Information Engineering and Technology Faculty

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Automatic Modulation Classification of Binary Digital Communication Signals

Bachelor Thesis

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Reviewer:

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This is to certify that:

(i) the thesis comprises only my original work towards the Bachelor Degree

(ii) due acknowledgement has been made in the text to all other material used

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15 May, 2010

Abstract

This thesis presents an automatic modulation classification algorithm that is based on a decision theoretic approach in which a set of decision criteria for classifying different types of digitally modulated signals is developed. The introduced algorithm aims is to classify three binary digitally modulated signals which are binary amplitude shift keying (BASK), binary frequency shift keying (BFSK) and binary phase shift keying (BPSK) in addition to the continuous wave (CW). Some channel impairments where taken into consideration such as additive white Gaussian noise (AWGN) and Flat fading. Four key features are used in the algorithm to classify the signals of interest, all of the four key features are derived from two instantaneous parameters which are instantaneous amplitude and instantaneous phase. A method for threshold determination is described in the presence of channel impairments. The performance of the algorithm is evaluated using computer simulations. The performance is measured in terms of the confusion matrix and the percentage of correct classification.

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List of Abbreviations

ASK	Amplitude Shift Keying
OOK	On-Off Keying
FSK	Frequency Shift Keying
PSK	Phase Shift Keying
BASK	Binary Amplitude Shift Keying
BFSK	Binary Frequency Shift Keying
BPSK	Binary Phase Shift Keying
ANN	Artificial Neural Network
OFDM	Orthogonal Frequency Division Multiplex
MASK	M-ary Amplitude Shift Keying
MFSK	M-ary Frequency Shift Keying
MPSK	M-ary Phase Shift Keying
SSB	Single Side Band
DSB	Double Side Band
AWGN	Additive White Gaussian Noise
SNR	Signal to Noise Ratio

List of Symbols

s(t)	Transmitted Signal
A	Signal Amplitude
m(t)	Message
θ	Signal Phase
f_c	Carrier Frequency
x(t)	Complex Envelope
a_{inst}	Instantaneous Amplitude
ϕ_{inst}	Instantaneous Phase
H	Histogram
a_{cn}	Centered Normalized Instantaneous Amplitude
a_c	Centered Instantaneous Amplitude
ζ	Number of negative elements of the centered normalized instantaneous amplitude values
$t\zeta$	Number of negative elements of the centered normalized instantaneous amplitude values threshold
P	Power of centered instantaneous amplitude
tP	Power of centered instantaneous amplitude threshold
σ^2	Variance of instantaneous phase

LIST OF SYMBOLS

tσ^2	Variance of instantaneous phase threshold
σ_{ap}	Standard deviation of the absolute value of the centered instantaneous phase
tσ_{ap}	Standard deviation of the absolute value of the centered instantaneous phase threshold
N_s	Total number of samples
Φ_{NL}	Centered Non-linear Component of Instantaneous Phase
C	Number of Samples in Φ_{NL}
f_s	Sampling Frequency
Φ_{uw}	Unwrapped Phase Sequence
r(t)	Received Signal
w(t)	Noise
F	Interference due to Flat fading

Chapter 1

INTRODUCTION

1.1 Motivation

Communication signals traveling in space are modulated with different types of modulation. The modulation types of the transmitted data are identified using modulation recognition by observing the received data. In the past, modulation recognition was performed manually and it's accuracy depended on the operator skills. Recently modulation recognition are performed automatically with more complicated machines and less human interference in the recognition process. Automatic modulation recognition is better than the manual modulation recognition which depends on the accuracy of the operator skills because if the received signal is applied to the wrong demodulator this may partially or completely damage the signal information. Automatic modulation recognition is in continuous development in the area of signal analysis. Recently the development of automatic modulation recognition became the interest of many research institutes as they became focused on developing automatic modulation recognition algorithms. Automatic modulation recognition is an intermediate step between signal detection and demodulation. It plays an important role in various civilian and military applications such as signal confirmation, interference identification, monitoring, spectrum management and surveillance. Automatic modulation recognizer can be used with an intelligent receiver, resulting in an increase in the transmission efficiency by reducing the overhead of the transmitted signal. Such applications have emerged the need for flexible intelligent communication systems, where the automatic modulation recognition of the modulation of detected signal is a major task.

1.2 Aim of the Project

The main aim of this thesis is to propose an automatic modulation classification algorithm for binary digital communication signals based on decision theoretic approach. The algorithm main aim is to classify between three digitally modulated signals which are BASK, BFSK, BPSK in addition to the CW signal. This thesis is organized as follows, it is divided into five chapters. Chapter one is an introduction which provides an idea about the problem and the aim of the thesis. In Chapter two a theoretic background on modulation and some basic terminologies used in addition to previous work are discussed. Chapter three presents the proposed algorithm for classifying BASK, BFSK, BPSK and CW signals. Computer simulations and performance evaluation are showed in Chapter four. Finally, Chapter five is a summary of the classification algorithm and its performance evaluation in addition to some suggestions for future work.

