4.1 Introduction

Most of today's radio systems are not aware of their radio spectrum environment and operate in a specific frequency band using a specific spectrum access system. Investigations of spectrum utilization indicate that not all the spectrum is used in space (geographic location) or time. A radio, therefore, that can sense and understand its local radio spectrum environment, to identify temporarily vacant spectrum and use it, has the potential to provide higher bandwidth services, increase spectrum efficiency and minimize the need for centralized spectrum management. This could be achieved by a radio that can make autonomous (and rapid) decisions about how it accesses spectrum. Cognitive radios have the potential to do this. Cognitive radios have the potential to jump in and out of un-used spectrum gaps to increase spectrum efficiency and provide wideband services.

4.2 System Assumptions

The system uses one frequency channel (200 Hz), which might be any communication channel in any network (WiMAX network, UMTS network, TV system, etc...). The Primary user is assumed to be transmitting in that specific spectrum band. The secondary user uses any spectrum sensing techniques to sense this specific spectrum band. If the spectrum band is free, the secondary user send data in this spectrum band as shown in figure (4.1).

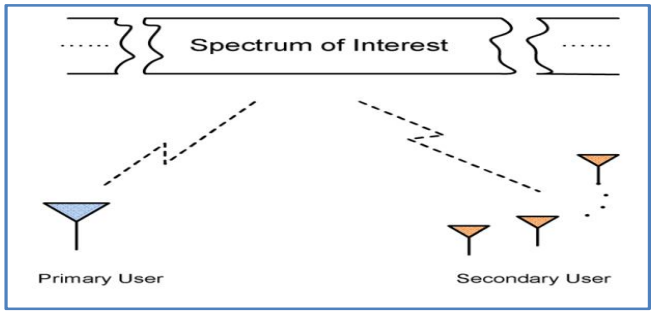

Figure (4.1): System diagram.

Two modulation techniques were assumed in this simulation; the BPSK (Binary Phase Shift Keying) and the QPSK (Quadrature Phase Shift Keying).

The two spectrum sensing techniques used to sense the spectrum were; the Energy Detection and the Matched filter detection algorithm. In the energy detection algorithm, the secondary user calculate the primary user signal power spectral density (PSD) and take the maximum PSD value at 200 Hz and compare it with a PSD value saved in secondary user device.In the matched filter, the secondary user correlate theprimary user signal with the reference signal saved in secondary user device.

The ASCCI code table was used to estimate the values of the thresholds and the reference signalsthat determine the presence or the absence of the user. The shortest message available in the ASCCI code table that can be transmitted by the primary user is the exclamation mark (!). Any massage that is larger than this mark in ASSCI codes; the system assumes the presence of the primary user. In the energy detection technique the PSD value of the exclamation mark (!) is calculated where it is set as the threshold. In the matched filter technique, the reference signal is the signal generated when an exclamation mark (!) is sent.

The system parameters are set as in Table (4.1).

Table (4.1): System Parameters.

Parameter	Value
Operating frequency	200 Hz
No. of sample per period	100
Roll-off factor	0.5

Parameter	Value
Over sampling factor	800
Channel impulse response	1
BPSK Threshold	57.6520 dB/Hz.
QPSK Threshold	40.3771 dB/Hz

4.3 Simulation Flowcharts

In this section the flowcharts of; the generation of the primary user's signals, the reference signal, the energy detection algorithm and the matched filter algorithm are presented.

1. Generation of Primary User Signal Flowchart

Figure 4.2 illustrates how the Primary user signal is generated.The user input any piece of text information; this is regarded as the information being sent by the Primary user in the channel.If any data is entered, it is processed and modulated to be transmitted either using BPSK or QPSK technique.Otherwise, if no data is entered, it is considered a spectrum hole.

2. Generation of the Reference Signal Flowchart

Figure 4.3 show how the reference signal is generated. The ASCCI code of the exclamation mark (!) is used as the reference signal. This data is processed and modulated using both BPSK and QPSK techniques.

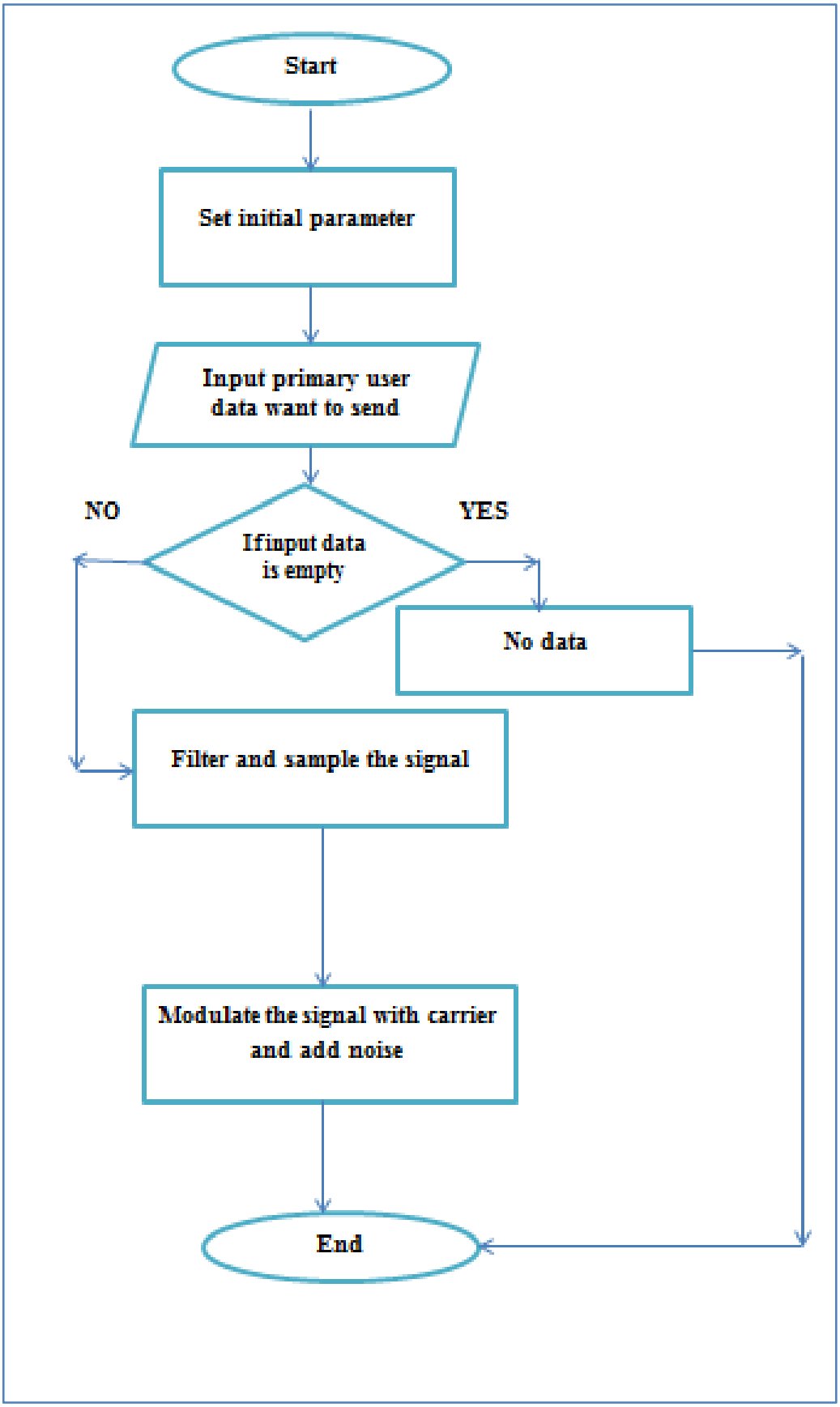

Figure (4.2): Flowchart of Primary User Signal Generation.

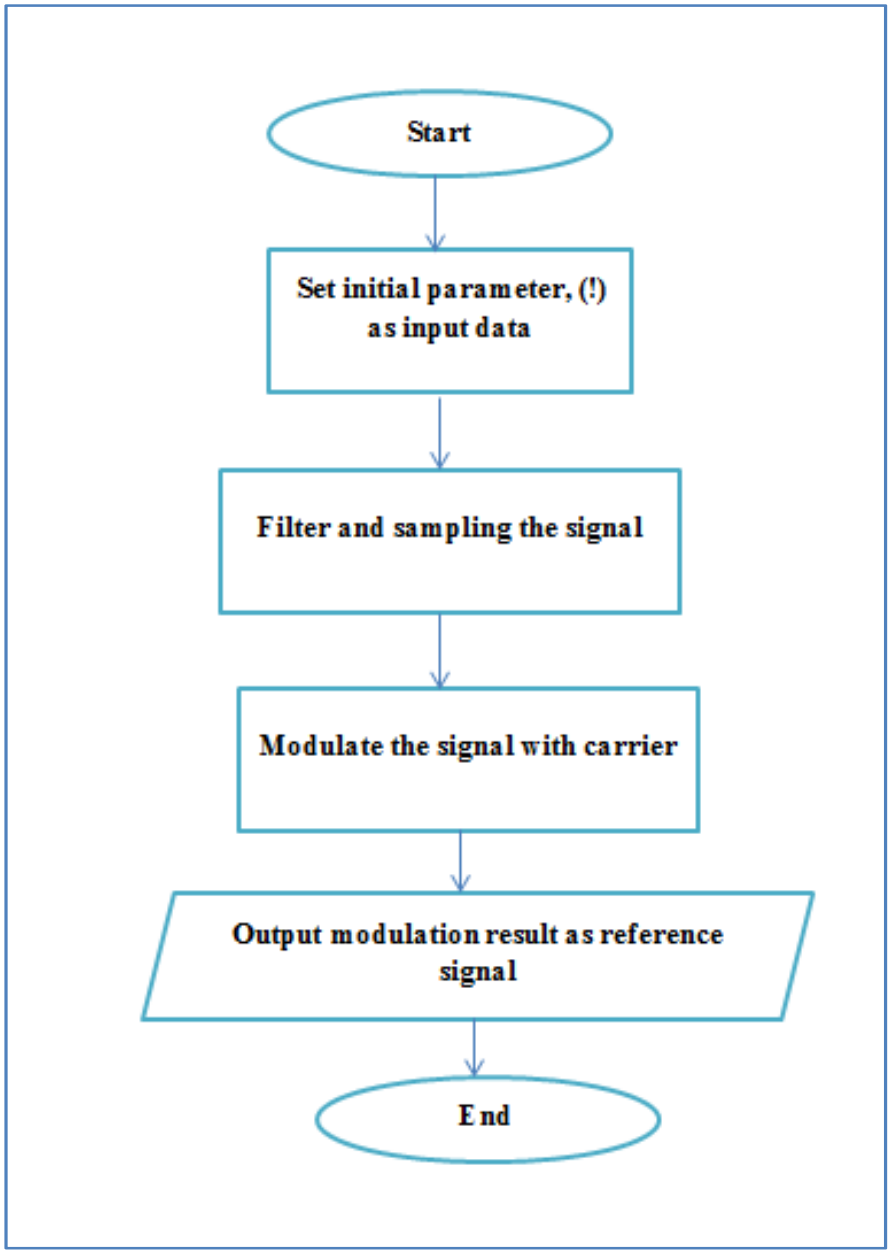

Figure (4.3): Flowchart of Reference Signal Generation.

3. Energy Detection Algorithm Flowchart

This spectrum sensing technique measures the energy received from the licensed Primary user. If the energy is less than a certain threshold value then it declares it as a spectrum hole. The energy detection algorithm flowchart is shown in Figure (4.4).

4. Matched Filter Algorithm Flowchart

This spectrum sensing technique is obtained by correlating a known original reference signal with a received signal from primary user.The flowchart of the matched filter algorithm is shown in Figure (4.5).

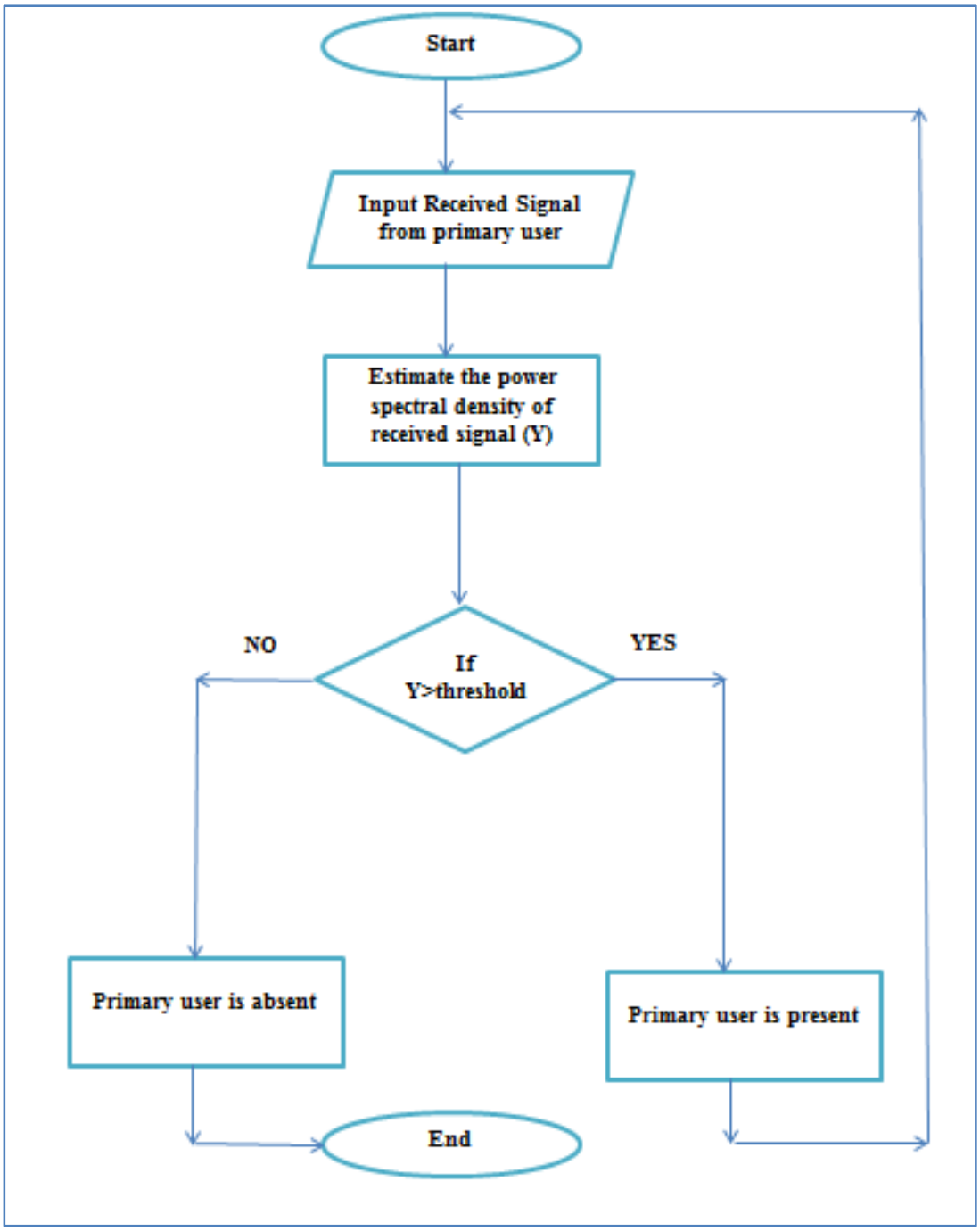

Figure (4.4): Flowchart of Energy Detection Algorithm.

