SIMULATION OF COGNITIVE RADIO SYSTEM APPLYING DIFFERENT WIRELESS CHANNEL MODELS

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ABSTRACT

Cognitive radio is an emerging technology, which aims to upgrade the spectrum utilization by allowing the secondary users to operate at the spectrum bands vacated by the primary users. A cognitive radio system model was simulated and the performance of the energy detector was evaluated by using different wireless channel models. These models include Additive White Gaussian Noise (AWGN) model, Rayleigh fading model, and Rician fading model. The simulation results show that by increasing the signal to noise ratio, the detection capability of the energy detector can be improved and the false alarm probability and the missed detection probability can be reduced. Moreover, the line of sight path strength of the Rician fading has a great effect on the energy detector performance. It was observed that, the line of sight path strength (k) of 20 can save the signal power by 40 dB over a single path transmission and 25 dB over a multipath transmission.

KEYWORDS

Cognitive Radio, Spectrum Sensing, Energy Detector & Wireless Channel Models

1. INTRODUCTION

Cognitive radio is a new technology designed specially to solve underutilization of the wireless spectrum. Previous experiments, reported in [1, and 2] show that the spectrum utilization of any fixed policy wireless network is within 6 % over the day. The spectrum is a valuable resource, which may be wasted if it is underutilized. Cognitive radio can improve the utilization of any wireless network by allowing secondary users to access the spectrum holes, or white spaces, left by primary users who are licensed and have the rights to access the spectrum at anytime and anywhere within the coverage area. The secondary users are guests; they can access the licensed spectrum only, when the primary users are absent. Moreover, secondary users have to vacate the channel, when the primary users start to access it. The presence and absence of the primary users can be determined by applying spectrum sensing techniques. There are a lot of spectrum sensing techniques, but the most popular methods are; matched filter detector, cyclostationary detector, and energy detector which are explained in [1].

In this paper, a cognitive radio system, built using the energy detector, is proposed to distinguish the primary users from the secondary users when the transmitted signal spectrum is presented.

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The ability of the energy detector to determine the empty slots within the spectrum, in order to be utilized by secondary users is verified. Moreover the energy detector performance is estimated using different wireless channel models.

The cognitive radio system is defined in Section 2. Subsequently, in Section 3, the spectrum sensing process of the cognitive radio system is stated. Different models used to represent the wireless channel behavior are explained in Section 4. Finally, in Section 5, the simulation results are discussed.

2. COGNITIVE RADIO

There are different definitions of the cognitive radio. One of them defines the cognitive radio as the radio system which can change its transceiver parameters based on the interaction with the surrounding radio environment and have complete awareness about the surrounding electromagnetic spectrum [1, and 2]. There is another definition that describes the cognitive radio as a soft ware defined radio that additionally senses its radio environment, tracks changes, and reacts up on its findings [3]. To have a cognitive system, it must have two capabilities; the cognitive capability and the reconfigureability. The cognitive capability refers to the ability of cognitive system to be fully aware about the surrounding electromagnetic spectrum through the cognitive cycle [2, and 4]. Reconfigureability is the process by which the cognitive radio system can adapt its transceiver parameters according to the new operating parameters. Since the cognitive radio becomes an important technique, it was supported by the standards of IEEE 802.22 and SCC41 [5, and 6]. A cognitive radio architecture was handled in [7], while the basic building blocks and a lot of elements which are necessary in this system were stated in [8].

The system model proposes five primary users; each user message is modulated by using an amplitude modulation (AM) technique, as shown in Figure 1 which presents the proposed system. The transmitted signal is the summation of five primary users' signals. Power spectral density (PSD) is estimated for the transmitted signal by applying periodogram method, which can help to display the cognition process among primary users and the secondary one. The secondary user will occupy the first vacant slot, and ask for emptying a slot, if all slots are occupied. The noise effect on the transmitted signal is studied by displaying the received signal spectrum after applying different signal to noise ratio values. The cognitive radio model was suggested before in [9], but the proposed model here extends the study to cover the attenuation effect and the fading channels.