Chapter 2

BACKGROUND

This chapter consists of two main sections. The first section is a theoretic background on modulation and some modulation terminologies. While the second section is a review of some relevant work that has been done and related to this thesis.

2.1 Theoretic Background and Modulation Terminologies

Modulation is the process of varying one of three properties either amplitude, frequency or phase of high frequency periodic wave called the carrier signal, with respect to a modulating signal. There are two types of modulations digital and analog modulation. If the amplitude of the modulating signal varies continuously with time, it is an analog signal and the modulation is referred to as analog modulation. On the other hand if the amplitude of the modulating signal varies only between a finite number of values and the change may occur only at distinct moments in time, the modulating signal is a digital signal and the modulation is referred to as digital modulation.

There are two modulation techniques used depending on the type of the carrier wave. If the carrier wave is a sine wave the modulation technique is called sinusoidal carrier modulation, but if the carrier wave consists of a series of pulses of constant amplitude and time duration that occur at regular time intervals the modulation technique is called pulse carrier modulation. After receiving the transmitted signal at the receiver side the inverse process of modulation

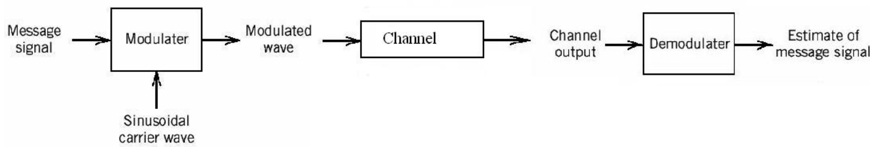

Figure 2.1: Block diagram of a modulation and demodulation process

is carried out on the received signal to extract the original message sent, this process is called demodulation. The device that performs modulation is called a modulator. While the device that performs the inverse operation of modulation is known as demodulator. Figure 2.1 shows a block diagram of a simple modulation and demodulation process. This thesis is mainly concerned with digital modulation using sinusoidal carrier modulation technique.

There are three methods for approaching the modulation recognition problems, these methods are the decision theoretic approach, the statistical pattern recognition approach and an artificial neural network approach (ANN). The work in this thesis follows the decision theoretic approach. In the decision theoretic approach, probabilistic and hypothesis testing arguments are employed to formulate the modulation recognition problem [1]. In a statistical pattern recognition approach, the classification system is divided into two subsystems. The first is preprocessing and feature extraction subsystem, whose function is to extract the predefined features from the received data of interest. The second subsystem is a pattern recognition subsystem, whose function is to indicate the modulation type of the signal. The final approach is the ANN which comprises three main stages, pre-processing and key features extraction, a training stage to adjust the classifier structure and finally, a test stage in which the performance evaluation of the chosen network is determined.

The digital modulation types that are used in this thesis are:

Binary amplitude shift keying (BASK): The binary signal in the BASK technique changes the amplitude of the carrier signal into two levels according to the message bit, while the frequency and phase of the carrier signal remains the same. If these levels are 0 and 1, this is a special case of the BASK and known as on-off keying (OOK). Figure 2.2 and Figure 2.3 shows a BASK modulated signal in both time and frequency domain.

Binary frequency shift keying (BFSK): The binary signal is used to switch the carrier frequency between two values. One value is used if the message bit is 1 and the other value is used if the message bit is 0. Figure 2.4 and Figure