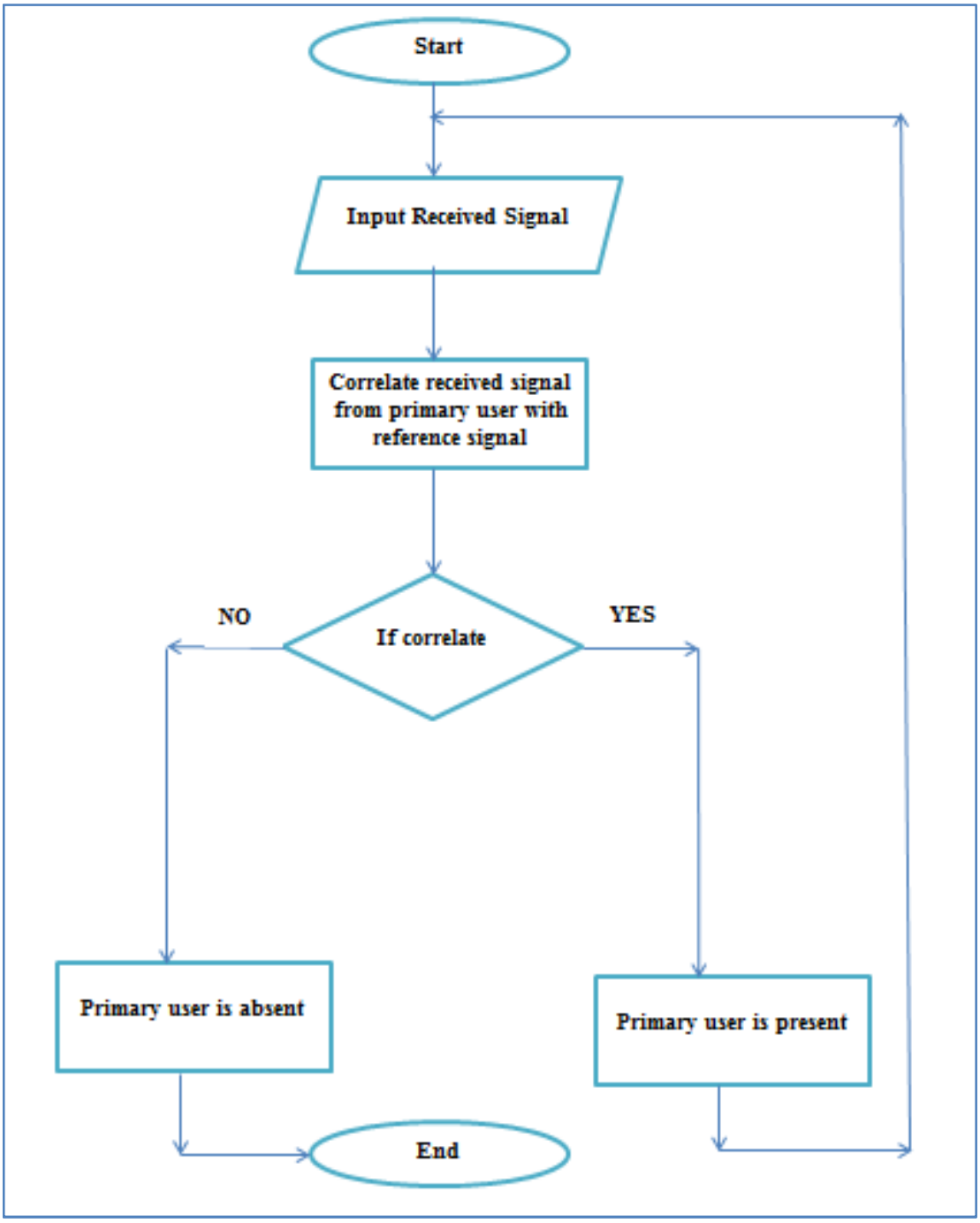

Figure (4.5): Flowchart of Matched Filter Algorithm.

4.4 Results and Discussion

Different scenarios were carried out to show how the two spectrum sensing techniques; the energy detection and the matched filter operate under different signal to noise ratio. In each scenario two cases were considered; Case1, where the primary user is using the channel. In this case, the word

"Cognitive" was used in the simulation as an example to indicate the presence of the primary user. Case 2, where the channel is a spectrum hole. In this case, no text was provided so as to indicate the absence of the primary user.

4.4.1 Energy Detection

1. Noiseless Channel

Figure 4.6 shows the output of the energy detector in case 1 using **BPSK** modulation technique. The figure shows that the frequency channel at 200 Hz is the tested channel. This is indicated by the peak value at exactly 200 Hz. The PSD value at this frequency is 75.4dB/Hz, which is greater than the specified PSD value saved in secondary user device indicating the presence of a primary user in the channel.

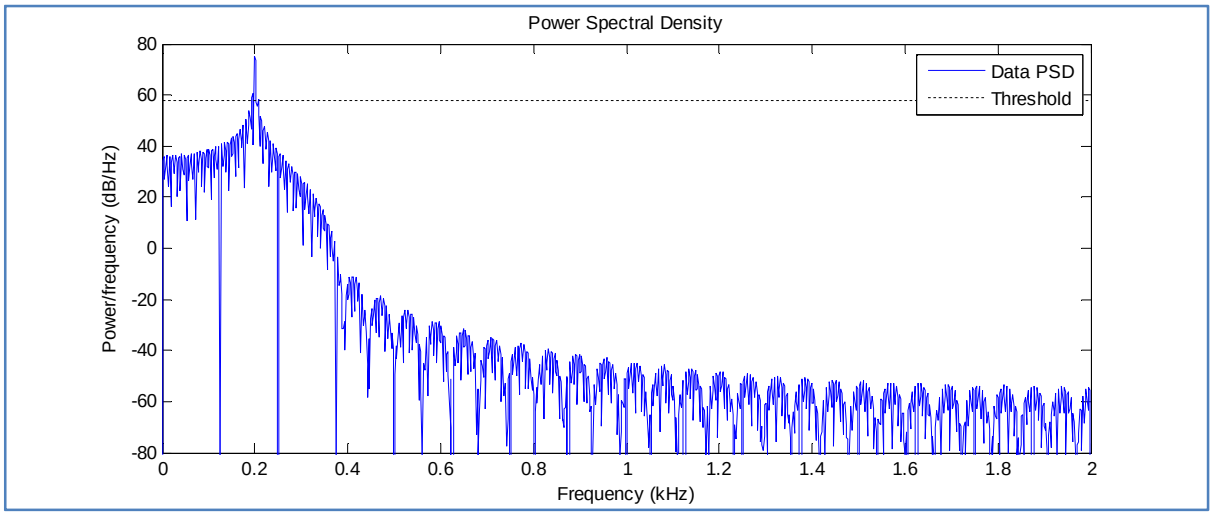

Figure (4.6): Energy Detection output with max PSD value of 75.4dB/Hz

Figure 4.7 shows the output of the energy detector in case 1 using **QPSK** modulation technique. The figure shows that the max PSD value at frequency 200 Hz is 61.21dB/Hz, which is greater than the specified PSD value saved in secondary user device indicating the presence of a primary user in the channel.

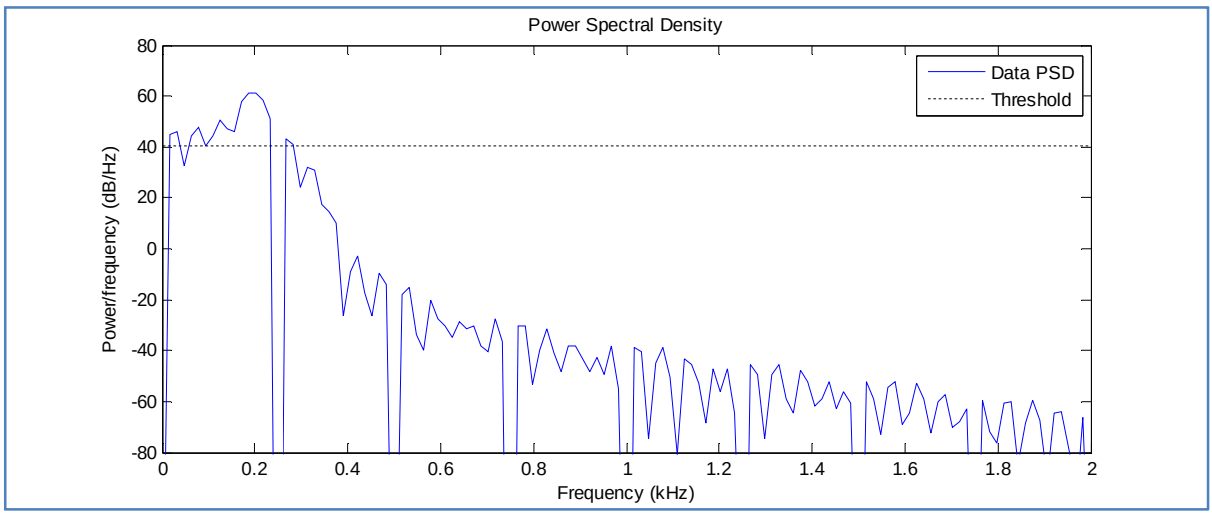

Figure (4.7):Energy Detection output with max PSD value of 61.2135dB/Hz.

Figure 4.8 shows the output of the energy detector in case 2 using **BPSK** modulation technique. The figure shows that the max PSD value at the frequency 200Hz is 27.28dB/Hz, which is less than the specified PSD value saved in secondary user device indicating the absence of the primary user in the channel.

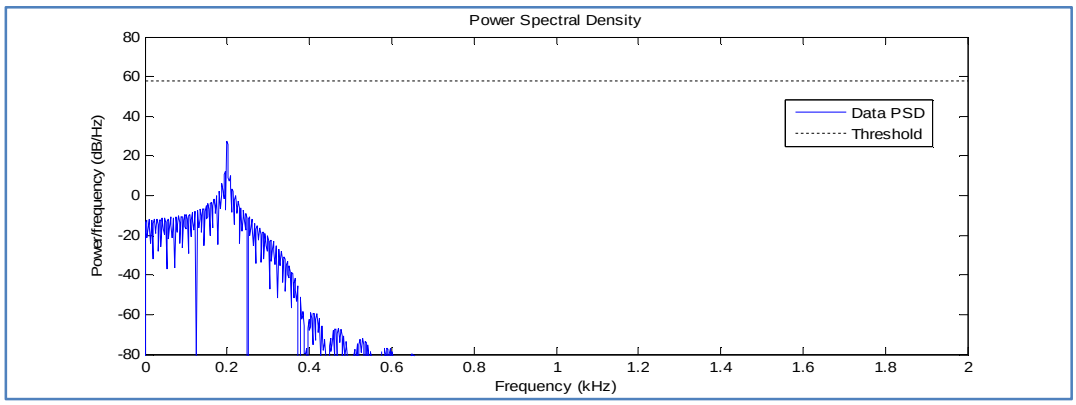

Figure (4.8): Energy Detection output with max PSD value of 27.2817dB/Hz.

Figure 4.9 shows the output of the energy detector in case 2 using **QPSK**. The figure shows that the max PSD value at the frequency 200Hz is 13.19dB/Hz, which is less than the specified PSD value of the QPSK saved in the secondary user device indicating the absence of the primary user in the channel.

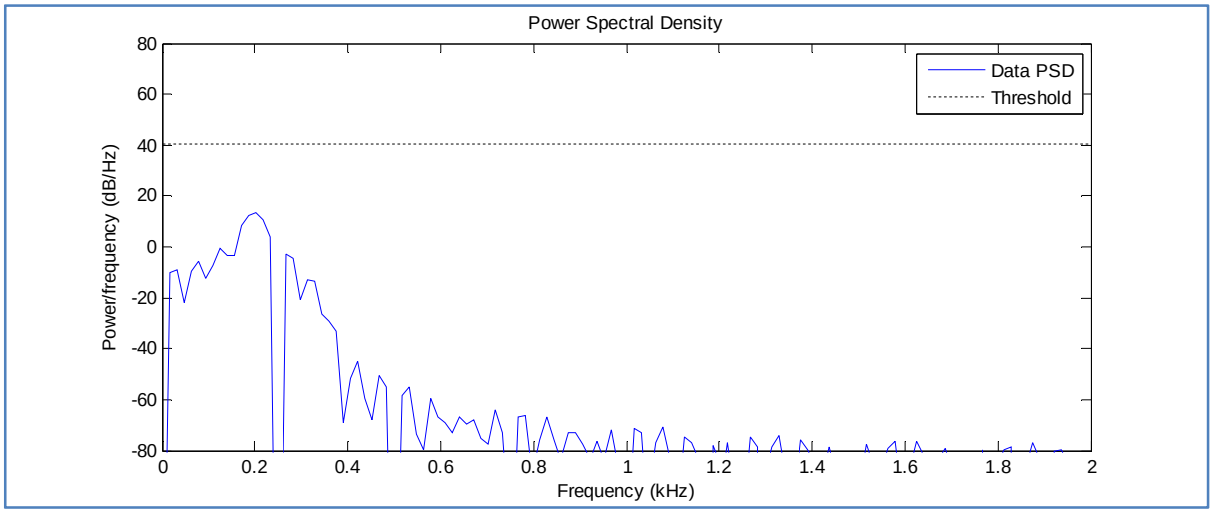

Figure (4.9): Energy Detection output with max PSD value of 13.1945dB/Hz.

2. Noisy channels

In this scenario different SNR values were used to simulate its effect.

A. Case 1 with BPSK modulation

Figure 4.10, 4.11, 4.12, 4.13, 4.14 and 4.15 show the output of the energy detector in case 1using **BPSK** modulation technique for the SNR values 15dB, 10dB, 0dB, -10dB, -30dB and -60dB respectively.