To explain the cognition process among the primary users and the secondary one, the primary users are chosen to have the frequencies of 1, 2, 3, 4, and 5 MHz, respectively. Figure 2(a) illustrates the PSD of the transmitted signal assuming 1^{st}, 3^{rd}, and 5^{th} primary users are present. Note that there are power peaks at their frequency bands and no power peaks at the 2^{nd}, and 4^{th} bands. Plotting the power spectral density allows the cognition of the user power value at a certain frequency band, so it is a good indicator for the user activity. Moreover, integrating the user power spectral density results in the user energy and this can be used to verify the energy detector performance. Figure 2(b) displays the PSD of the transmitted signal, when the secondary user accesses the 2^{nd} slot. In this case, there are power peaks at this slot due to the secondary user activity. Figure 2(c) illustrates the transmitted signal spectrum, when the secondary user accesses the 4^{th} slot, and hence the power peaks exist at this slot. Figure 2(d) shows the PSD of the transmitted signal, when the 5^{th} primary user leaves, so that there are no power peaks at the 5^{th} slot. The secondary user accesses the 5^{th} slot after the primary user departure, so the power peaks appear at this slot, as shown in Figure 2(e).

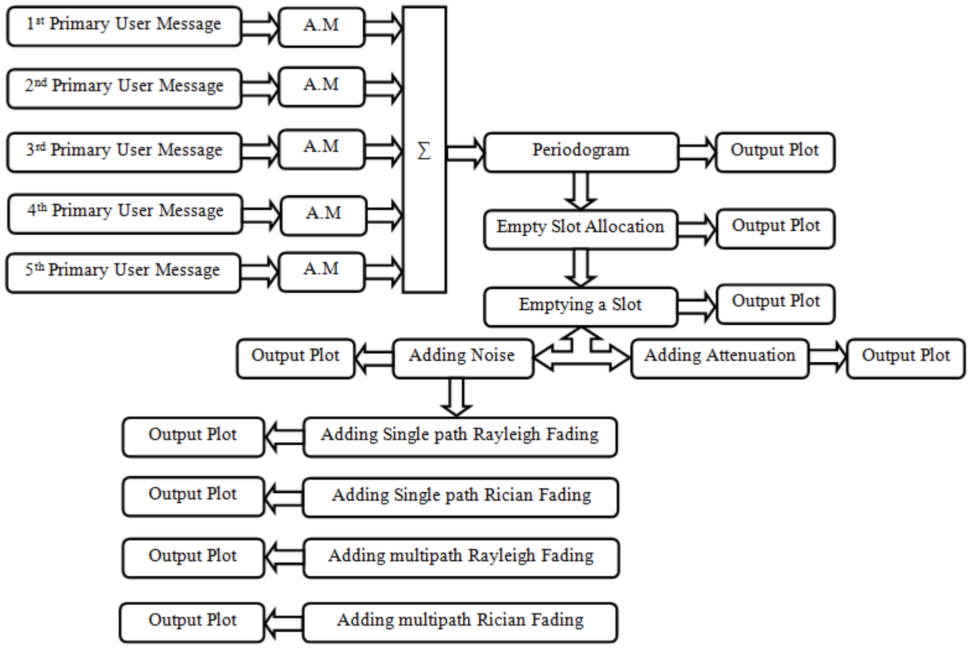
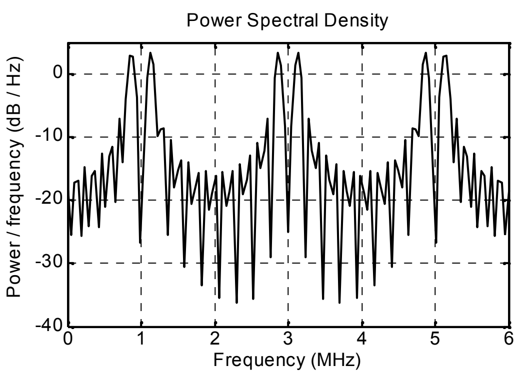
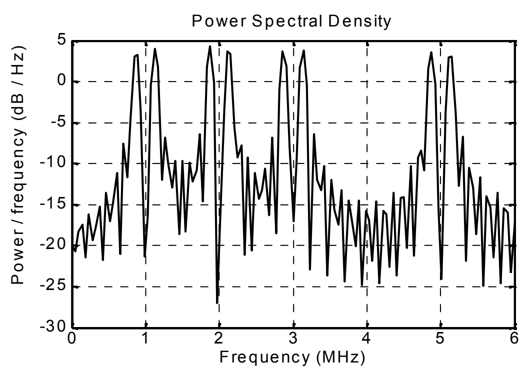


Figure 1. The proposed cognitive radio model.