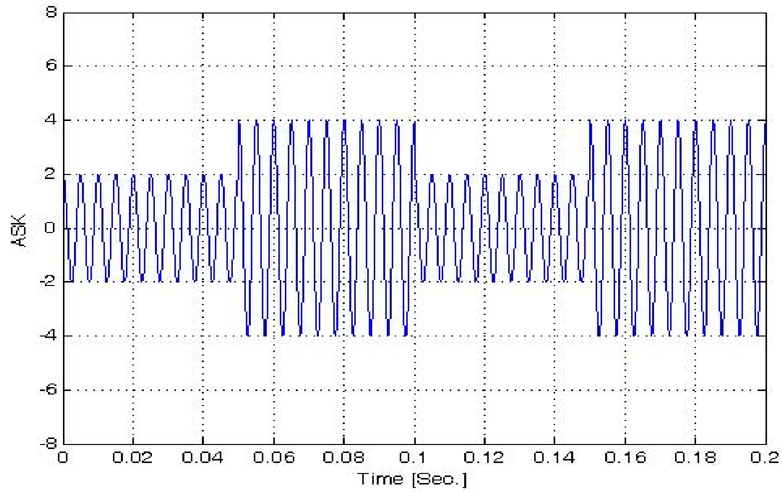

Figure 2.2: BASK modulated signal in time domain representation

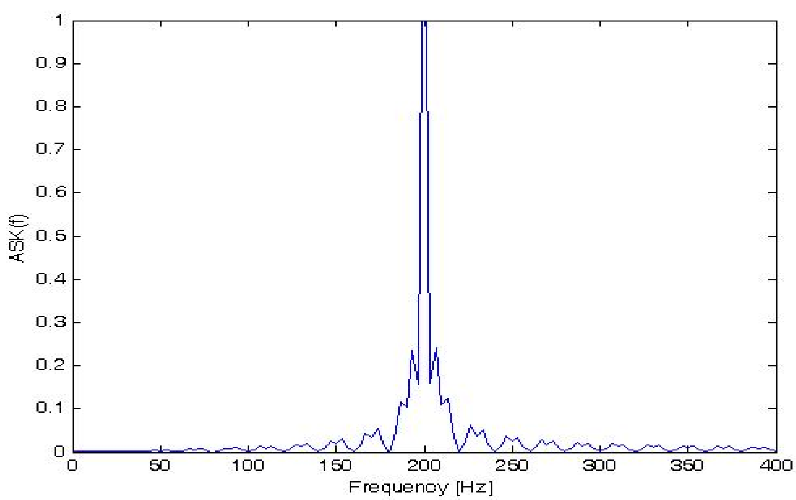

Figure 2.3: BASK modulated signal in frequency domain representation

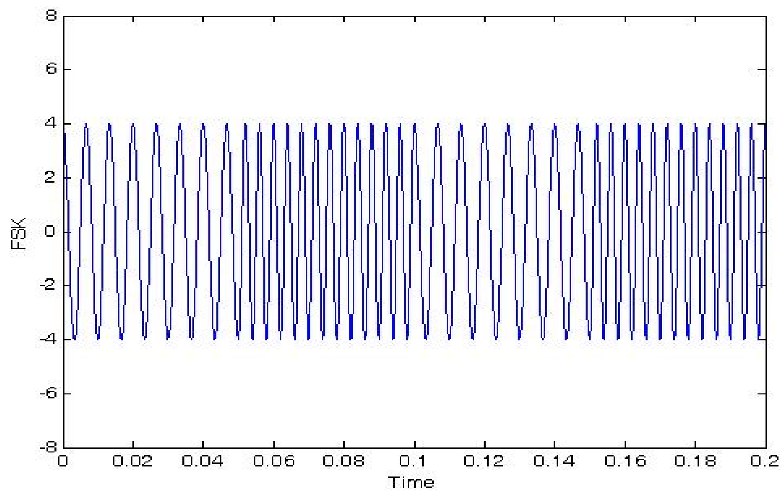

Figure 2.4: BFSK modulated signal in time domain representation

2.5 shows a BFSK modulated signal in both time and frequency domain.

Binary phase shift keying (BPSK): The binary message changes the carrier phase between two values according to the message signal. the phase difference between these two angles are 180°. Figure 2.6 and Figure 2.7 shows a BPSK signal in time and frequency domain.

2.2 Relevant Work

Liedtke [3] is one of the first authors to publish about the modulation recognition process. Liedtke introduced a modulation recognizer, using the pattern recognition approach, for some types of digital modulations ASK2, FSK2, PSK2, PSK4, PSK8 and CW. The key features used to discriminate between these types are the amplitude histogram, the amplitude variance, and the frequency variance. In [3], all the signal parameters are exactly known, can be recognized at SNR$\geq$18 dB.

In [4] Jondral proposed a modulation recognizer utilizing the pattern recognition approach for recognition of both analog and digital modulation types. The types that can be classified by this recognizer are AM, SSB, ASK2, PSK2, FSK2 and FSK4. The key features used to discriminate between the modulation types are the instantaneous amplitude, phase and frequency histograms. In [4],