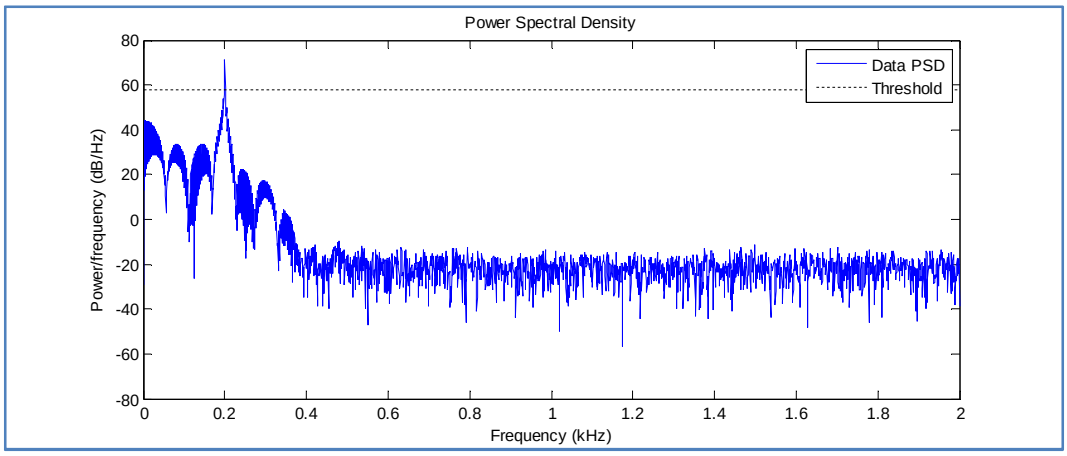

Figure (4.10): Energy Detection output with PSD of 71.2955dB/Hz at 15dB

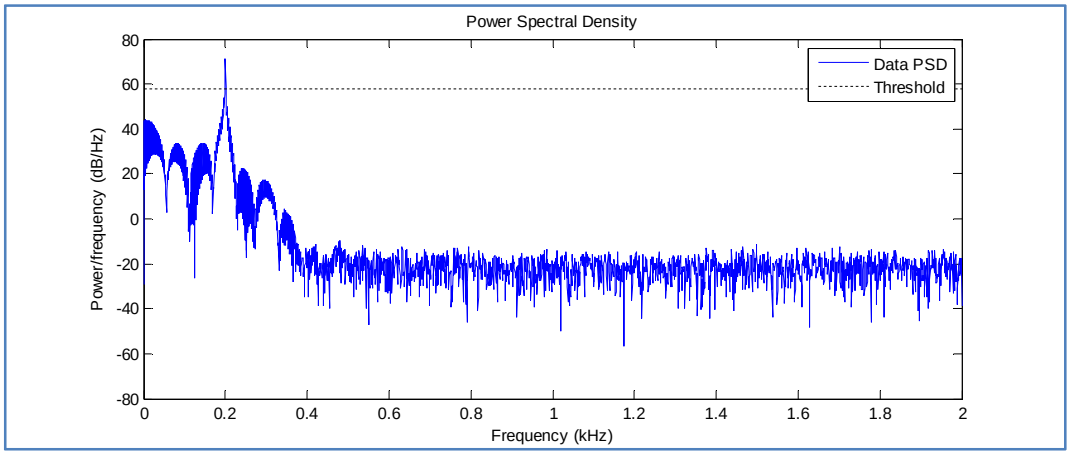

Figure (4.11): Energy Detection output with PSD of 71.2950dB/Hz at 10dB

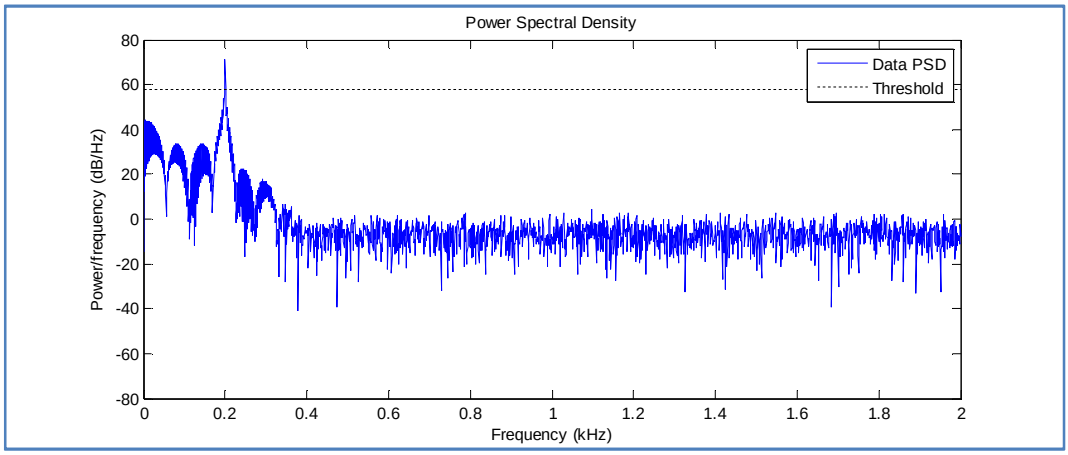

Figure (4.12): Energy Detection output with PSD of 71.2943dB/Hz at 0dB

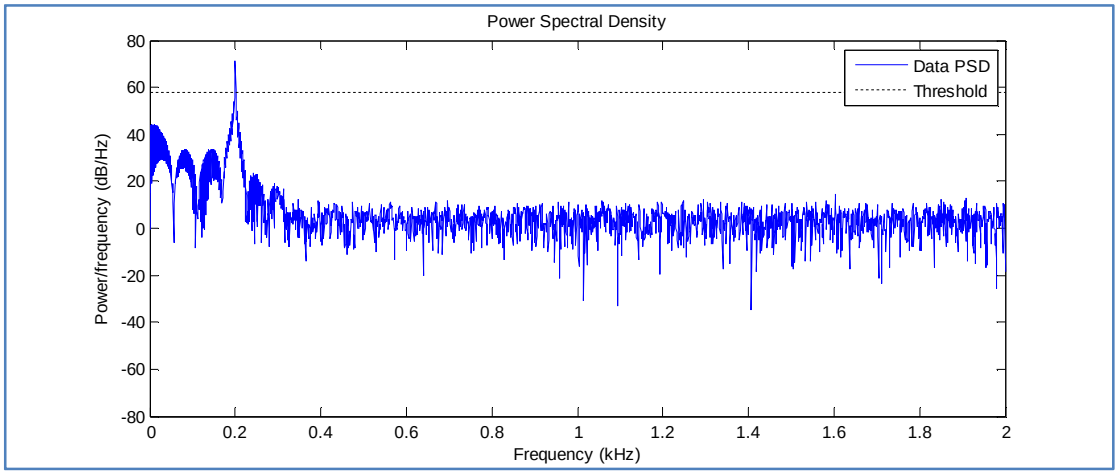

Figure (4.13): Energy Detection output with PSD of 71.2898dB/Hz at -10dB

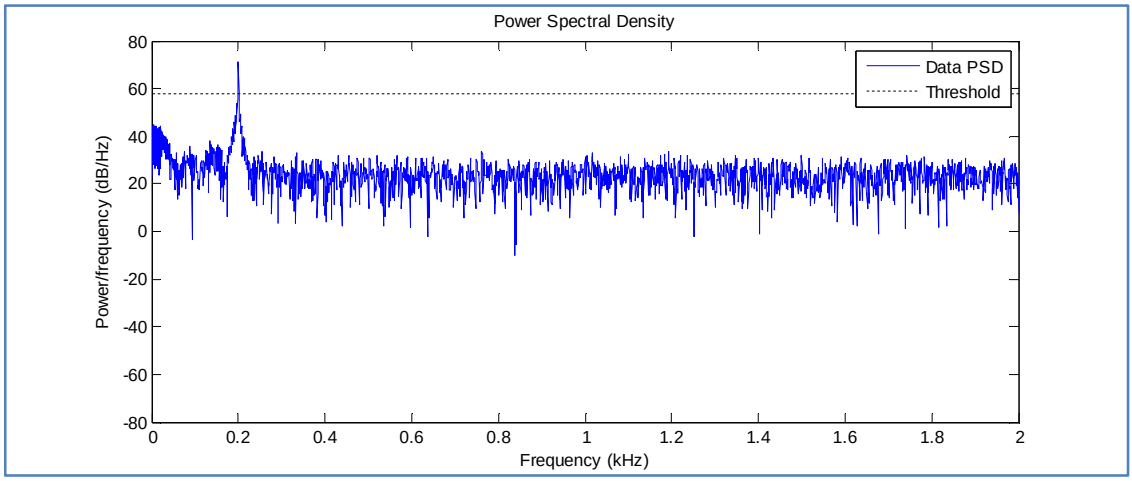

Figure (4.14): Energy Detection output with PSD of 71.2890dB/Hz at-30dB

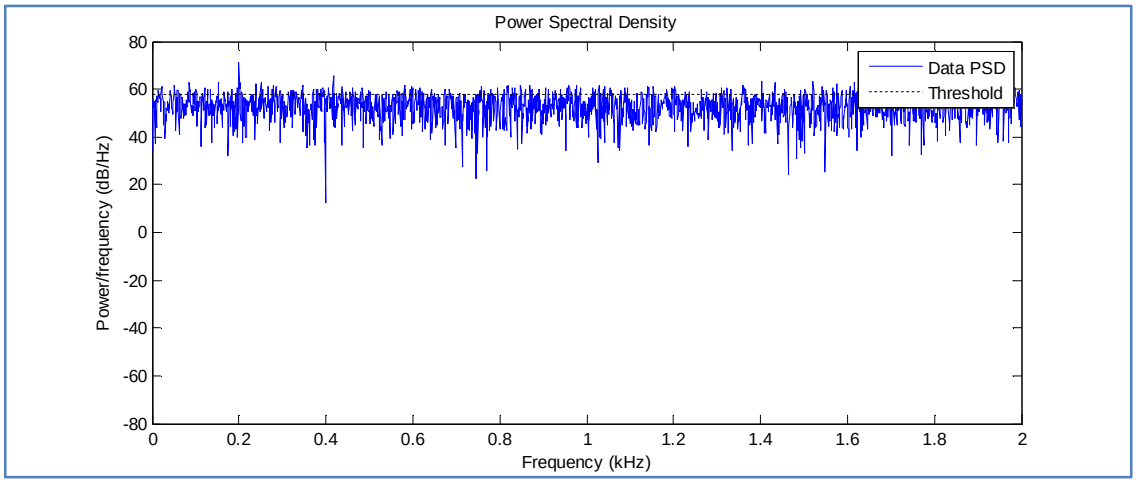

Figure (4.15): Energy Detection output with PSD of 71.1431B/Hz at -60dB

The introduction of noise into the channel resultedin a decrease in the max PSD value at the frequency 200Hz. The max PSD obtained at 200Hz were 71.2955dB/Hz, 71.2950dB/Hz, 71.2943dB/Hz, 71.28.98dB/Hz, 71.28.90dB/Hz, 71.1431dB/Hz, for the SNR 15dB, 10dB, 0dB, -10dB,-30dB and -60dB respectivelyindicating the presence of a primary user in the channel. It was notice that the max PSD was around 7.1%less than the max PSD in the noiseless.

Figure 4.15show that if the channel suffers from very low SNR conditionssuch as -60dB, this will generate high peaks of noise which is translated by the detector as a high PSD peak value. As a result the detector detects the presence of a user although it is a spectrum hole.

B. Case 1 with QPSK modulation

Figure 4.16, 4.17, 4.18, 4.19, 4.20 and 4.21 show the output of the energy detector in case 1 using **QPSK** modulation technique for the SNR values 15dB, 10dB, 0dB, -10dB, -30dB and -60dB respectively.

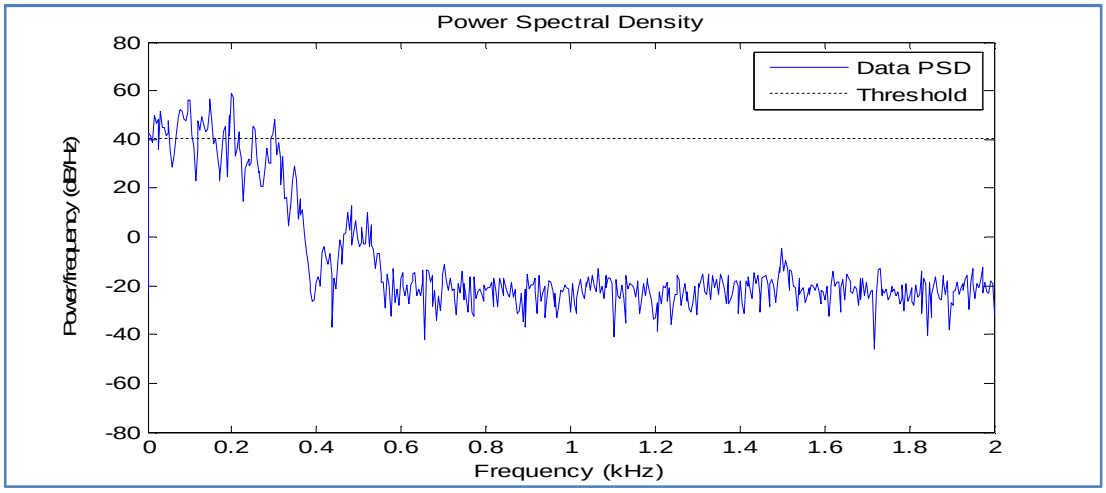

Figure (4.16): Energy Detection output with PSD of 58.8337dB/Hz at 15dB

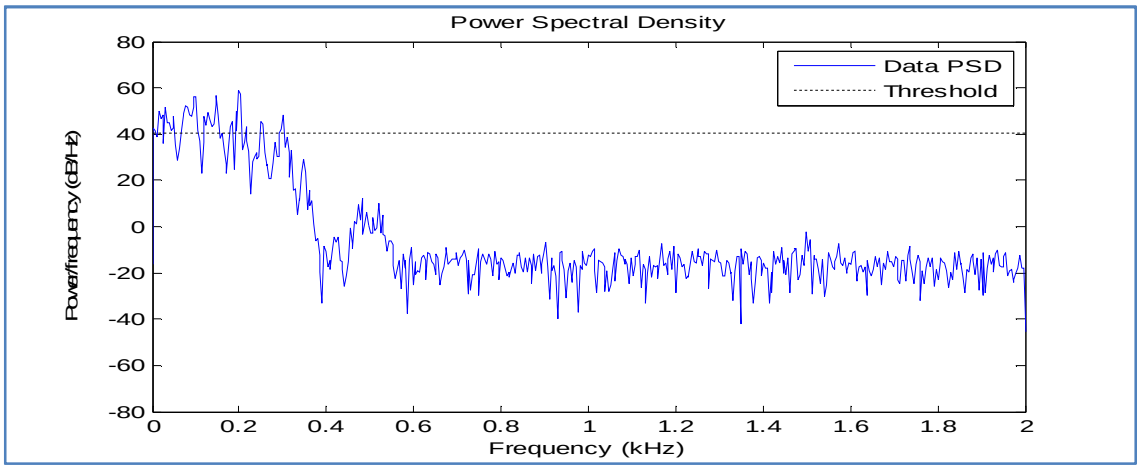

Figure (4.17): Energy Detection output with PSD of 58.8345dB/Hz at 10dB

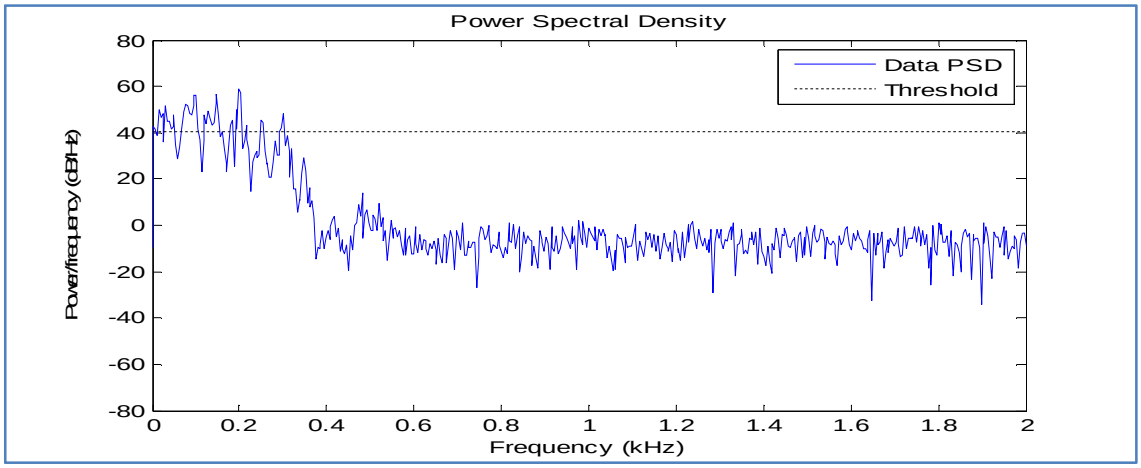

Figure (4.18): Energy Detection output with PSD of 58.8322dB/Hz at 0dB

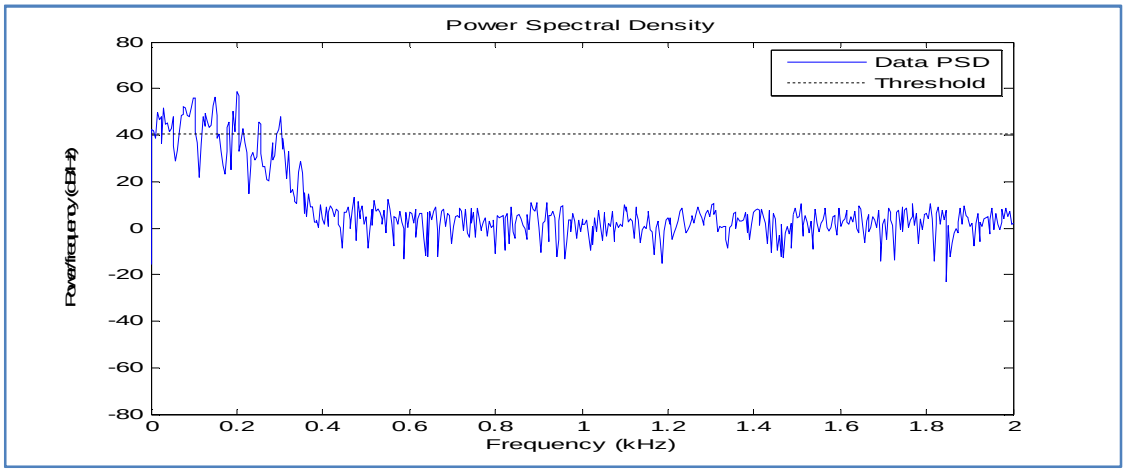

Figure (4.19): Energy Detection output with PSD of 58.8153dB/Hz at -10dB

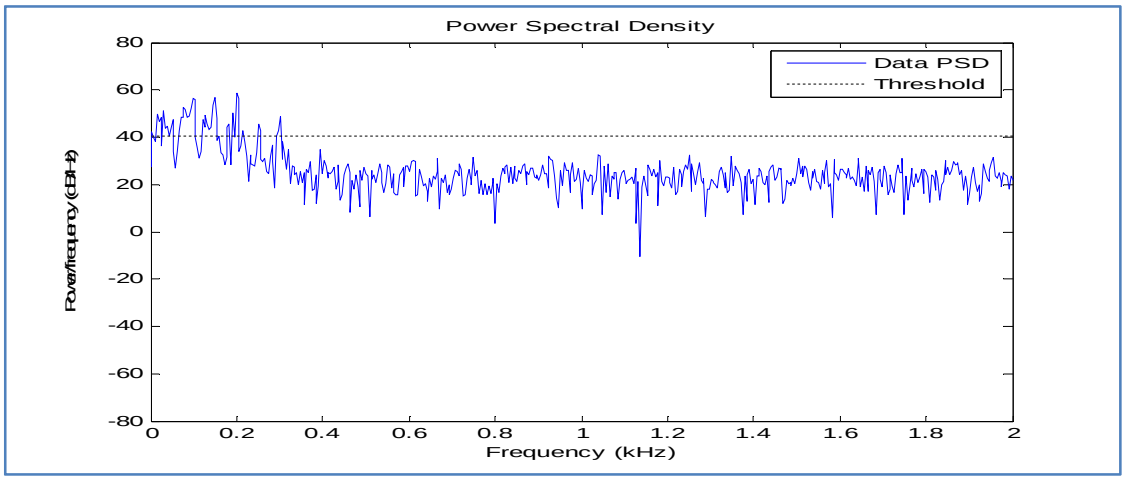

Figure (4.20): Energy Detection output with PSD of 58.7672dB/Hz at -30dB

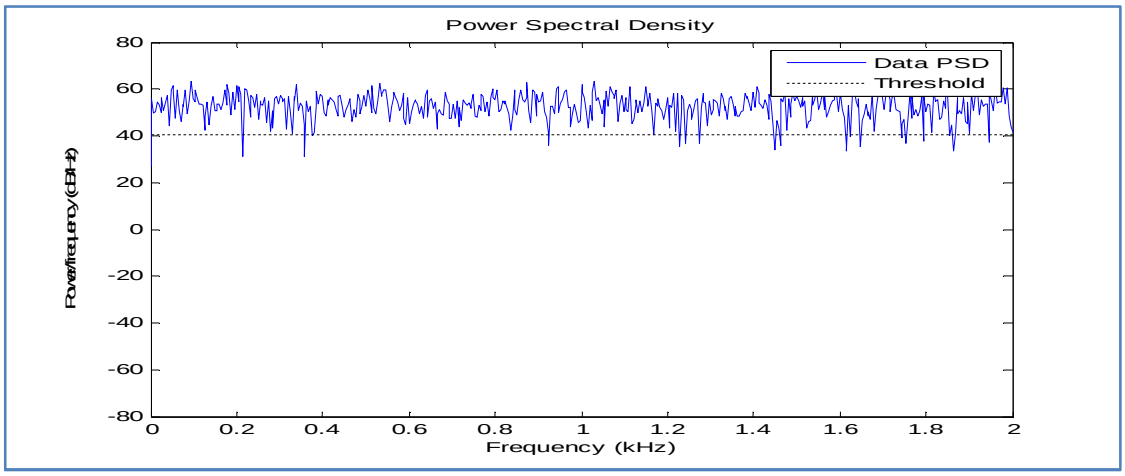

Figure (4.21): Energy Detection output with PSD of 63.3689dB/Hz at -60dB.