(a)



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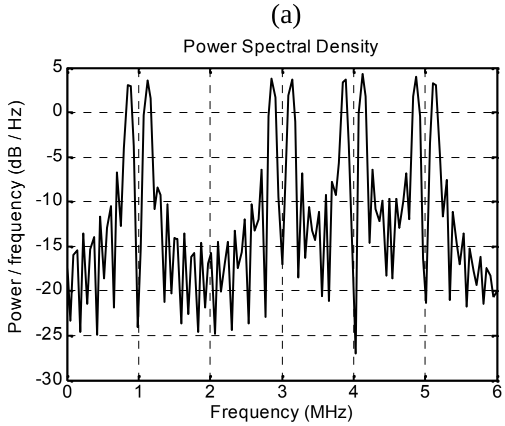

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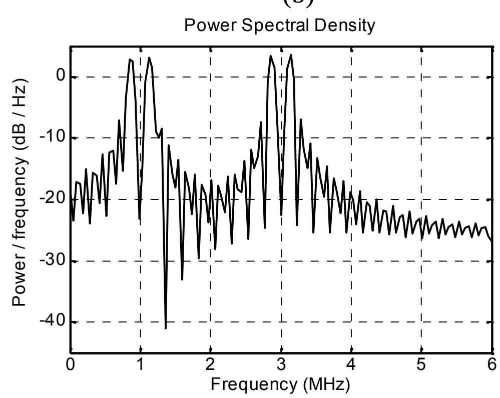
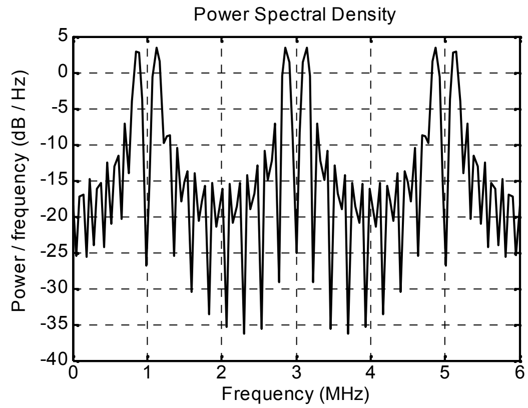


(d)



(e)

Figure 2. The cognition and the spectrum sharing process among five primary users and the secondary user.

3. SPECTRUM SENSING IN COGNITIVE RADIO

Spectrum sensing is the process that the cognitive user can determine the spectrum holes or white spaces left by primary users [1, and 2]. Spectrum holes are the frequency bands, or the time slots provided for a primary user operation, but they may be vacant at certain location and time. The success of secondary users to utilize these bands depends on their detection capability. Spectrum sensing can be considered as the most important stage in any cognitive radio system. If it is not carried out properly, the cognitive radio system will not be successful. There are a lot of spectrum sensing methods; such as matched filter detector, cyclostationary feature detector, and energy detector.

The ability of matched filter to increase the signal to noise ratio at the sampling instant is the key for being used as a sensor [10, 11, and 12]. Unfortunately, it cannot be used without the existence of priori information about the primary user signal. Pilot signals are used to overcome this problem.

The cyclostationary detector depends on estimating the spectral correlation of the received signal and then decides the presence or absence of a primary user [10, 11, and 12].The signal is cyclostationary, if its mean and autocorrelation function are periodic. The modulated signals are cyclostationary with a spectral correlation, but the noise is a random signal with no correlation.

Energy detector is the best spectrum sensing method when no priori information about the primary user signal is available. The energy detector block diagram is presented in Figure 3 [9]. In the beginning, a secondary user scans a certain spectrum band which is licensed for a primary user, and then the received signal is converted to the digital domain by means of an A/D converter. Fast Fourier Transform (FFT) is an important stage, which is used to obtain the spectral components of the received digital signal. The signal energy can be obtained if the summation of the squared spectral components of the signal is averaged over certain time interval. The calculated energy is compared to a threshold value to decide if the primary user is present or absent. The primary user is present, if the received energy is more than the threshold value.

Threshold value is an important factor to determine the performance of the detector. It has a great effect on the probability of detection and the probability of false alarm. However the energy detector design is simple, it has several limitations; such as it has a high false alarm probability due to the noise uncertainty, more samples are required to achieve acceptable performance, and it has a low performance when shot noise and fading channels are applied [10, 11, and 12].

The performance of the energy detector can be evaluated by three parameters and they are; the probability of detection, the probability of missed detection, and the probability of false alarm. The probability of detection is the number of the detected primary users (identified by the energy detector) divided by the total number of the primary users who are assumed to be present in the beginning. The probability of missed detection is the number of primary users that cannot be detected, divided by the total number of primary users who are assumed to be present in the beginning. The probability of false alarm is the number of the detected primary users divided by the total number of primary users who are assumed to be absent in the beginning. The performance of the energy detector is evaluated by sending first, third, and fifth primary users when the second and the forth primary users are absent. Then, its ability to identify the present primary users from the absent ones is checked.