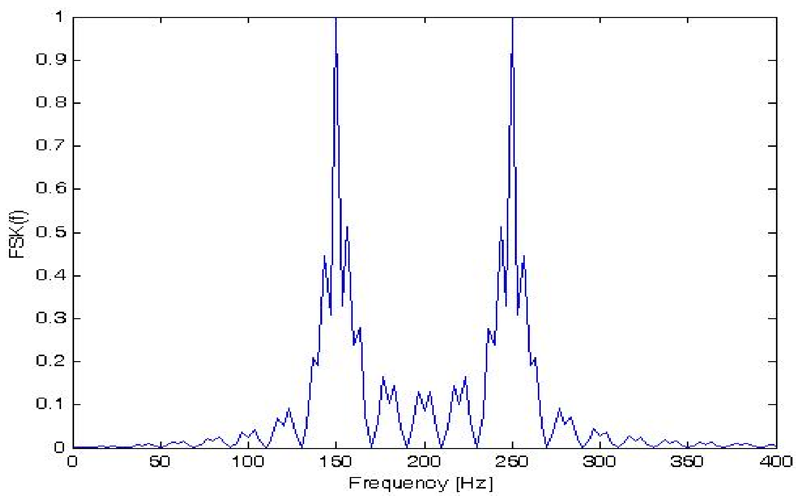

Figure 2.5: BFSK modulated signal in frequency domain representation

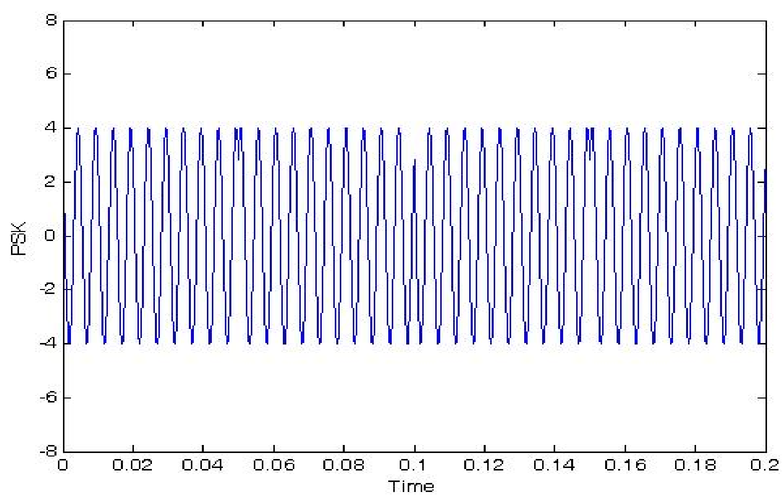

Figure 2.6: BPSK modulated signal in time domain representation

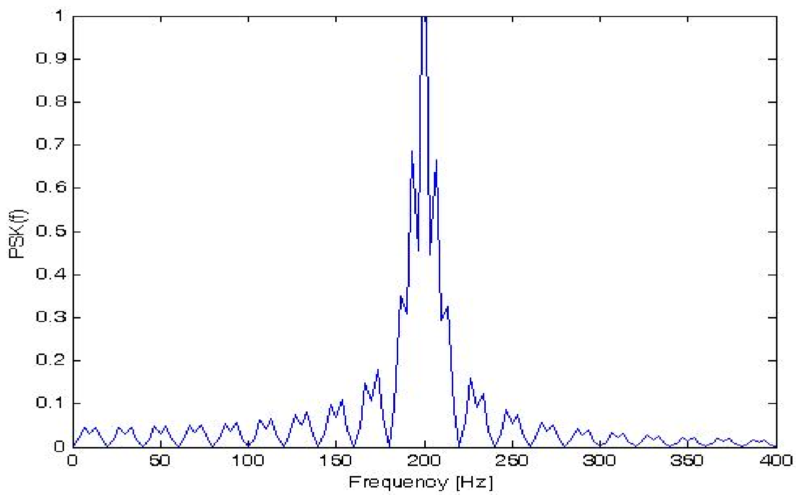

Figure 2.7: BPSK modulated signal in frequency domain representation

it is claimed that all the mentioned modulation types have been classified with success rate$\geq$90% except for the SSB 83% and the FSK4 88%.

In [5] DeSimio and Glenn introduced an adaptive technique for classifying some types of digital modulations ASK2, PSK2, FSK2 and PSK4 using pattern recognition approach. The key features are the mean and variance of the envelope, the magnitude and location of the two largest peaks in the signal spectrum, the magnitude of the spectral component at twice the carrier frequency of the signal square, and the magnitude of the spectral component at four times the carrier frequency of the signal raised to the fourth power. This classifier is trained using the values of the extracted key features at SNR of 20 dB. The only thing that is mentioned about the performance evaluation of this recognizer is its ability to discriminate between PSK2 and PSK4 at a SNR of 5 dB.

Dominges et al. [6] followed the pattern recognition approach. The classifier is a general approach for both analog and digital modulations. The key features are the histograms of the instantaneous amplitude, phase and frequency. The types that can be classified by this classifier are AM, SSB, DSB, FM, ASK2, PSK2, FSK2, ASK4, PSK4 and CW. they claimed that this recognizer performed well at SNR$\geq$40 dB. But at SNR=10 dB, the percentage of correct modulation recognition is 0% for all digital modulation types except for PSK4 7%. At SNR=15 dB FSK4 is 56%, FSK2 is 84% and ASK4 is 87%.

Nagy [7] introduced a modulation recognizer for multi-channel systems.This recognizer was accomplished by dividing the analyzed signal into individual components and each signal component is classified using a single tone classifier. The types that have been classified by this recognizer are CW, ASK2, PSK2, PSK4 and FSK2. Finally, it is claimed that three signals CW, PSK2 and PSK4 have been classified with a success rate greater than 90% at SNR of 10 dB and the ASK2 with success rate of 87%.

Assaleh et al. [8] proposed a modulation recognizer for CW, PSK2, PSK4, FSK2 and FSK4. The key features are the mean and the standard deviation of the instantaneous bandwidth, the height of the spikes in the differential instantaneous frequency. It was found that the success rate for the different modulation types of interest is greater than 99% at SNR of 15 dB.