The introduction of noise into the channel resulted in a decrease in the max PSD value at the frequency 200Hz. The max PSD obtained at 200Hz were;58.5337dB/Hz, 58.8345dB/Hz, 58.8322dB/Hz, 58.8153dB/Hz, 58.7672dB/Hz, 63.3689dB/Hz, for the SNR 15dB, 10dB, 0dB, -10dB,-30dB and -60dBrespectively,indicating the presence of a primary user in the channel. It was notice that the max PSD was around 5.9 %less than the max PSD in the noiseless.

Figure 4.16 shows that under very low SNR conditions such as -60dB, high peaks of noise are generated which are translated by the detector as a high PSD peak value. As a result the detector detects the presence of a user in the entire spectrum.

C. Case 2 with BPSK modulation

Figure 4.22, 4.23, 4.24, 4.25, 4.26 and 4.27 show the output of the energy detector in case 2 using **BPSK** modulation technique for the SNR values 15dB, 10dB, 0dB, -10dB, -30dB and -60dB respectively.

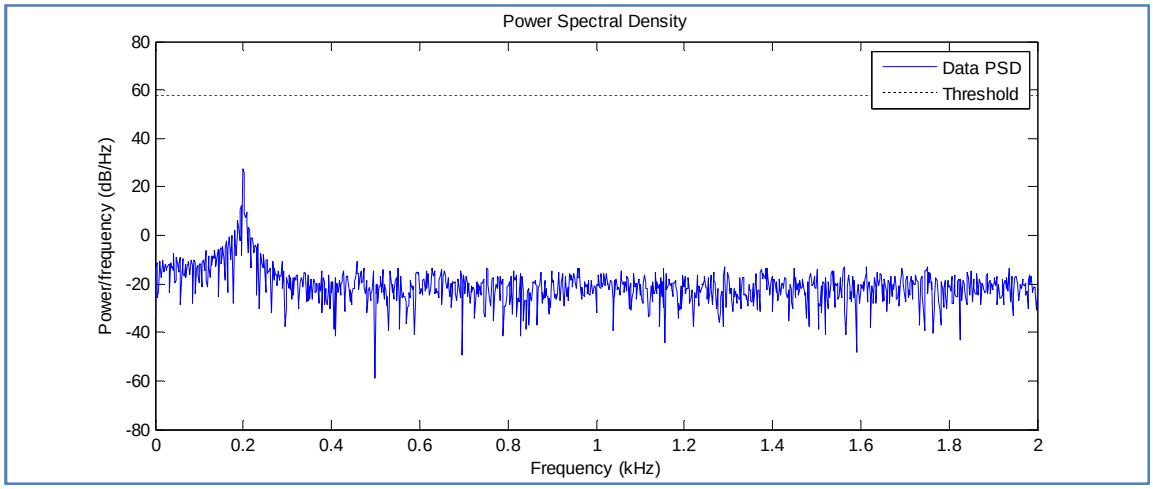

Figure (4.22): Energy Detection output with PSD of 27.2724dB/Hz at 15dB

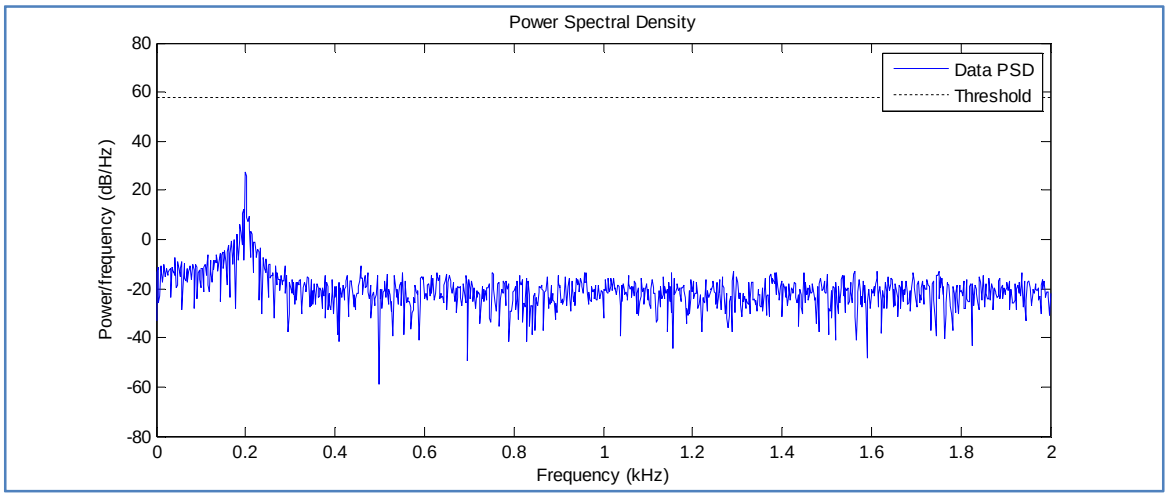

Figure (4.23): Energy Detection output with PSD of 27.2750dB/Hz at 10dB

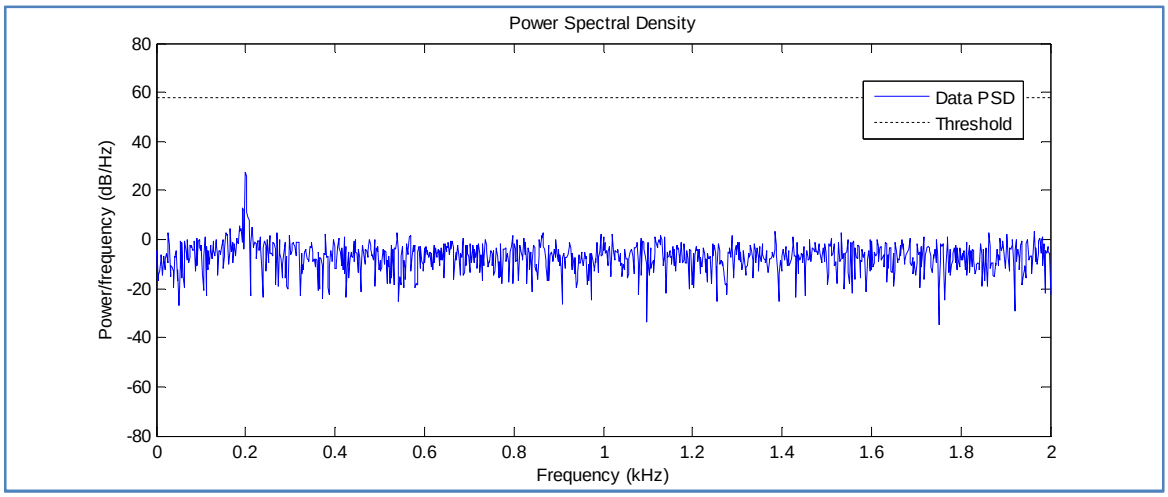

Figure (4.24): Energy Detection output with PSD of 27.2891dB/Hz at 0dB

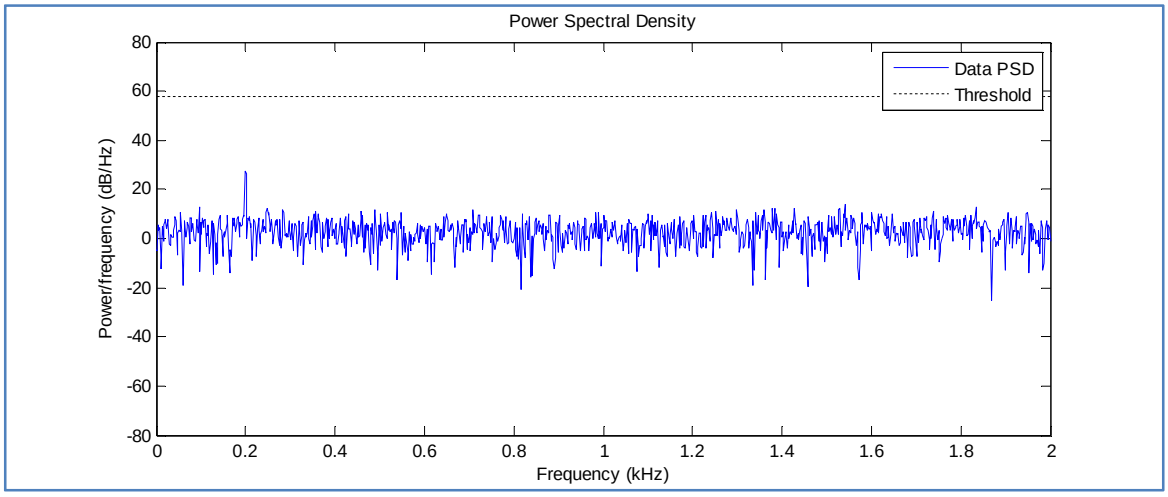

Figure (4.25): Energy Detection output with PSD of 27.5443dB/Hz at -10dB

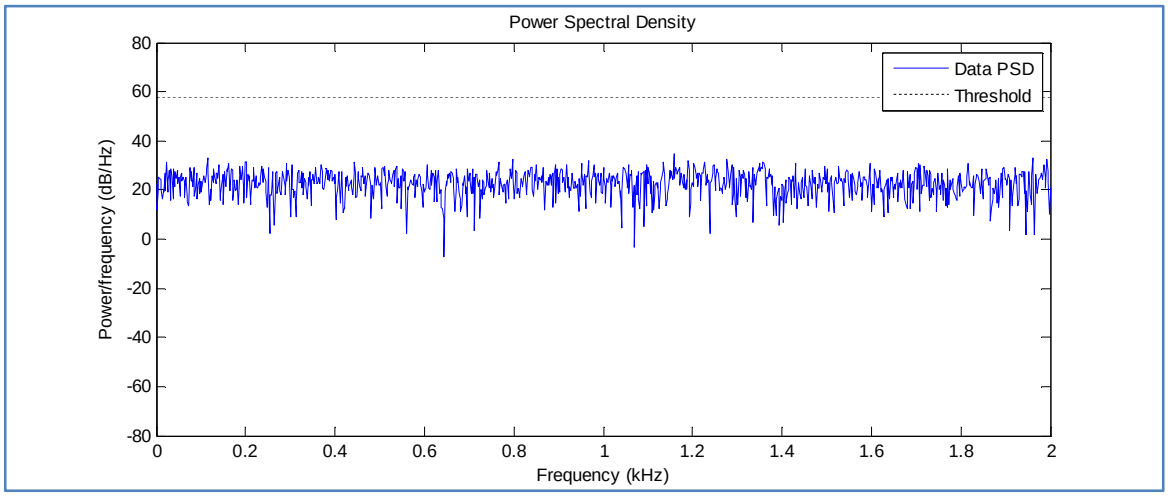

Figure (4.26): Energy Detection output with PSD of 27.2891dB/Hz at -30dB

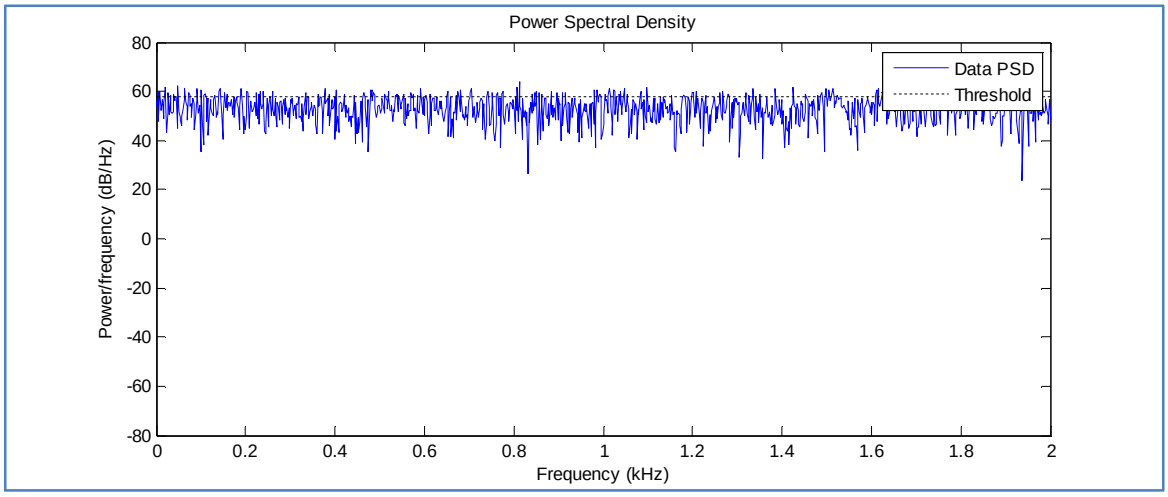

Figure (4.27): Energy Detection output with PSD of 63.7898dB/Hz at -60dB

The results showed that since there was no data entered, then the noise level in the system was affected by the different SNR values.

The noise level NSD (Noise Spectral Density)increases or decreases depending on the SNR value.

Since that the $NSD_{dB} = 10 \log10 (P_N / P_S)$

And the$SNR_{dB} = 10 \log10 (P_S / P_N)$,

$SNR_{dB} = - NSD_{dB}$

Where P_S is a signal power, P_N is a noise power.

Figure 4.27 show that although there was no primary user, the detector detected the presence of a user in the spectrum. This was the result of an increase in the noise level that reached the specified threshold and was translated by the detector as a high PSD peak value.

D. Case 2 with QPSK modulation

Figure 4.28, 4.29, 4.30, 4.31, 4.32 and 4.33 show the output of the energy detector in case 2 using **QPSK** modulation technique for the SNR values 15dB, 10dB, 0dB, -10dB, -30dB and -60dB respectively.