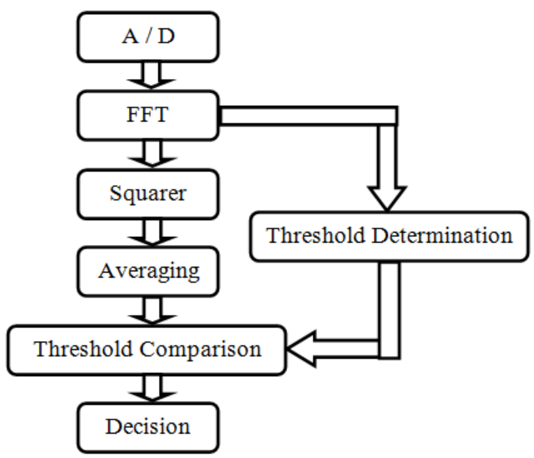


Figure 3. The block diagram of the digital energy detector.

4. WIRELESS CHANNEL MODELS

The difference between a wire and a wireless communication is the channel. A wireless channel behavior varies with the time. However all the models, used to describe the behavior of a wireless link, are not exactly accurate, they can provide an acceptable approximation. There are a lot of models that can describe the wireless channel behavior; such as an Additive White Gaussian Noise model and the fading models. Rayleigh and Rician models are the most famous models of fading.

4.1. Additive White Gaussian Noise

The simplest radio environment, in which a wireless communications system operates, is the Additive White Gaussian Noise (AWGN) environment [13]. A random signal is added to the transmitted signal due to the channel effect. So that, the received signal, s(t), can be expressed as;

$$s(t) = x(t) + n(t) \qquad (1)$$

where *x(t)* is the transmitted signal, and *n(t)* is the background noise.

4.2. Fading Channels

A fading channel is the communication channel that has to face different fading phenomenon during the signal transmission [13, 14, 15, 16, and 17]. The main cause of fading is the multipath propagation. The signal arrives to the receiver from different paths, which have different delays and different path gains. These paths of propagation may be constructive or destructive. The received signal is the algebraic summation of the different paths of propagation, so some of the paths are added and the other are subtracted.

4.2.1. Rayleigh Fading Model

The Rayleigh fading is primarily caused by multipath reception of the transmitted signal. It can model the wireless channel, when there is no direct line of sight between the transmitter and the receiver. This fading model considers the signal arrived to the receiver as the algebraic summation of the received signals from different paths, in absence of the direct line of sight between the transmitter and receiver. Consider the transmitted signal, *x(t),* is;

$$x(t) = \cos(\omega_c t) \qquad (2)$$

where ω_c is the transmitted signal frequency in rad/sec, so the received signal, *s(t),* can be written as;

$$s(t) = \sum_{i=1}^{N} a_i \cos(\omega_c t + \phi_i) \qquad (3)$$

Where *N* is the number of paths, ϕ_i is the phase shift of each path, which depends on the delay difference and takes values from 0 to 2π , and a_i is the amplitude of each path *i*. When there is a relative motion between the transmitter and the receiver, the term $\omega_{di} = \frac{\omega_c v}{c} \cos\psi_i$ should be added to represent the Doppler Effect, and hence the received signal can be expressed as;

$$s(t) = \sum_{i=1}^{N} a_i \cos(\omega_c t + \omega_{di} t + \phi_i) \qquad (4)$$

where ω_{di} is the Doppler frequency of path *i*, v is the velocity of a mobile unit, c is the velocity of the light, and ψ_i is the received signal direction relative to the motion direction of the antenna. The received signal can be separated into inphase and quadrature components as follow;

$$s(t) = I(t)\cos\omega_c t - Q(t)\sin\omega_c t \qquad (5)$$

The inphase and quadrature components can be expressed as;

$$I(t) = \sum_{i=1}^{N} a_i \cos(\omega_{di} t + \phi_i) \qquad (6)$$

$$Q(t) = \sum_{i=1}^{N} a_i \sin(\omega_{di} t + \phi_i) \tag{7}$$

and the envelope of *s(t)*, *r*, can be calculated as;

$$r = \sqrt{[I(t)]^2 + [Q(t)]^2} \tag{8}$$

If N is large enough, the inphase and quadrature components can have a Gaussian distribution. The probability density function (pdf) of the received signal envelope can be expressed as;

$$f(r) = \frac{r}{\sigma^2} \exp(-\frac{r^2}{2\sigma^2}) \qquad r \geq 0 \tag{9}$$

where σ^2 is the variance.