Azzouz and Nandi [9] introduced a modulation recognizer, following the decision theoretic approach to discriminate between ASK2, ASK4, PSK2, PSK4, FSK2 and FSK4 signals. The used key features are the maximum value of the spectral power density, the standard deviation of the direct value centered non-linear component of the instantaneous phase, the standard deviation of the absolute value of the centered non-linear component of the instantaneous phase, the standard deviation of the absolute value of the normalized centered instantaneous amplitude of a signal segment and the standard deviation of the absolute value of the normalized centered instantaneous frequency. It was found that the success rate for the different modulation types of interest was greater than 90% at SNR of 10 dB. However at SNR=20 dB the success rate is $\geq$95%.

Azzouz and Nandi [10] introduced two algorithms to discriminate between analogue and digital signals. The difference between the two algorithms is that in the first one the decision theoretic approach is used while in the second one the artificial neural network approach (ANN) is used. For the first algorithm, it was found that all modulation types of interest had been correctly classified at SNR of 15 dB with success rates greater than 88 %. For the second algorithm, it was found that all modulation types of interest had been correctly classified at SNR of 15 dB with success rate $>$88%. Finally, in the decision theoretic algorithm the overall success rate is $>$94% at SNR of 15 dB, while the overall success rate is $>$96% at SNR of 15 dB for the ANN algorithm.

Dobre, O.A. Abdi, A. Bar-Ness and W. Su [11] provided a survey of different modulation recognition techniques, and compared between them in a systematic way. The two general classes of automatic modulation identification algorithms was discussed in detail, which rely on the likelihood function and features of the received signal, respectively. The contributions of numerous articles was summarized in compact forms. The reported results in the paper have been obtained under different conditions. So, some major techniques was simulated under the same conditions, which allows a fair comparison among different methodologies.

K. N. Haq , A. Mansour and S. Nordholm [12] presented some problems related to automatic recognition of digital modulation. First of all, Azzouz and Nandi's algorithm [2] has been discussed. The algorithm was modified were some new statistical parameters have been applied. Then a new method has been proposed and presented to recognize Orthogonal frequency Division Multiplex (OFDM) signal, in presence of some other digital modulated signal and Additive White Gaussian Noise (AWGN). A new key feature for extracting OFDM has been developed. Simulation result showed that the key feature is capable to classify OFDM from QAM and BPSK even in the lower signal to noise ratio.

Chapter 3

AUTOMATIC MODULATION CLASSIFICATION ALGORITHM

In this chapter a decision theoretic based algorithm for automatic modulation classification of digital communication signals is introduced. All the key features used to distinguish between signals results from two main parameters instantaneous amplitude and instantaneous phase. The algorithm main aim is to classify four binary digital signals which are CW, BASK, BFSK and BPSK. Two cases of the received signal is introduced one case is without channel impairments and the other case is after adding channel impairments. These channel impairments are AWGN and Flat fading.

3.1 Main Parameters Used in Algorithm

In this section the calculation of the instantaneous amplitude and instantaneous phase is shown in it's ideal case without adding any channel impairments. The calculation of the two parameters is achieved using the complex envelope technique as follows:

Let the modulated signal s(t) be:

$$s(t) = A\,m(t)\,cos(2\pi f_c t + \theta(t)) \tag{3.1}$$

Where A is a constant, m(t) is the message either 0 or 1, f_c is the carrier frequency, t is the bit duration and $\theta(t)$ is the phase. Then extracting the complex envelope x(t) as follows:

$$x(t) = Re\left\{Am(t)e^{j2\pi f_c t}\right\} \tag{3.2}$$

Where Re{x} means the real part of x. So the complex envelope x(t) is as shown:

$$x(t) = Am(t) \tag{3.3}$$

The instantaneous amplitude a_{inst} is the absolute value of the complex envelope as shown:

$$a_{inst} = |Am(t)| \tag{3.4}$$

Figures 3.1, 3.2, 3.3 and 3.4 shows the instantaneous amplitude of the four signals of interest in the algorithm.