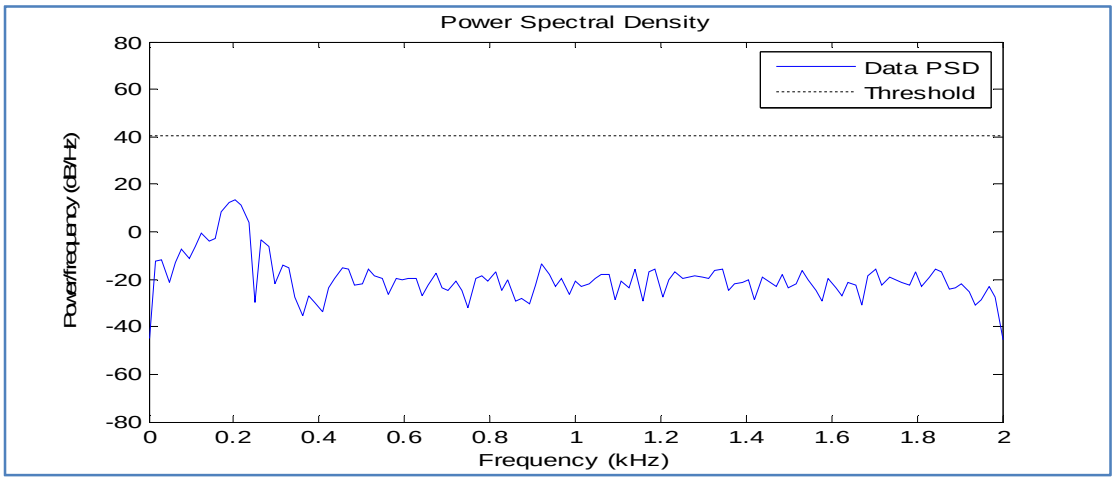

Figure (4.28): Energy Detection output with PSD of 13.3552dB/Hz at 15dB

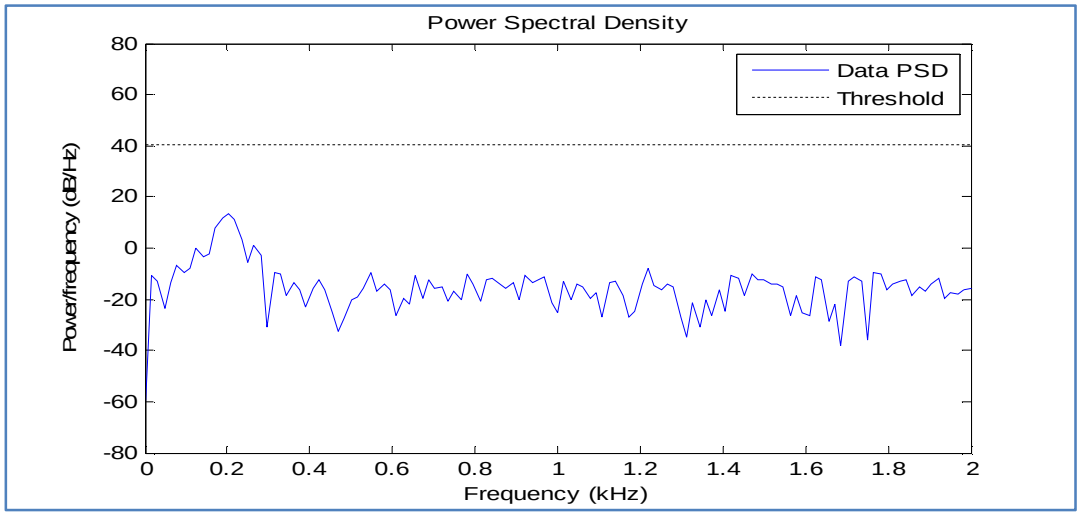

Figure (4.29): Energy Detection output with PSD of 13.3285dB/Hz at 10dB

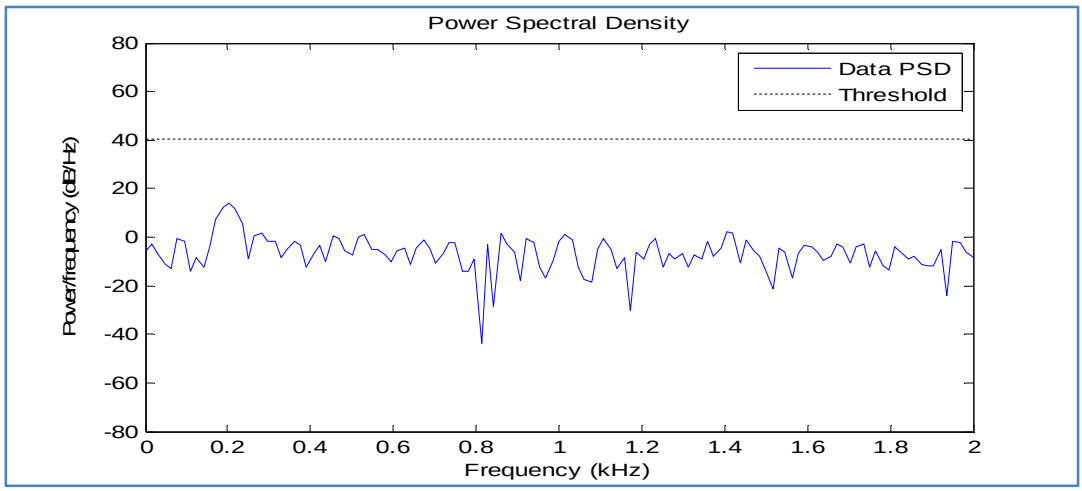

Figure (4.30): Energy Detection output with PSD of 13.8263dB/Hz at 0dB

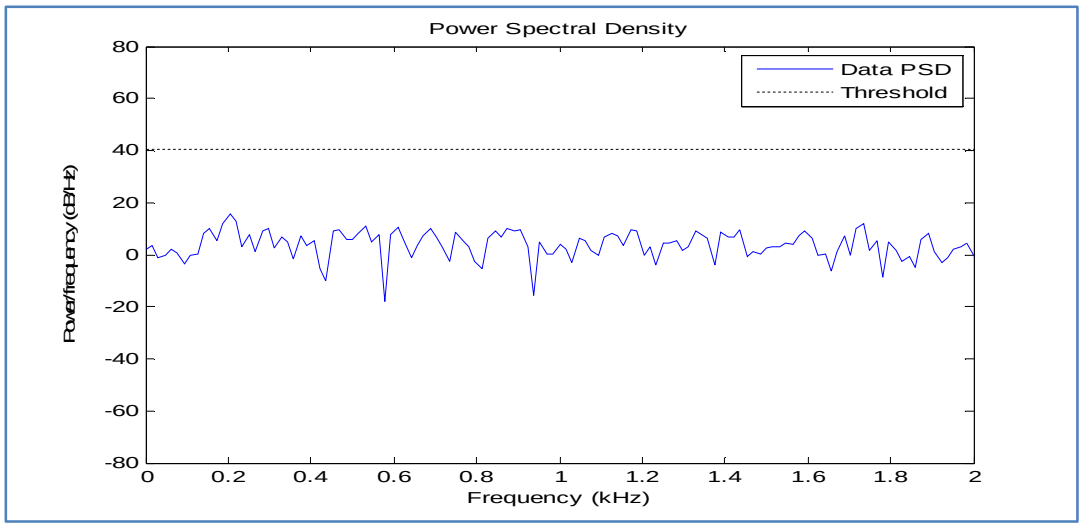

Figure (4.31): Energy Detection output with PSD of 15.8759dB/Hz at -10dB

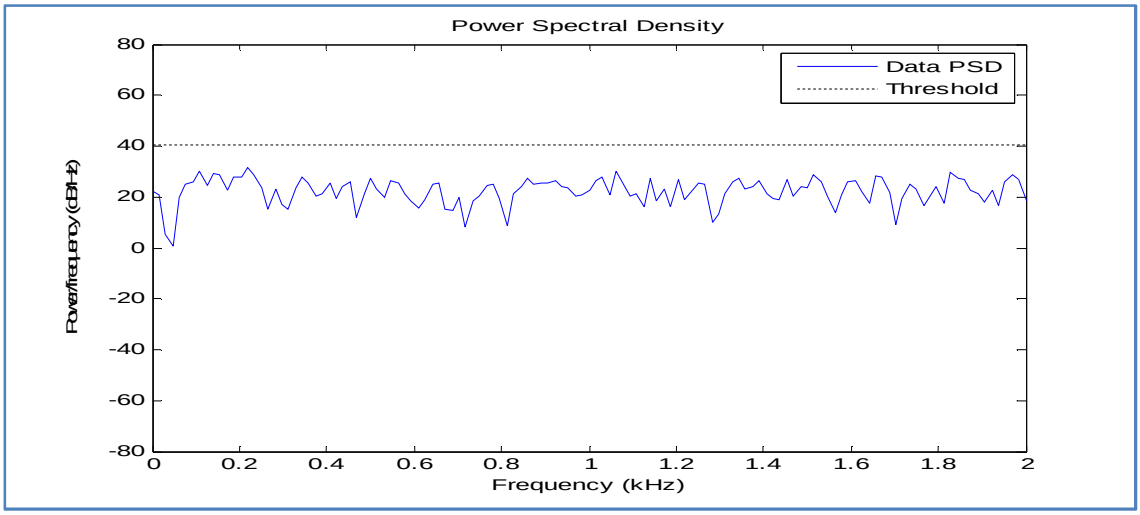

Figure (4.32): Energy Detection output with PSD of 31.4859dB /Hz at -30dB

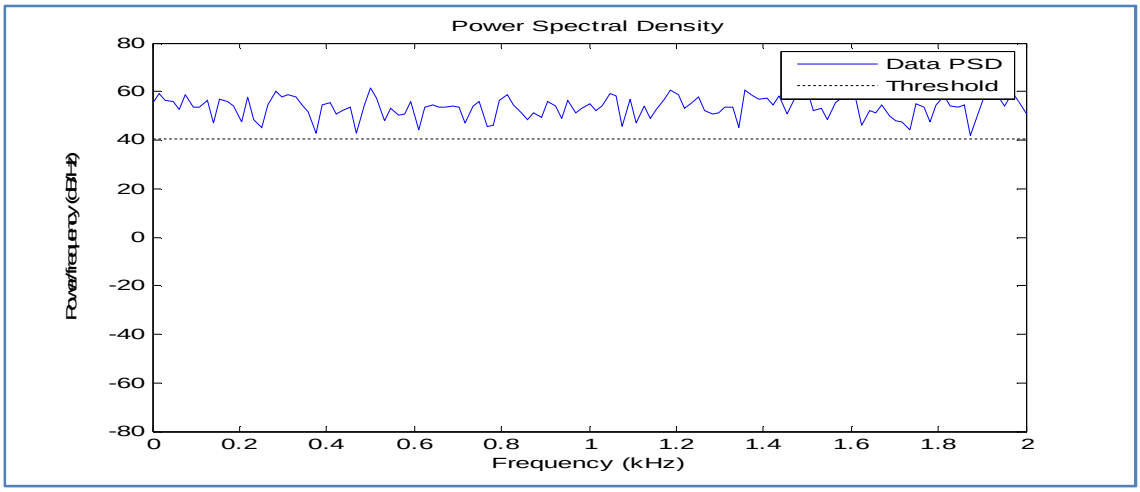

Figure (4.33): Energy Detection output with PSD of 62.3621dB/Hz at -60dB

The absence of a primary user means that no signal is being transmitted in the spectrum. This means that only noise is detected by the energy detector. Since the noise level PSD = -SNR then the noise PSD will increase or decrease with the same amount of the SNR.

Figure 4.33 show that although the primary user was absent, the detector detected his presence in the spectrum. This was the result of the increase in the noise level that reached the specified threshold and was translated by the detector as a high PSD peak value.

The main drawback of the energy detection algorithm is that it cannot distinguish between the noise and the energy of the signal. Under very low

SNR conditions, the energy detector detects the additive white Gaussian noise (AWGN) with high energy values as the presence of a primary user in the entire spectrum used.

4.4.2 Matched Filter

Different scenarios were carried out to show how the two spectrum sensing techniques operate under different signal to noise ratio. In each scenario two cases were considered; Case1, where the primary user is using the channel. In this case, the word “Cognitive” was used in the simulation as an example to indicate the presence of the primary user. Case 2, where the channel is a spectrum hole. In this case, no text was provided so as to indicate the absence of the primary user.

1. Noiseless channel

Figure 4.34 shows the output of the matched filter detector in case 1 using **BPSK** modulation technique.The received signal from primary user and reference signal are correlated indicating the presence of a primary user. Although the received signal from the primary user and reference signal has different amplitudes, but the similarity is clear.The amplitude of the correlated signal is double of the amplitude of reference signal.

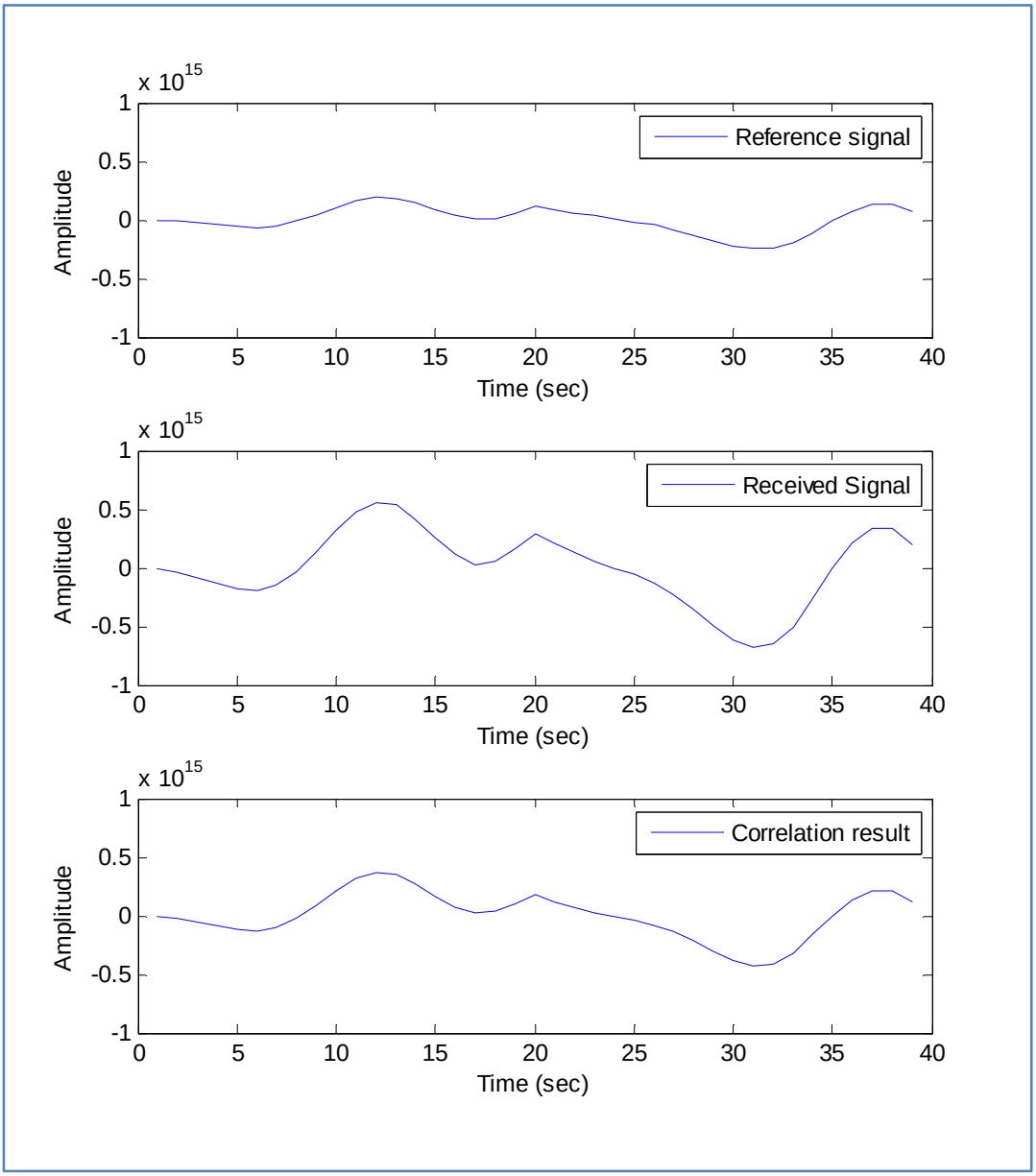

Figure (4.34): Matched Filter output of case 1 in noiseless channel using BPSK.

Figure 4.35 shows the output of the matched filter detector in case 1 using **QPSK** modulation technique.The received signal from primary user and reference signal are correlated indicating the presence of a primary user in the channel. The amplitude of correlated signal is **double** of the amplitude of reference signal.Note that any modulation technique has different reference signals. These reference signals have same amplitudes but different bit rate.

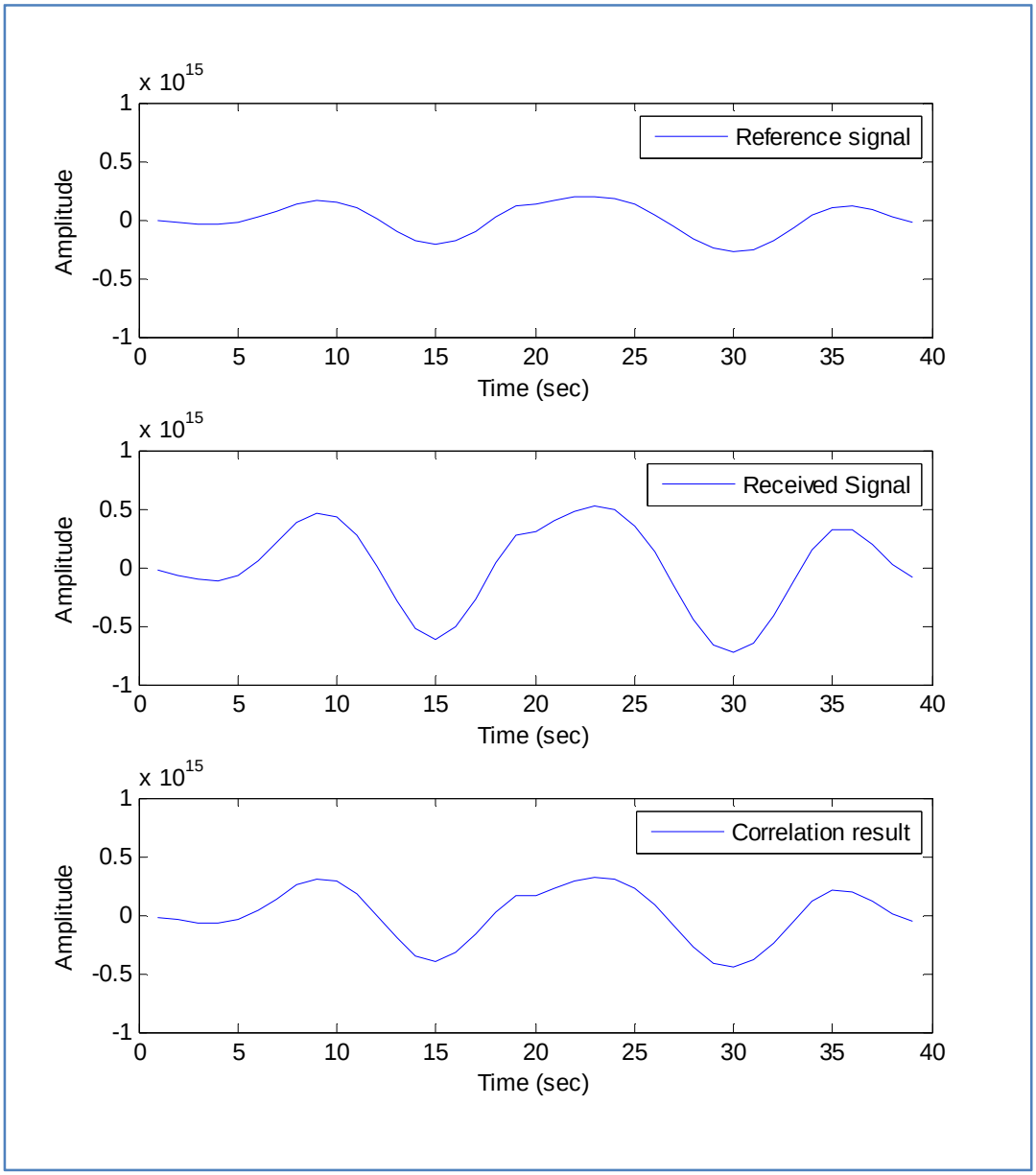

Figure (4.35): Matched Filter output ofcase 1 in noiseless channel using QPSK.

Figure 4.36 shows the output of the matched filter detector in case 2 using BPSK modulation technique. Since no data is entered, there is nothing to be received. As a result there is no correlation between the received and the reference signal.