4.2.2. Rician Fading Model (Nakagami-n model)

This model is similar to the Rayleigh fading model except, the existence of a strong dominant component. This dominant component is a stationary (non fading) component and it is commonly known as the LOS (Line of Sight) component. The received signal can be expressed as;

$$s(t) = \sum_{i=1}^{N-1} a_i \cos(\omega_c t + \omega_{di} t + \phi_i) + k_d \cos(\omega_c t + \omega_d t) \tag{10}$$

where K_d is the line of sight path strength, ω_{di} is the Doppler spread of each indirect component, and ω_d is the Doppler spread of the strong line of sight component. The envelope of the Rician fading,*r*, has a probability density function *f(r)*;

$$f(r) = \frac{r}{\sigma^2} \exp(-\frac{r^2 + k_d^2}{2\sigma^2}) I_o(\frac{r k_d}{\sigma^2}) \qquad r \geq 0 \tag{11}$$

where $I_o()$ is the 0th order modified Bessel function of the first kind.

The Rician fading is usually described by a K factor $K(dB) = 10\log_{10}(\frac{k_d^2}{2\sigma^2})$, which is an indication of the component strength of the direct line of sight. The Rician fading can be reduced to a corresponding Rayleigh one, if $k_d = 0$ or $\frac{k_d^2}{2\sigma^2} \prec\prec \frac{r^2}{2\sigma^2}$ as the direct path is eliminated, $K(dB) = -\infty$.

5. SIMULATION RESULTS

In this section, the proposed system, shown in Figure 1, is simulated, and the effect of adding noise to the transmitted signal is investigated. The 1st, 3rd, and 5th primary users are assumed to be present and the secondary user accesses the second slot. Figure 4(a) shows the received signal spectrum when S/N= 14 dB. It is obvious that when the signal to noise ratio has a large value, the received signals still can be differentiated and recognized. Figure 4(b) presents the case when signal to noise ratio S/N= 6 dB. It is clear that, as the signal to noise ratio becomes lower, the signals can also be identified, but it is more distorted than the previous case. Figures 4(c) and 4(d) display the PSD of the received signal when S/N= -6 dB, and S/N= -14 dB respectively. In this case, the signal to noise ratio has a low values. Therefore the signals become more distorted and cannot be identified.