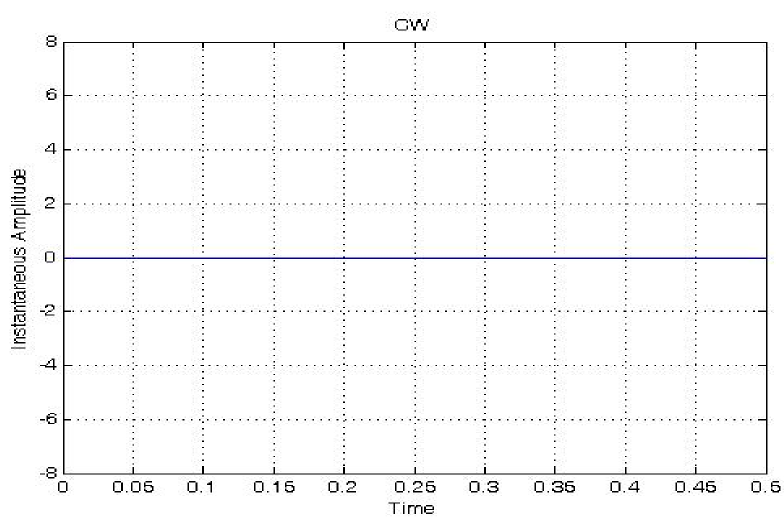

Figure 3.1: CW instantaneous amplitude

As for the instantaneous phase ϕ_{inst}, it is the angle of the complex envelope

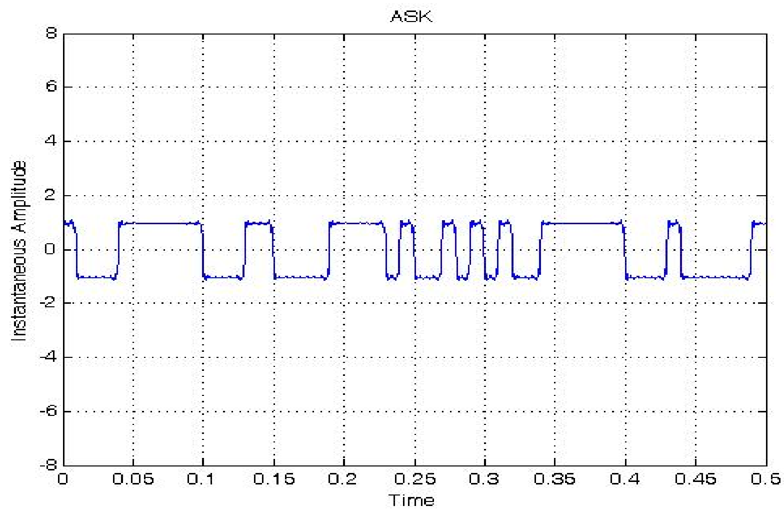

Figure 3.2: BASK instantaneous amplitude

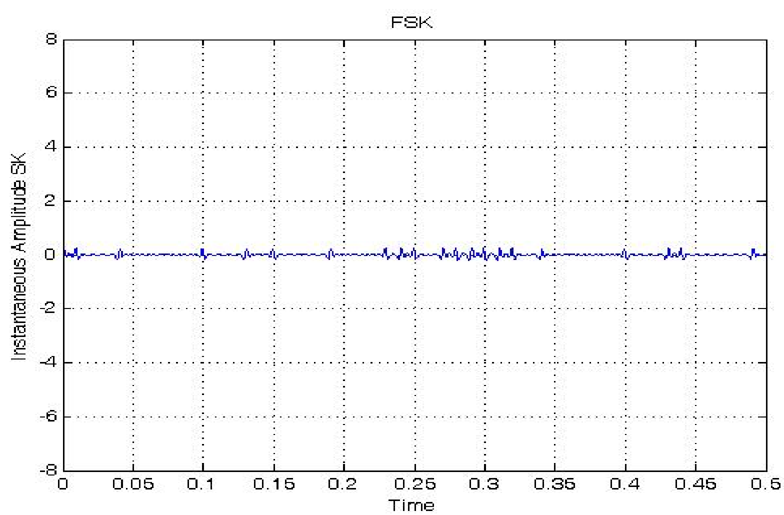

Figure 3.3: BFSK instantaneous amplitude

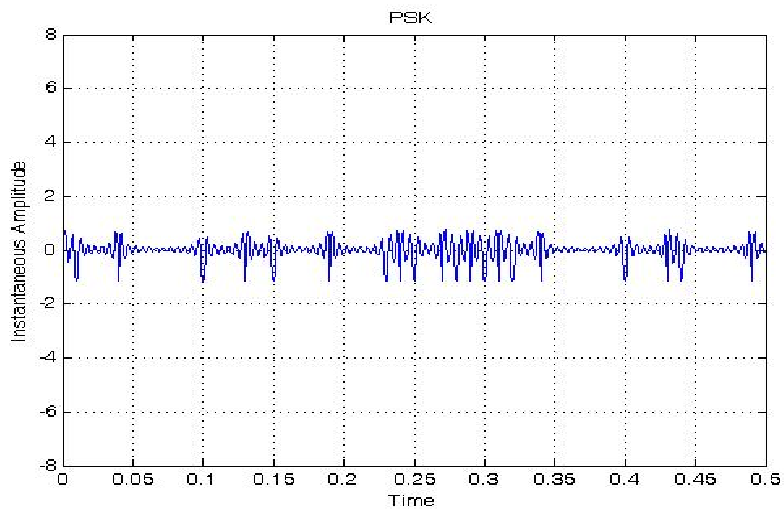

Figure 3.4: BPSK instantaneous amplitude

as shown:

$$\phi_{inst} = \angle Am(t) \tag{3.5}$$

Figures 3.5, 3.6, 3.7 and 3.8 shows the instantaneous phase of the four signals of interest in the algorithm.

Figures from 3.1 to 3.8 shows differences between the signals in both parameters the instantaneous amplitude and instantaneous phase which the algorithm will make use of, this is illustrated later in the following section.