Figure 4.37 shows the output of the matched filter detector in case 2 using QPSK modulation technique. Since no data is entered, the received signal is

a straight line. As a result the received signal is not correlated with the reference signal.

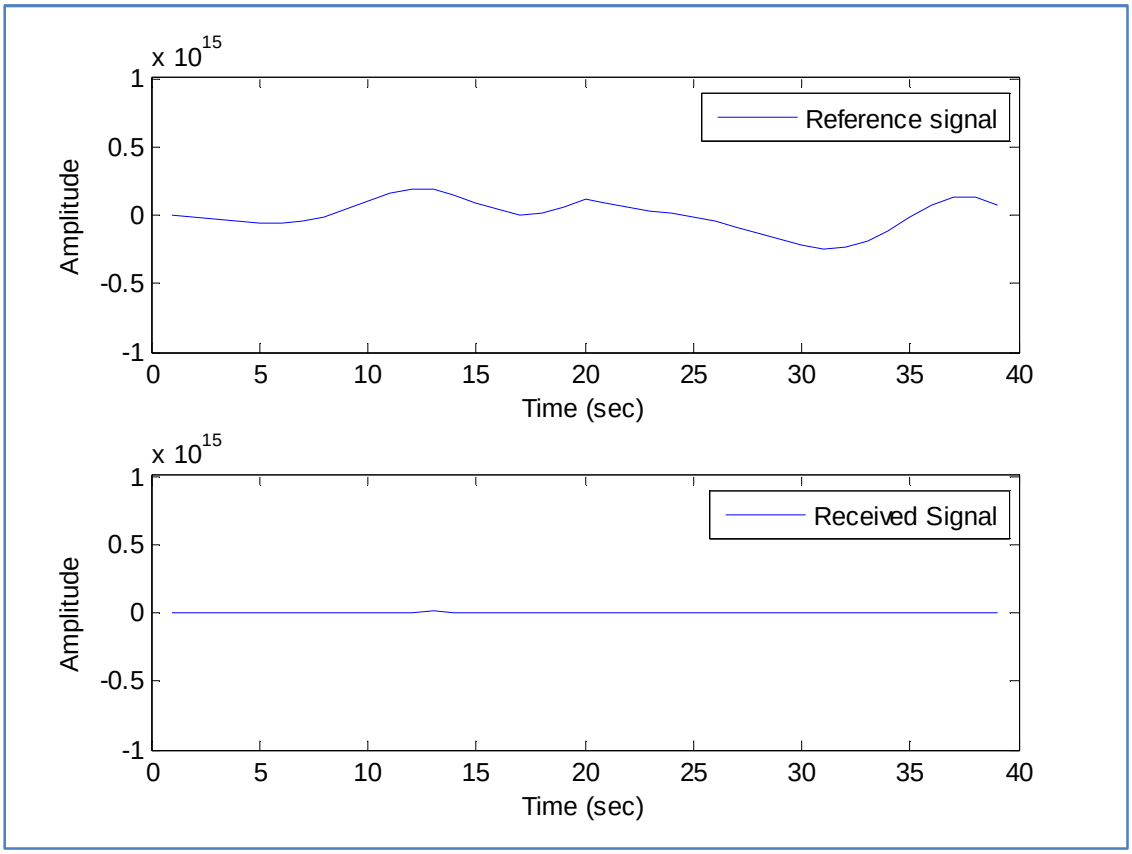

Figure (4.36): Matched Filter output of case 2 in noiseless channel using BPSK.

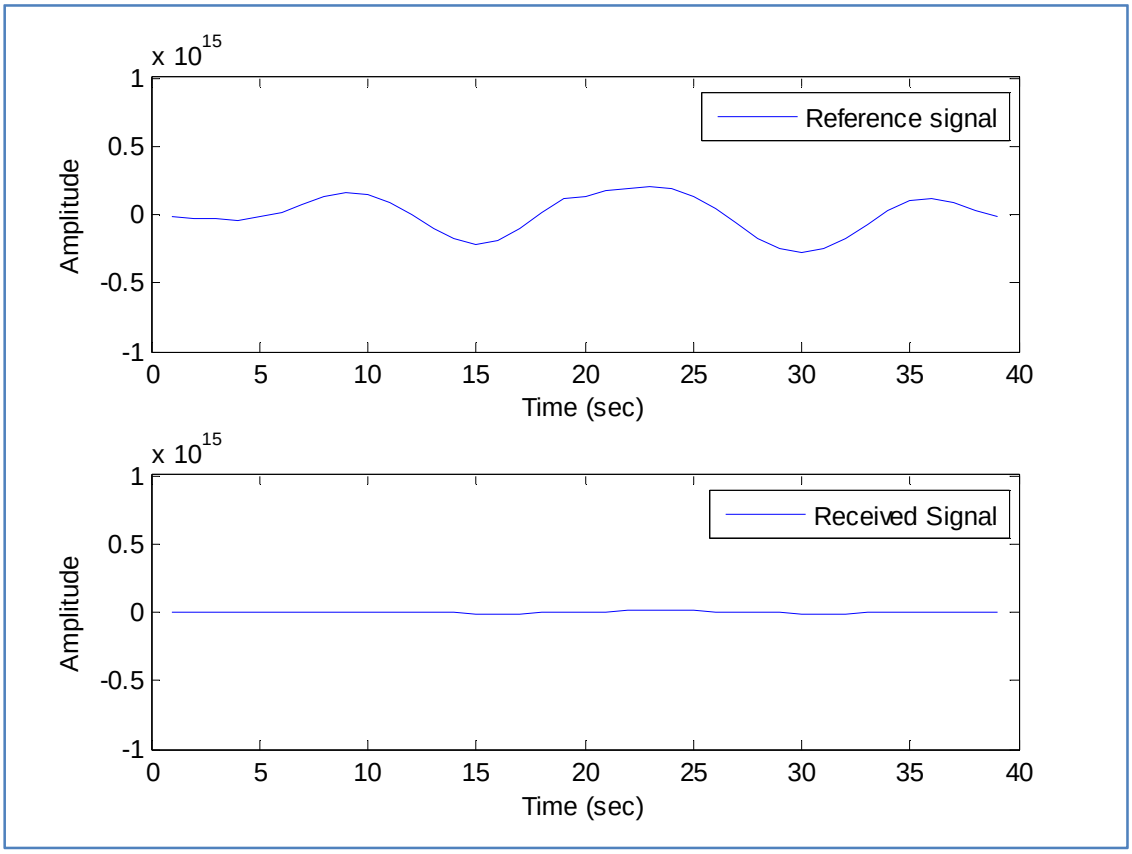

Figure (4.37): Matched Filter output of case 2 in noiseless channel using QPSK.

2. Noisy channels

In this scenario different SNR values were used to simulate its effect.

A. Case 1 with BPSK modulation

Figure 4.38, 4.39 and 4.40 show the output of the matched filter in case 1using **BPSK** modulation technique for the SNR values 15dB, 10dB and 0dB respectively.

The introduction of SNR of 15dB into the channel did not affect the received signal from the primary user. The received signal was correlated with the reference signal. The amplitude of the correlated signal is **1.096 times** the amplitude of reference signal as shown in Figure 4.38.

Notice that this increasing in correlated signal amplitudecaused by decreasing in SNR (from infinity to 15 dB).

Figure 4.39 shows the result of the matched filter when an SNR of 10dB was introduced into the channel. Although more noise was introduced yet it was still correlated with the reference signal. The amplitude of the correlated signal is **1.139 times** the amplitude of reference signal.

It was noticed that when the SNR decrease the amplitude of the signal decrease. This is due to that the received signal is a combination of the signal and noise and since the$SNR = 20 \log10 (A_S / A_N)$

Where A_S is a signal amplitude (measured in volts), and $A_N$is a noise amplitude (measured in volts).

Then any decrease in the SNR results in an increase in the noise which results in an increase in the amplitude of the signal.

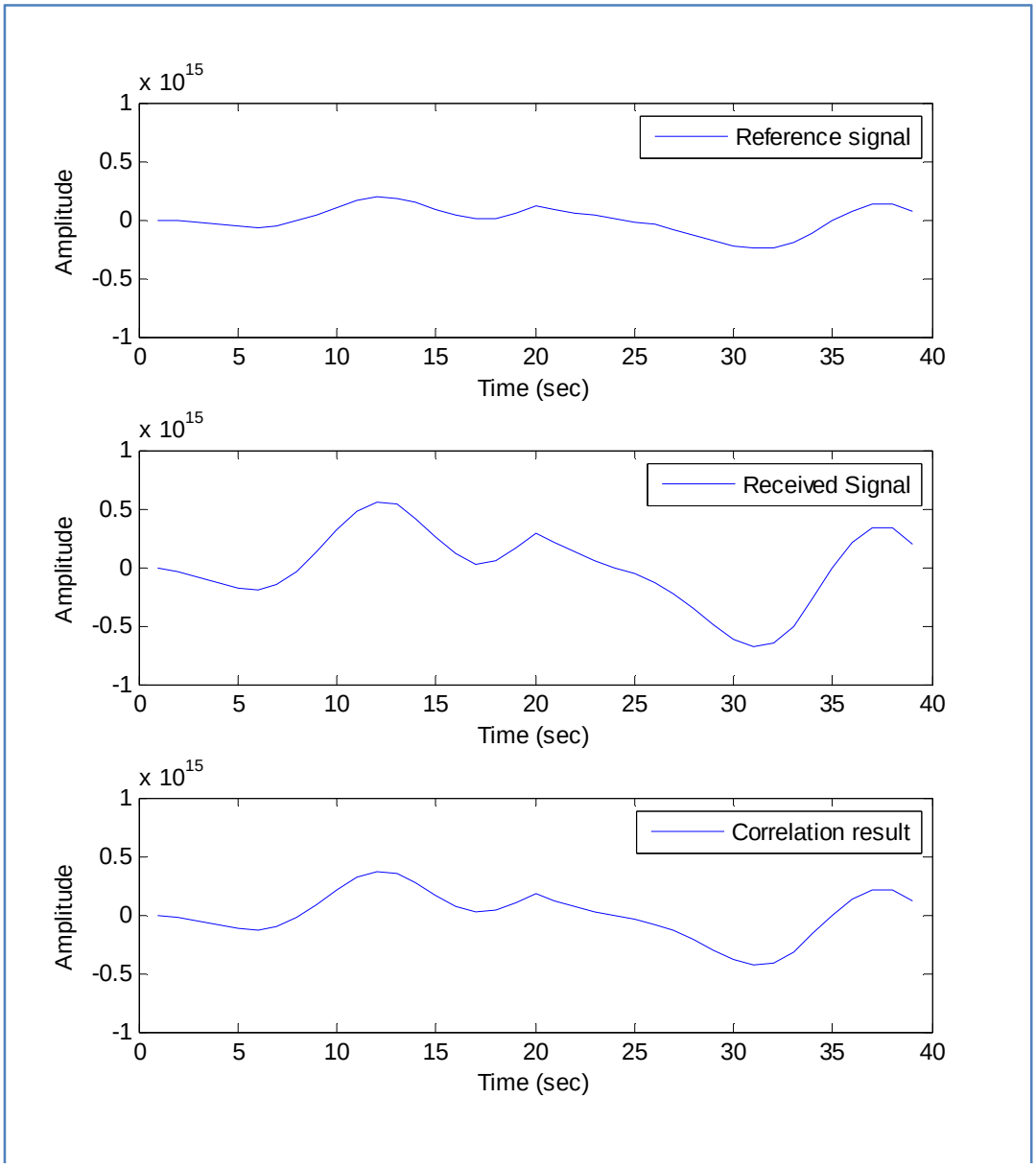

Figure (4.38): Matched Filter output of case 1 at 15dB.

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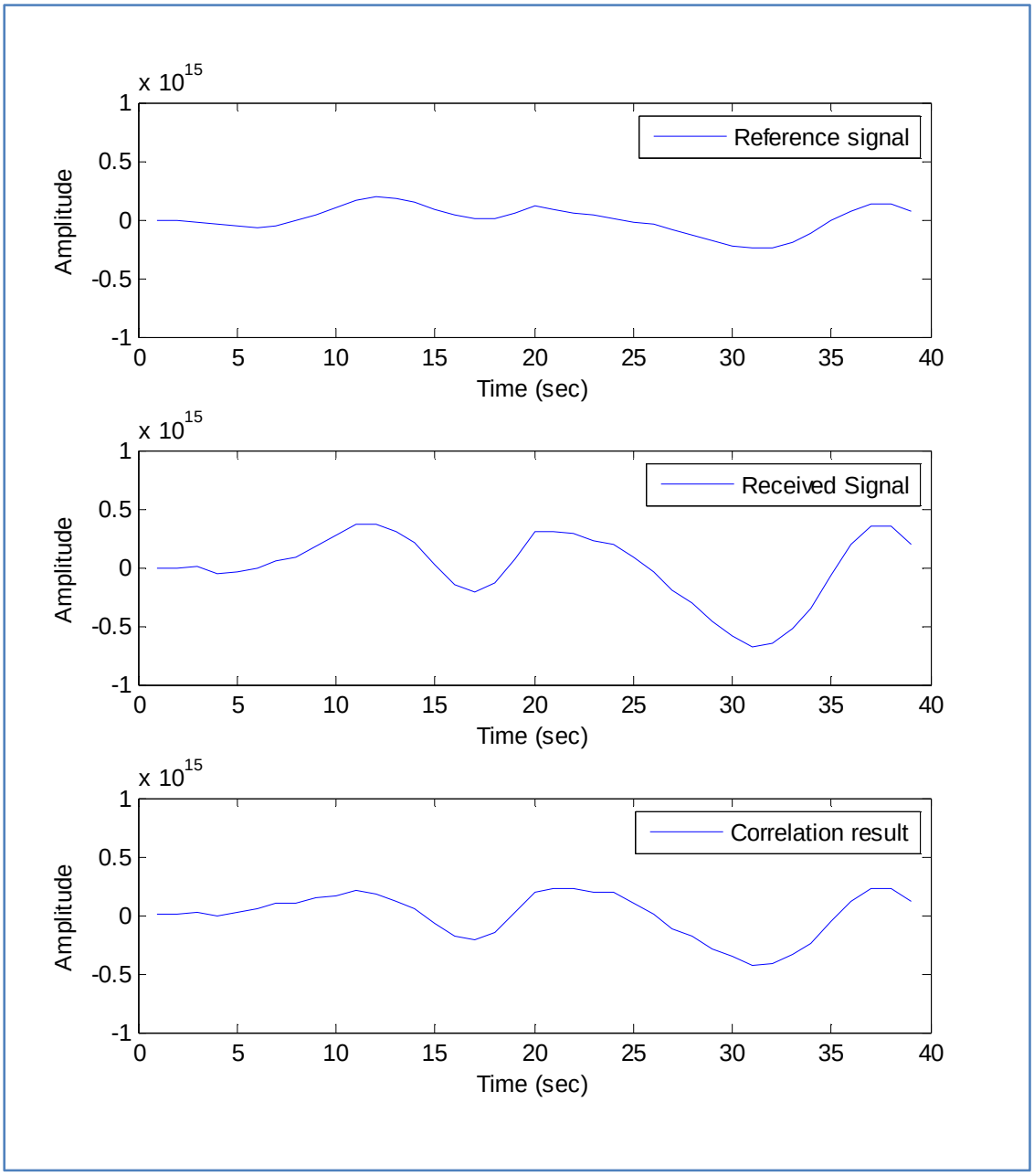

Figure (4.39): Matched Filter output of case 1 at10dB

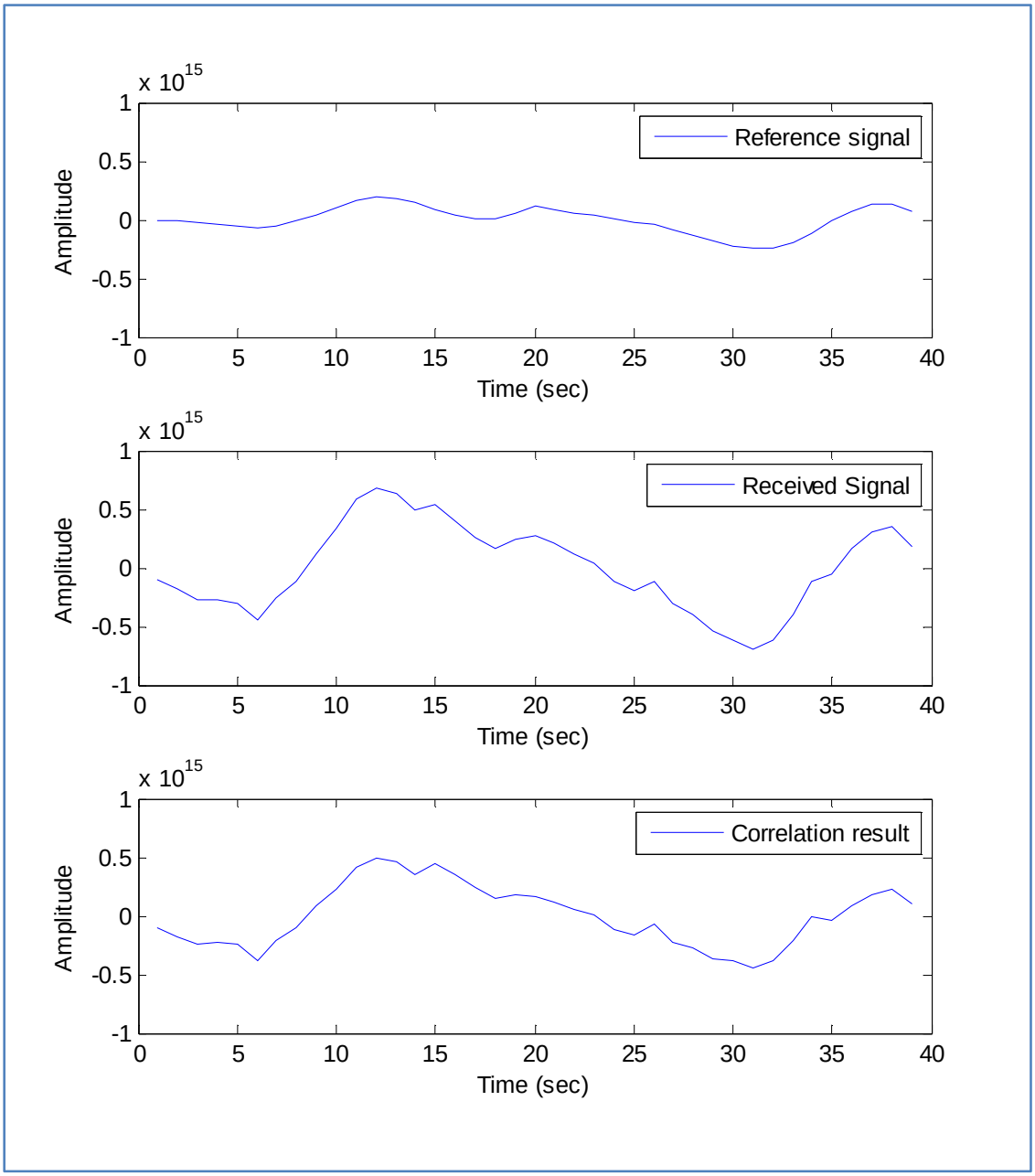

Figure (4.40): Matched Filter output of case 1 at0dB

Reducing the SNR to 0dB resulted in the received signal being distorted by noise and as a result there was no correlation with the reference signal as shown in Figure 4.40.