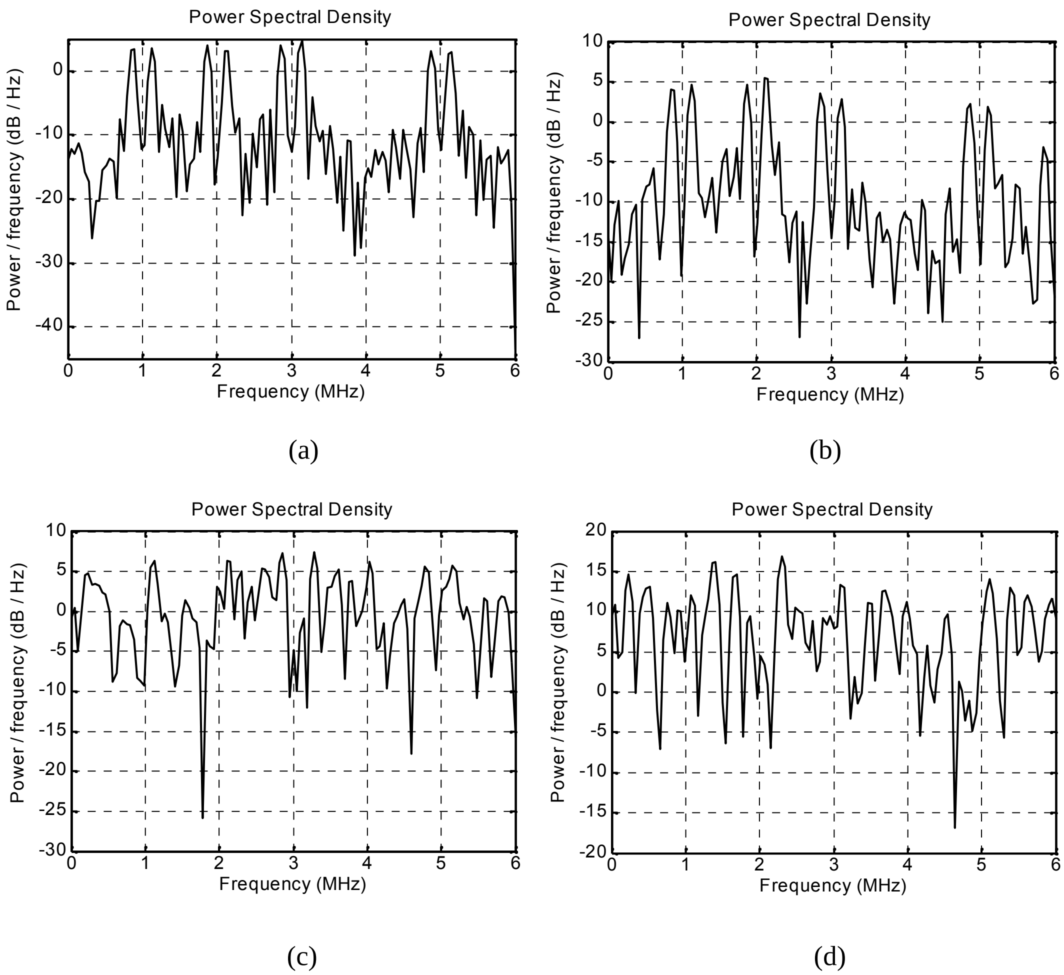


Figure 4. The noise effect on the transmitted signal spectrum at S/N of a) 14 dB, b) 6 dB, c) -6 dB, and d) -14 dB.

Table 1 shows the noise effect on the performance of the energy detector. From Table 1, it is obvious that the signals, arrive with high signal to noise ratio values, can be detected easily. On the other hand, the performance of the energy detector becomes not slightly satisfied, when the signal to noise ratio value decreases. There is a tradeoff between the signal to noise ratio and the false alarm probability to achieve a certain performance. By allowing the energy detector to detect the weak signals, it becomes more prone to the false alarms.

Table 1. The performance of the energy detector in its digital form applying AWGN.

Signal / Noise	P_d	P_{fa}	P_{md}
14	1	0	0
12	1	0	0
10	1	0	0
8	1	0	0
6	1	0	0
4	1	0	0
2	1	0	0
-2	1	0	0
-4	1	0.5	0
-6	1	0.5	0
-8	1	0.5	0
-10	1	1	0
-12	1	1	0
-14	0.66	1	0.33

The attenuation effect on the transmitted signal waveform is studied, and the performance of the energy detector is evaluated using different attenuation values. From Figure 5(a, b, and c), which plots the attenuated amplitude of the received signal versus the time, it is obvious that more attenuation leads to more loss of the signal amplitude. Moreover, increasing the attenuation percentage results in decreasing the probability of detection and increasing the missed detection probability, as shown in Table 2 that states the performance of the energy detector in this case. The energy detector performance becomes worse when the received signals have a high attenuation percentage.

Table 2. The energy detector performance applying different attenuation percentage.

Attenuation	P_d	P_{fa}	P_{md}
10 %	1	0	0
20 %	1	0	0
30 %	1	0	0
40 %	1	0	0
50 %	0	0	1
60 %	0	0	1
70 %	0	0	1
80 %	0	0	1
90 %	0	0	1