3.2 Key Features Extraction

In this section the calculation of the key features are derived. To differentiate between the four signals of interest, the following key features are used:

- Number of negative elements of the centered normalized instantaneous amplitude(ζ):

This feature is better explained using the histogram of the centered normalized instantaneous amplitude. By definition the histogram is a statistical graph that represents the frequency of values of a quantity by vertical rectangles of varying heights and widths. It can be expressed as:

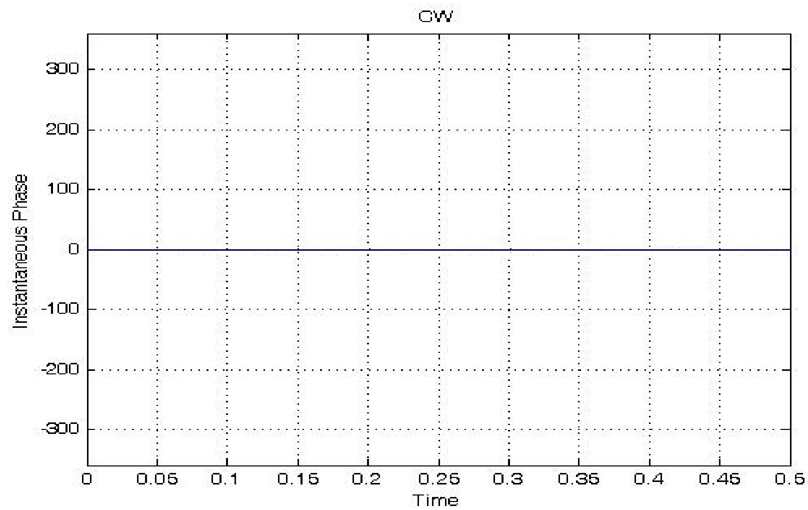

Figure 3.5: CW instantaneous phase

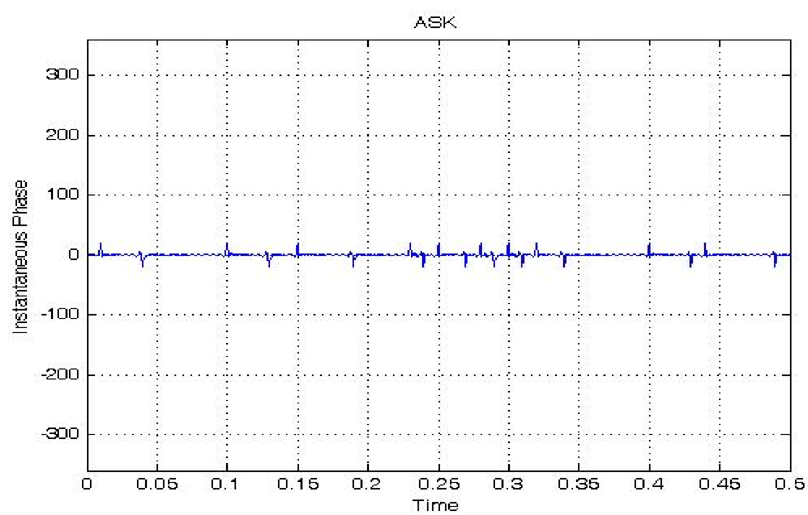

Figure 3.6: BASK instantaneous phase

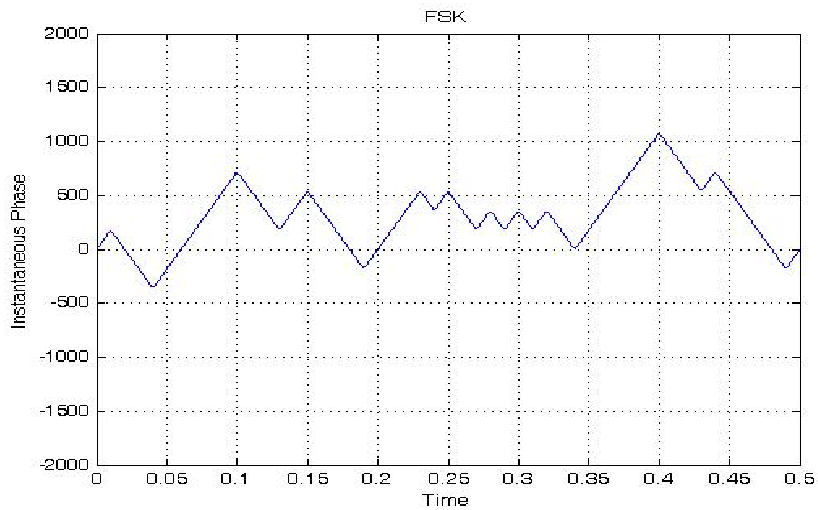

Figure 3.7: BFSK instantaneous phase

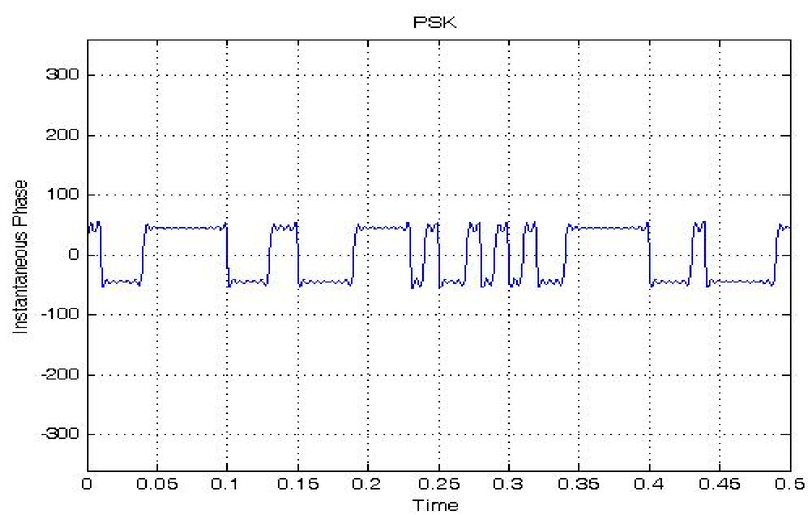

Figure 3.8: BPSK instantaneous phase

$$H(a_{cn}) = \sum_{i=1}^{\infty} a_{cn}(i) \tag{3.6}$$