B. Case 1 with QPSK modulation

Figure 4.41, 4.42, and 4.43 show the output of the matched filter detector in case 1 using **QPSK** modulation technique for the SNR values 15dB, 10dB and 0dB respectively.

The introduction of noise into the channel resulted in a distorted in received signal from primary user. The received signal is not affected by noise in SNR of 15dB (it's correlated with reference signal). The amplitude of correlated signal is **1.412 times** the amplitude of reference signal as shown in Figure 4.41. Notice that this increasing in correlated signal amplitudecaused by decreasing in SNR to 15 dB.

Figure 4.42 shows the received signal has a negligible distorted in SNR of 10dB (still it's correlated with reference signal). The amplitude of correlated signal is **1.7074times** the amplitude of reference signal.Here note that the SNR is decreasing to 10dB also the correlated signal amplitude is increasing.

This is due to that the received signal is a combination of the signal and noise and since theSNR = 20 log10 (A_S / A_N)

Then any decrease in the SNR results in an increase in the noise which results in an increase in the amplitude of the signal.

In SNR of 0dB the received signal is distorted by noise and as a result there was no correlation with the reference signal as shown in figure 4.43.

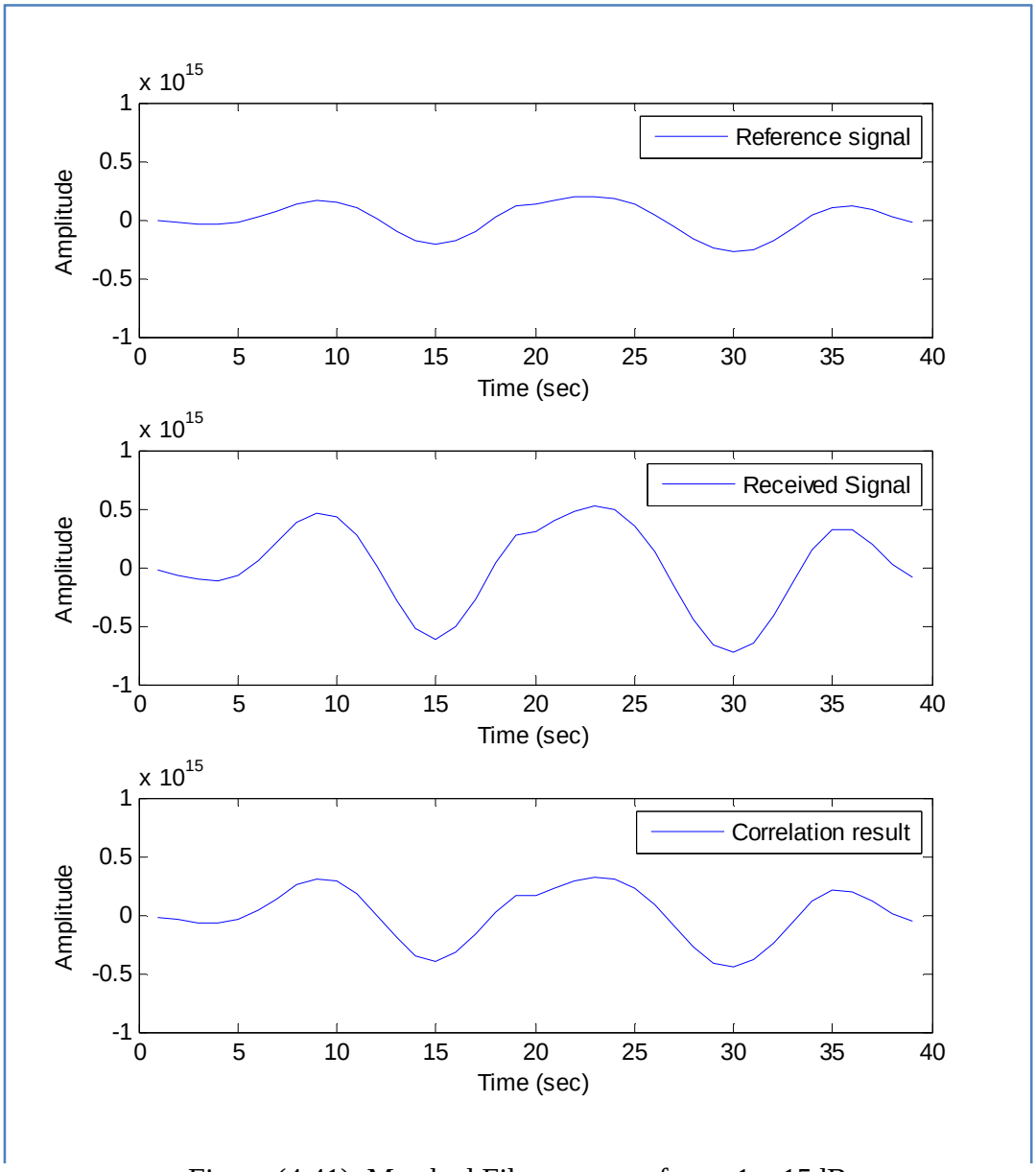

Figure (4.41): Matched Filter output of case 1 at15dB

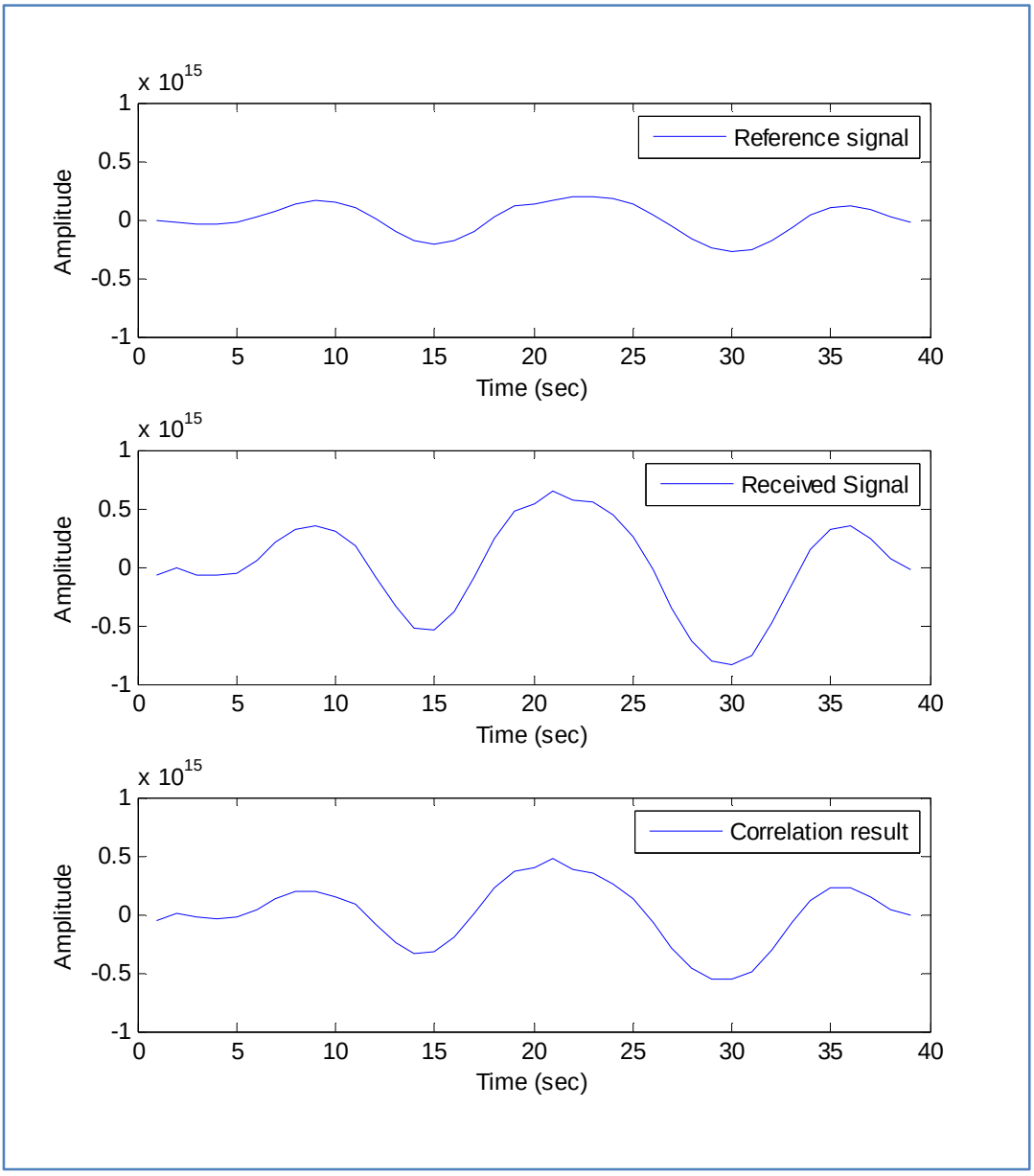

Figure (4.42): Matched Filter output of case 1 at10dB

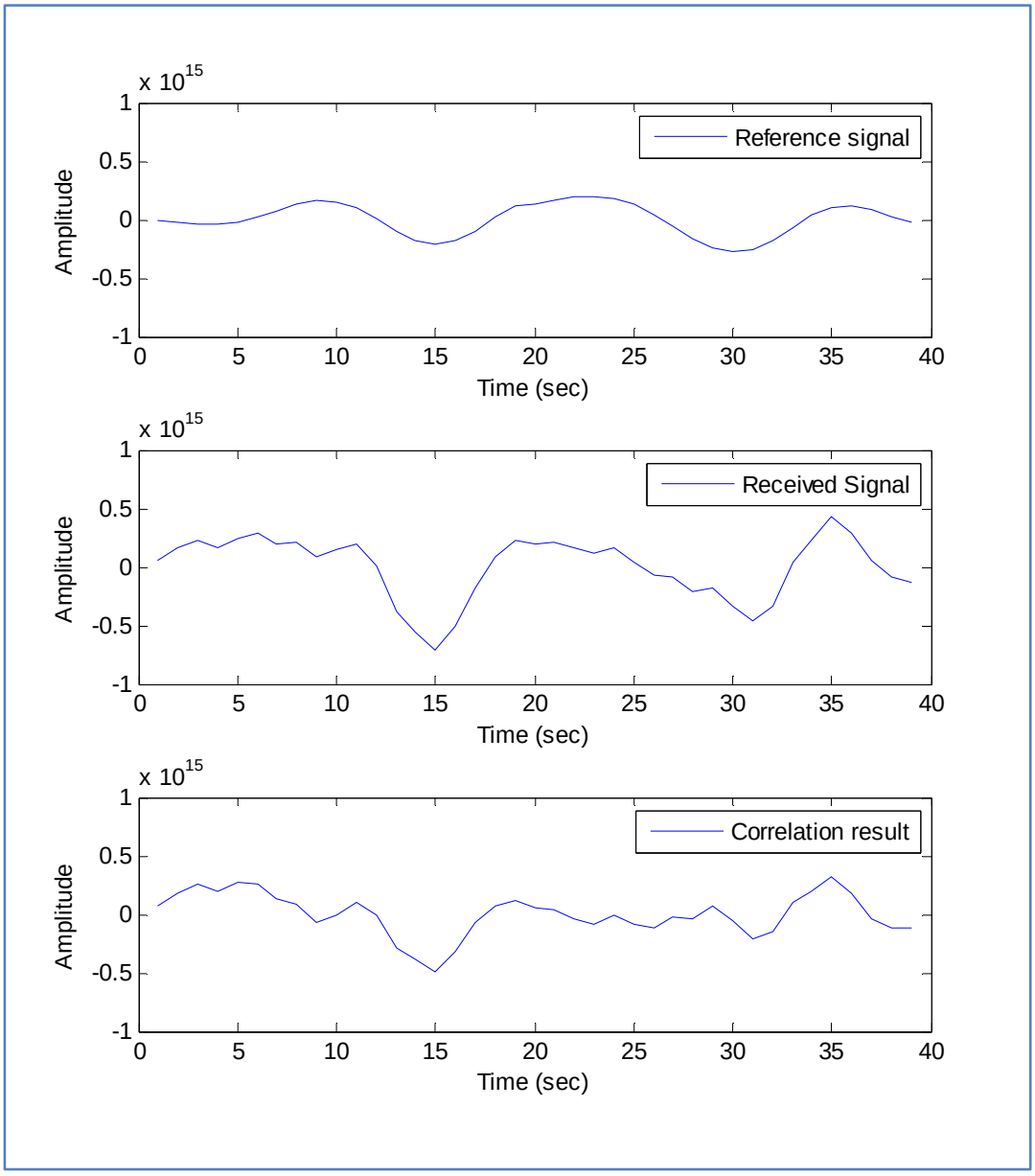

Figure (4.43): Matched Filter output of case 1 at0dB.

From this experimental concluded that QPSK affected by noise more than BPSK. This difference is also results from their differencesbit rates.

C. Case 2 with BPSK modulation

Figure 4.44, 4.45, and 4.46 show the output of the matched filter detector in case 2 using **BPSK** modulation technique for the SNR values 15dB, 10dB and 0dB respectively.