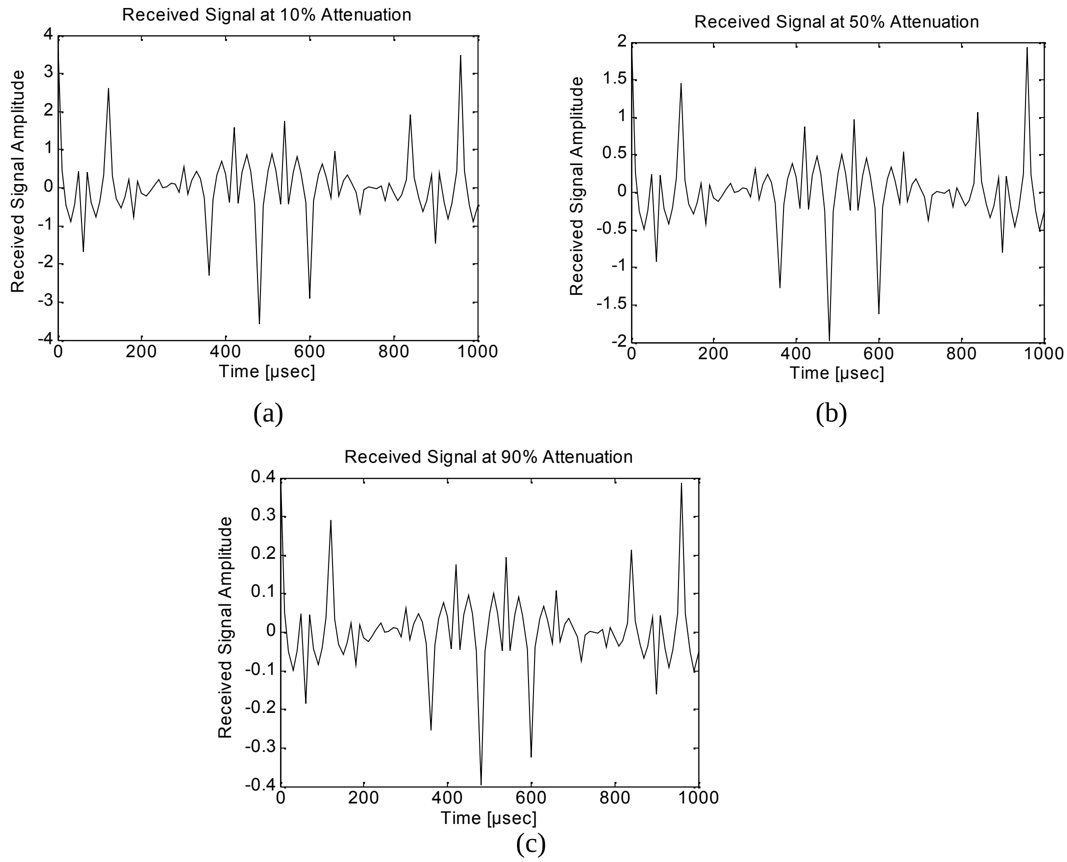


Figure 5. The received signal waveform at attenuation values of a) 10%, b) 50%, and c) 90%.

The effect of a single path Rayleigh fading (supposing that the mobile user has a velocity (v) of 216 Km/h) on the transmitted signal is studied. From the simulation results, it was found that the minimum S/N value, which can make the probability of detection of the energy detector have a value of one with no false alarms, is equal to 40 dB. The reason for this low performance is the fading, which causes a great reduction of the signal strength, and consequently the performance of the energy detector is degraded. The fading causes an inter modulation distortion, therefore new frequency components appear in the received signal as shown in Figure 6, which displays the received signal spectrum at S/N value of 40 dB. The signal power of each user escapes to these new frequency components, and hence the power loss is increased.

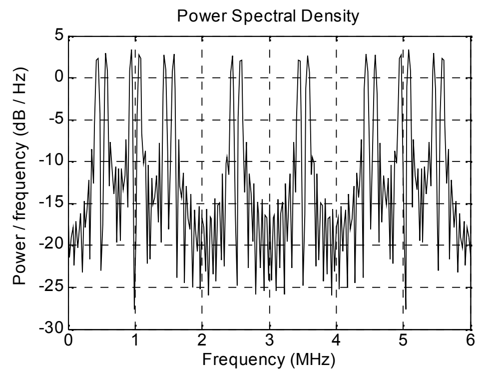


Figure 6. The received signal spectrum applying a single path Rayleigh fading channel at S/N value of 40 dB.

The effect of a single path Rician fading (*v*=216 Km/h and k=0.1) on the transmitted signal is studied. The minimum S/N value, which can make the probability of detection of the energy detector have a value of one with no false alarms, was computed and it is equal to 40 dB. Figure 7 displays the received signal spectrum at S/N value of 40 dB. The performance in this case is similar to the corresponding one which applies a single path Rayleigh fading, since the value of k factor is very small.

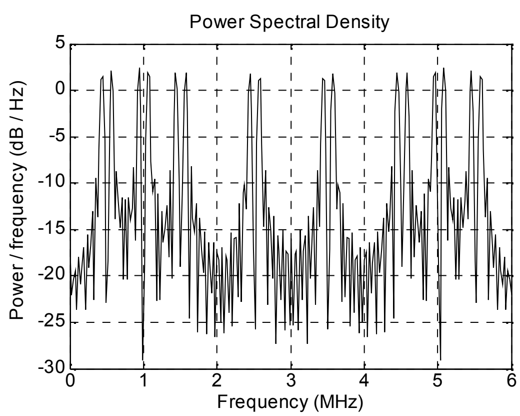


Figure 7. The received signal spectrum applying a single path Rician fading (k=0.1) at S/N value of 40 dB.

The effect of a single path Rician fading (*v*=216 Km/h and k=20) on the transmitted signal is studied. By increasing the value of k to be 20, the minimum value of S/N, which can make the probability of detection of the energy detector have a value of one with no false alarms, is decreased to 0 dB. Figure 8 displays the received signal spectrum at S/N value of 0 dB. The performance in this case is very good and similar to the corresponding one without fading. This is due to the effective line of sight component.

