the radio signal propagation characteristics are more favorable. The imbalance between spectrum scarcity and spectrum underutilization is inappropriate, when significant amount of radio spectrum is needed to provide everywhere wireless broadband connectivity. Spectrum sharing, which is one of the efforts to utilize the available spectrum more efficiently through opportunistic spectrum usage, has become an exciting and promising concept. It is divided into spectrum bands that are allocated to different services. The increase of wireless services and devices for uses such as mobile communications, Wi-Fi, and TV broadcast. Spectrum sharing is viewed as an approach for improving the utilization natural resource. There are three viewpoints of spectrum sharing as sensing, flexible, and non-interfering. In sensing, a radio must be able to detect and identify the unused spectrum. A radio must be able to change frequency into the spectrum hole. Detecting unused spectrum must without harmful interference to other users.

The challenge of spectrum sharing is sensing. The paradigm is to detect which part of the spectrum is currently unused, and then do the transmission at that frequency band. Users are classified as licensed users and unlicensed users. Unlicensed users can access and share the spectrum only if they cause limited interference to licensed users or when licensed users are inactive. One of the problems in spectrum sensing is the delay between sensing and decision. In general, sensing method can be separated into two methods. Energy based sensing or power based sensing methods and waveform based sensing methods. Energy based sensing is the common method to sensing. The signal detection process is comparison between the output of signal detector and threshold SNR. The receiver is low computational and complexities because of it does not need

signal information. The threshold used in this method based on noise variance and signal fading environment. It is known that noise is uncertainty and limited performance detector. Hence, energy based sensing may be fail. In the very low SNR, energy detection is not good performance. This method needs the stationary of signal strength. This is impossible because of channel and the received signal and noise are both changing. Moreover an increased measurement time is disadvantage of the energy based sensing.

While energy sensing is more general, waveform sensing is outperforms in short measurement time and reliability. The characteristic of target signal and signal pattern are considered. Signal pattern include pilot signal, modulation types, frequency characteristics and etc. Hence, waveform sensing can achieve good performance even low SNR and strongly fading channel. Although in low SNR under noise uncertainty and fading environments are fundamental limits in energy based sensing performance, waveform based sensing can be performed. However, waveform sensing is only work when signal patterns is known. Some tradeoffs should be considered while selecting a sensing method. Time sensing, signal interference, computational complexities, probability of detection, probability of false alarm, are all important.

The key aspects of a spectrum sharing are combination-based sensing is most effective in practical because it is robust and requires short measurement time. Combination based sensing between energy detection and waveform sensing as a solution to problems that occur due to uncertainty of noise, multipath fading, and sensing time. To ensure operation, fading channel is first considered. There are two steps for detection strategies for this problem. The fading channel must identified by radio systems. Classification of signal fading can be classified into three types that indicate the level of signal fading. Rayleigh fading represents strongly signal fading environment. Rayleigh fading is the specialized model for stochastic fading when there is no line of sight signal. Rician fading occurs when one of the paths, typically a line of sight signal, is much stronger than the others. This model is based on the assumption that a direct line of sight (LOS) signal components exist during cell transmission. The Nakagami fading is more flexibility than Rayleigh fading and Rician fading because it is based on empirical measurement. The performance of energy based sensing is limited when Rayleigh fading does hold. It is hard to detect the desired signal because of work poorly at low SNR and weak signal. Moreover, increased sensing time is the disadvantage of energy detector in weak signal. The second strategy is spectral signal waveform for feature detection. There should be a priori information about target signal and patterns or pilot signal. The performance will be improved by waveform based sensing. The combination of energy based sensing, waveform based sensing may be needed in a practical environment. This is practically possible to correctly identify the signal transmission.