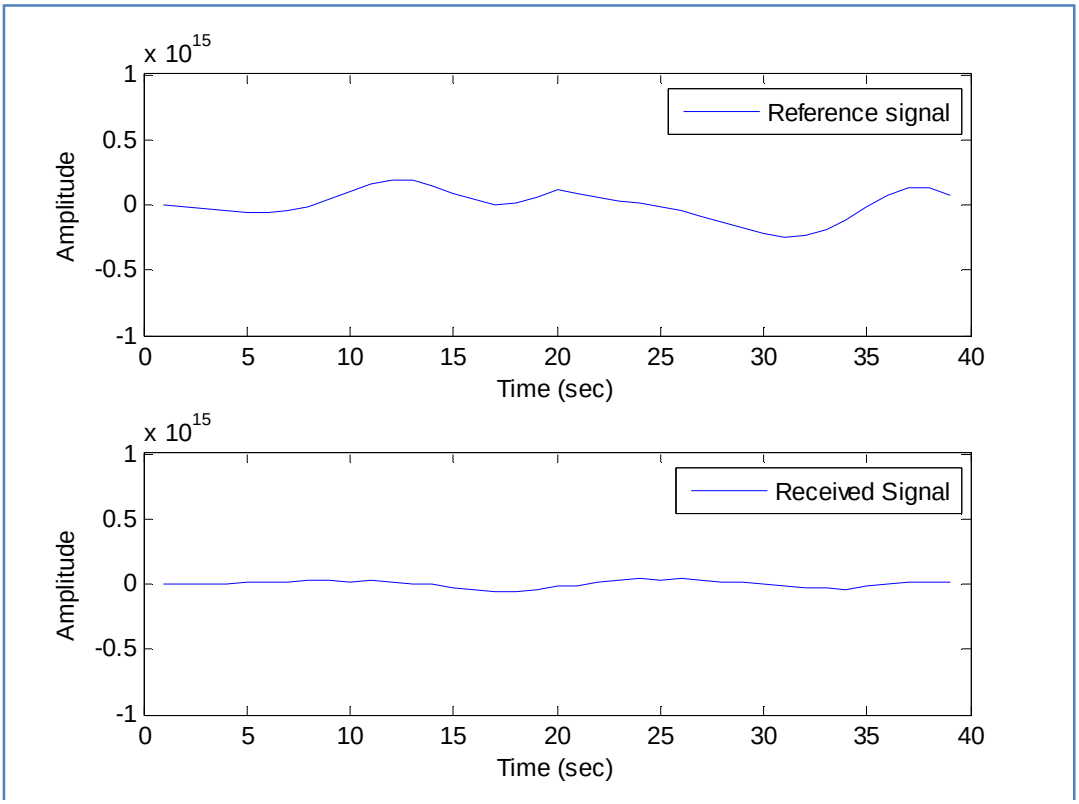

Figure (4.44): Matched Filter output of case 2at15dB

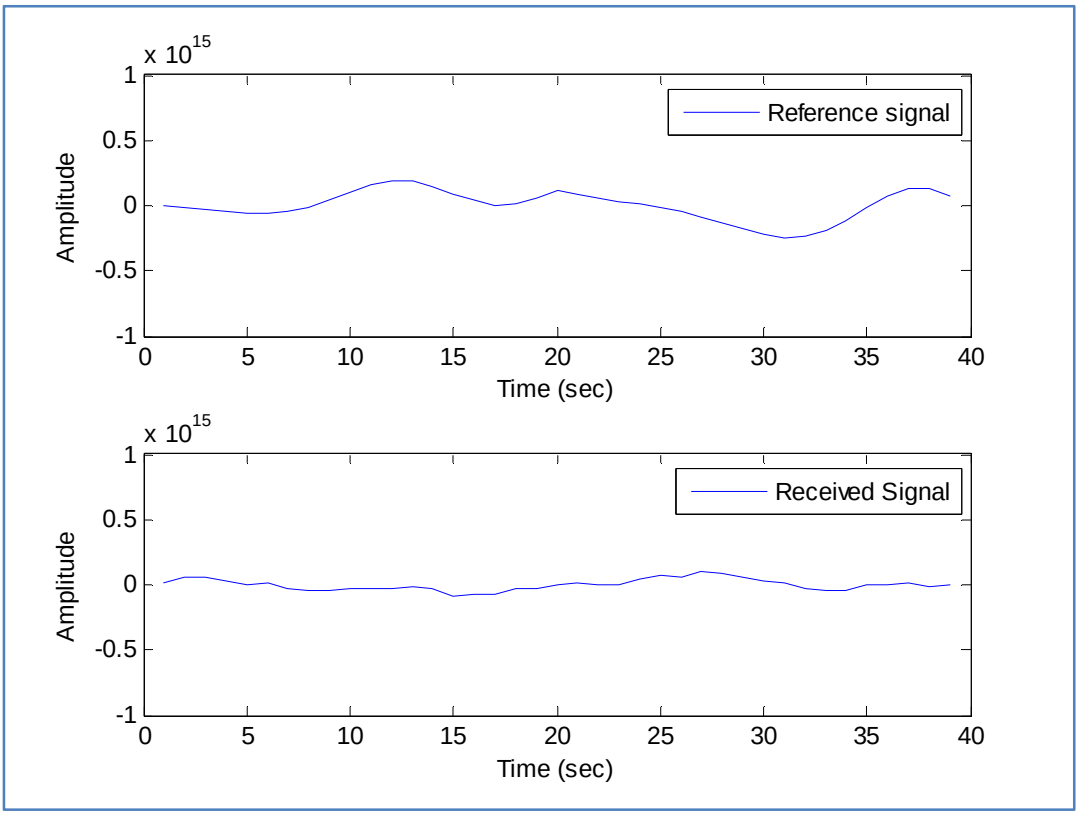

Figure (4.45): Matched Filter Output of case 2at10dB

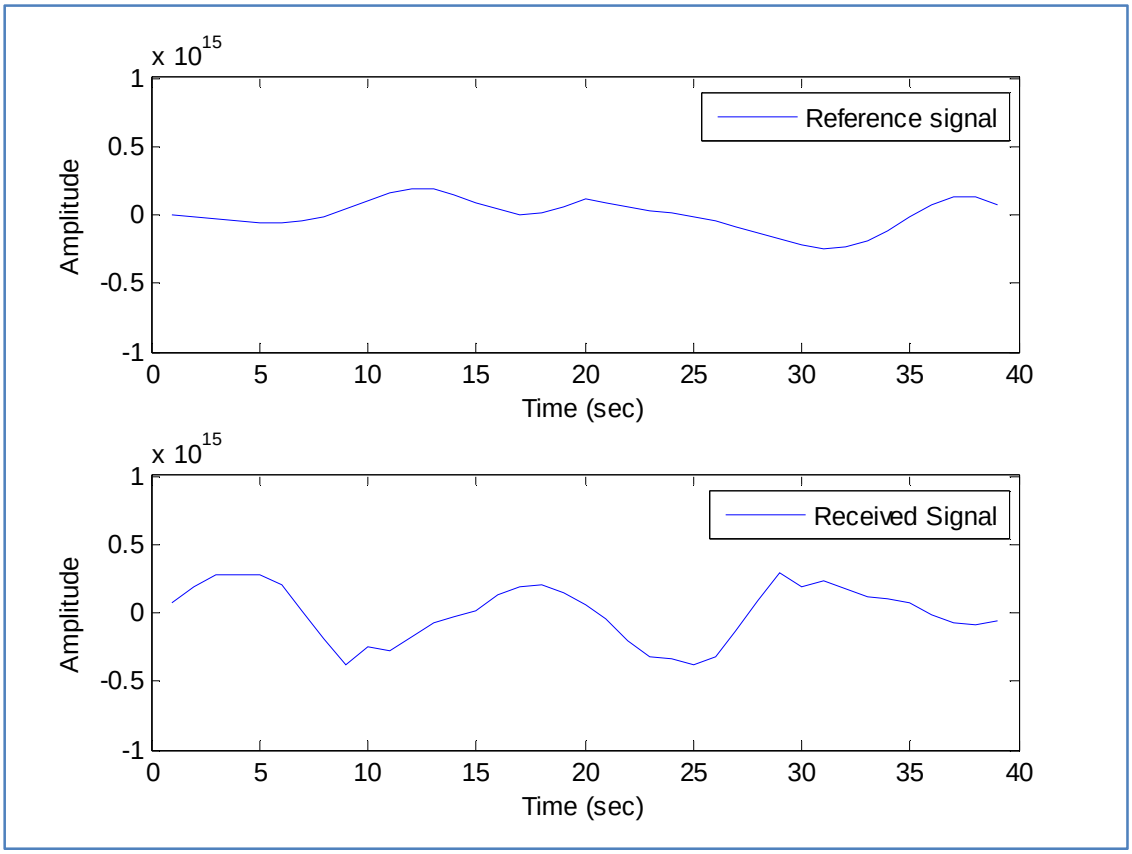

Figure (4.46): Matched Filter output of case 2 at0dB

In this case, all received signals not correlatedbecause no text was provided so as to indicate the absence of the primary user.

D. Case 2 with QPSK modulation

Figure 4.47, 4.48, and 4.49 show the output of the matched filter detector in case 2 using **QPSK** modulation technique for the SNR values 15dB, 10dB and 0dB respectively. In this case, all the received signals are not correlatedbecause no text was provided so as to indicate the absence of the primary user.

The results conclude thatthe matched filter work properly in SNR greater than 10dB. Table (4.2) discusses the Performance of the energy detection and matched filter algorithms under different SNR.

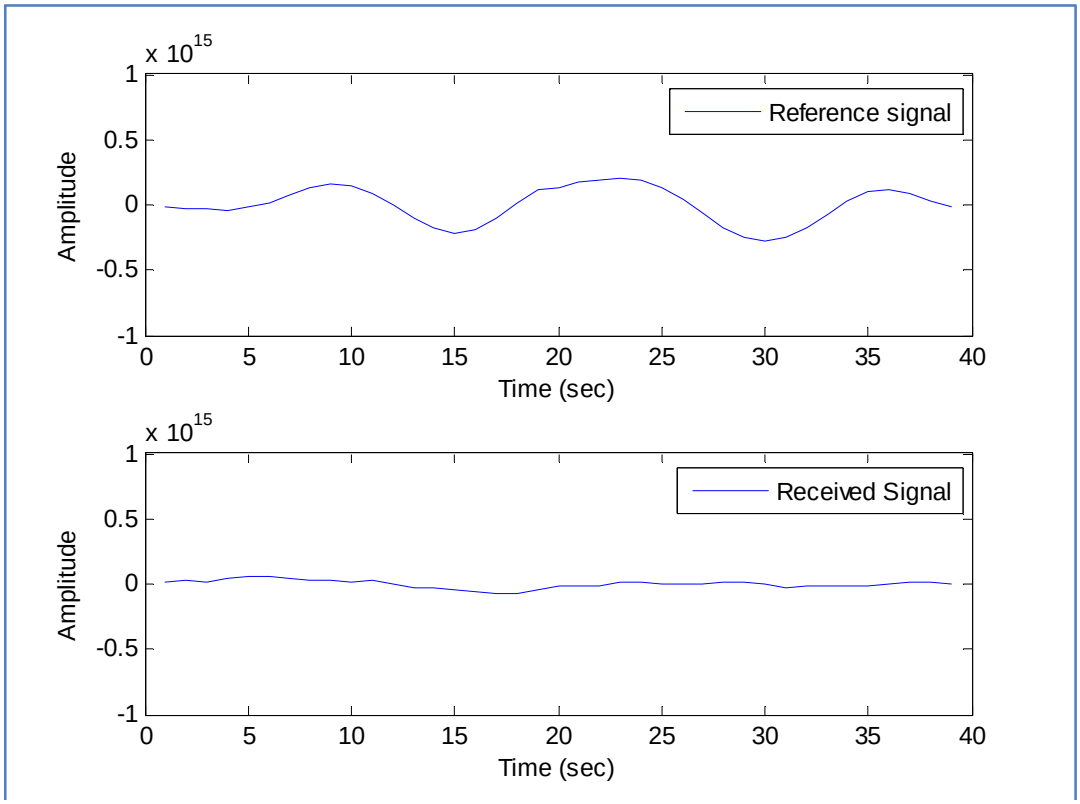

Figure (4.47): Matched Filter output of case 2at 15dB.

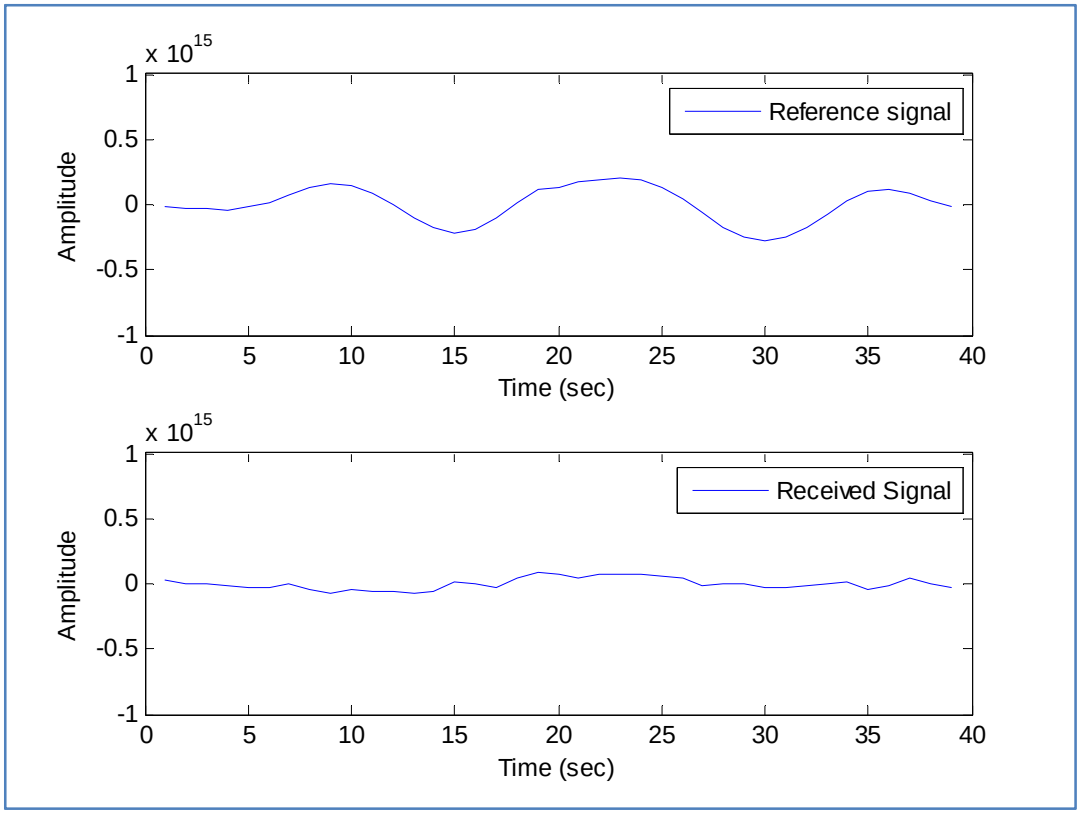

Figure (4.48): Matched Filter output of case 2at 10dB.

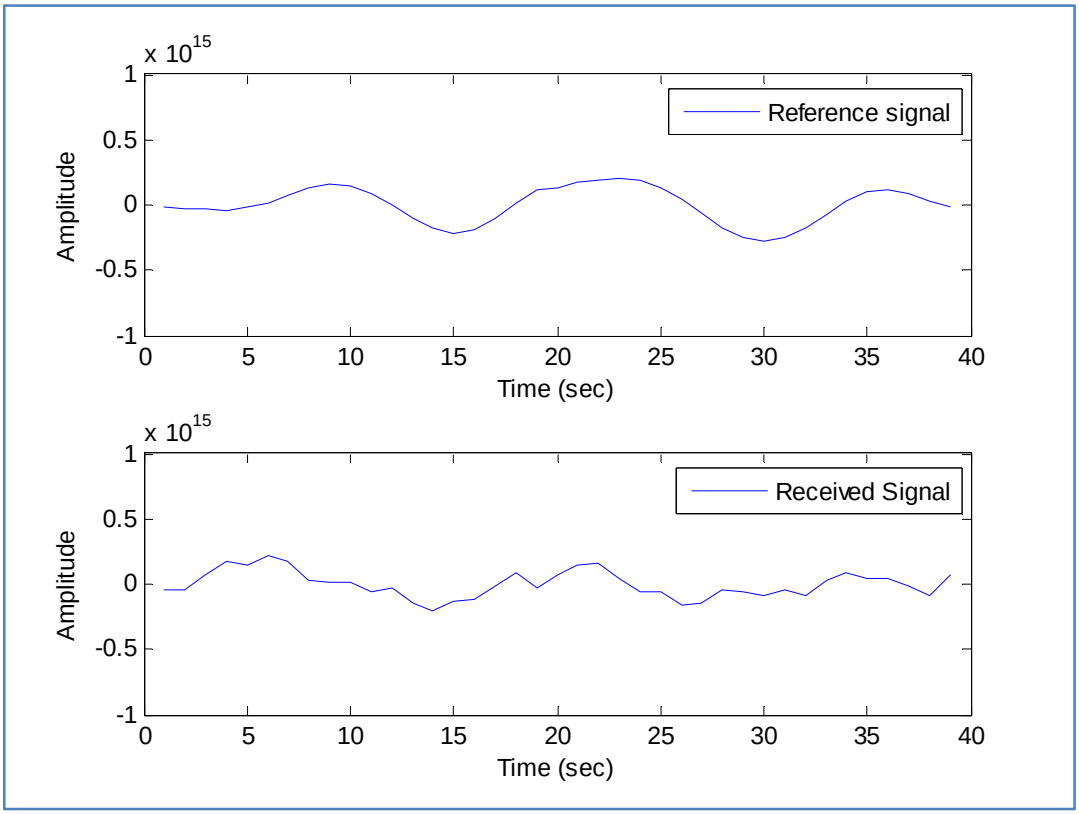

Figure (4.49): Matched Filter output of case 2at 0dB.

Table (4.2) Performance of the Energy Detection and Matched Filter Under Different SNR.

SNR	Primary User State	Energy Detection Performance	Matched Filter Performance
Above 15 dB	Present	Signal is Detected	Signal is Detected
	Absent	Signal is Not Detected	Signal is Not Detected
15 dB	Present	Signal is Detected	Signal is Detected
	Absent	Signal is Not Detected	Signal is Not Detected
10 dB	Present	Signal is Detected	Signal is Detected
	Absent	Signal is Not Detected	Signal is Not Detected
0 dB	Present	Signal is Detected	**Signal is Not Detected**
	Absent	Signal is Not Detected	**Signal is Not Detected**
-10 dB	Present	Signal is Detected	**Signal is Not Detected**
	Absent	Signal is Not Detected	**Signal is Not Detected**

SNR	Primary user state	Energy Detection Performance	Matched Filter Performance
-30 dB	Present	Signal is Detected	**Signal is Not Detected**
	Absent	Signal is Not Detected	**Signal is Not Detected**
-60 dB	Present	Signal is Detected	**Signal is Not Detected**
	Absent	**Signal is Detected**	**Signal is Not Detected**