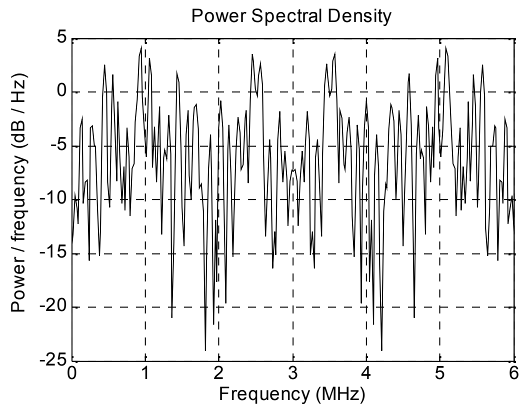


Figure 8. The received signal spectrum applying a single path Rician channel (k=20) at S/N value of 0 dB.

From the simulation results of different Rician fading models, it is obvious that; the value of k factor has a great effect on the performance of the energy detector. When it is very small, a Rician fading and a Rayleigh fading have the same effect on the performance of the energy detector. On the other hand, when k factor has higher values, the performance of the energy detector becomes better. This result agrees with the theoretical analysis of the difference between Rayleigh and Rician fading.

The effect of a multipath Rayleigh fading (*v*=216 Km/h) on the transmitted signal is studied. It is noticed that; the minimum S/N value, which can make the probability of detection of the energy detector have a value of one with no false alarms, is equal to 60 dB. Figure 9 displays the received signal spectrum at S/N value of 60 dB. The performance in this case is very poor.

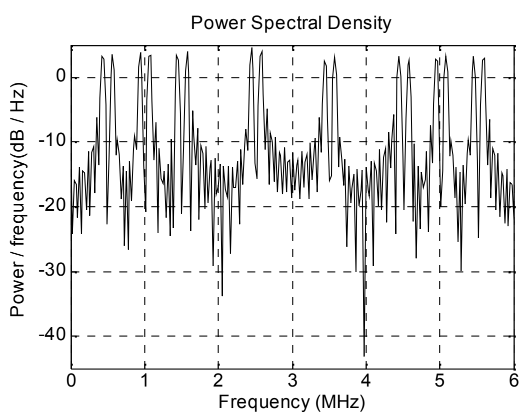


Figure 9. The received signal spectrum applying a multipath Rayleigh fading channel at S/N value of 60 dB.

The effect of a multipath Rician fading (*v*=216 Km/h and k=20) on the transmitted signal is studied. By increasing the value of k to be 20, the minimum value of S/N, which can make the probability of detection of the energy detector have a value of one with no false alarms, is decreased to 35 dB. Figure 10 displays the received signal spectrum at S/N value of 35 dB. The performance in this case is better than a Rayleigh multipath case due to the existence of the efficient direct line of sight component.

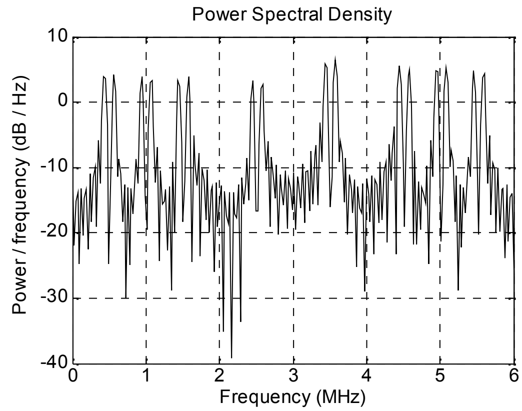


Figure 10. The received signal spectrum applying a multipath Rician fading channel at S/N value of 35 dB.

6. CONCLUSIONS

The cognitive radio simulation model was proposed, and the ability of the secondary users to identify the spectrum bands vacated by primary users was illustrated. The transmitted signal power spectral density was plotted and it is obvious that there are power peaks at the primary user who is presented, and no power peaks at the user who is absent. When the secondary user accesses certain spectrum slot, the power peaks can be observed at this slot. The energy detector performance in its digital form was evaluated applying an Additive White Gaussian Noise (AWGN) channel and the fading channels. From the simulation results, it is obvious that the performance of the energy detector is better, when an AWGN channel is applied than the fading channels. The simulation results of the proposed energy detector, when Rician fading model is applied, show the great effect of the line of sight strength on the detector performance. The energy detector performance is the same, applying Rayleigh channel and Rician channel, when k factor is small. This result agrees with the theoretical analysis of the difference between Rayleigh and Rician fading. The energy detector performance becomes better, when k factor is increased. It was observed that; the line of sight path strength (k) value of 20 can save the signal power by 40 dB over a single path transmission and 25 dB over a multipath transmission.

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