Where a_{cn} is the centered normalized instantaneous amplitude. In this case the histogram represents the number of elements of the centered normalized instantaneous amplitude having the same value. The first key feature is the number of elements of the centered normalized instantaneous amplitude having values less than -0.3. The value -0.3 is obtained by observing the histogram of the instantaneous amplitude of the four signals of interest as shown in Figures 3.9, 3.10, 3.11 and 3.12. It is clear from the figures that the number of elements having values less than -0.3 differ in each signal. Specifically the value of -0.3 is chosen as it gives a comfortable gap between the number of elements of the four signals of interest.

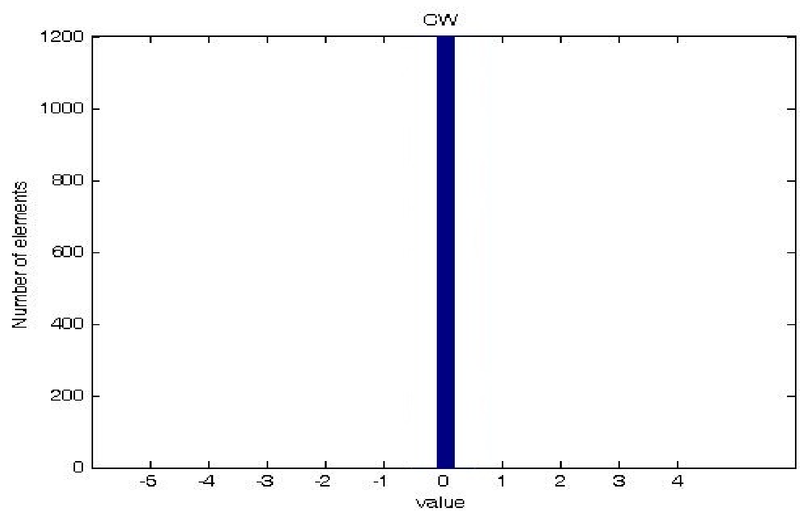

Figure 3.9: The centered normalized instantaneous amplitude histogram for CW signal

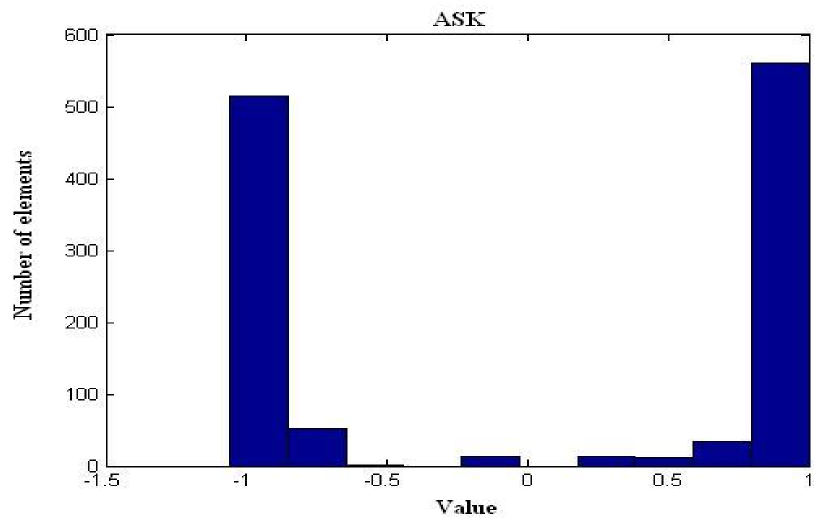

Figure 3.10: The centered normalized instantaneous amplitude histogram for BASK signal

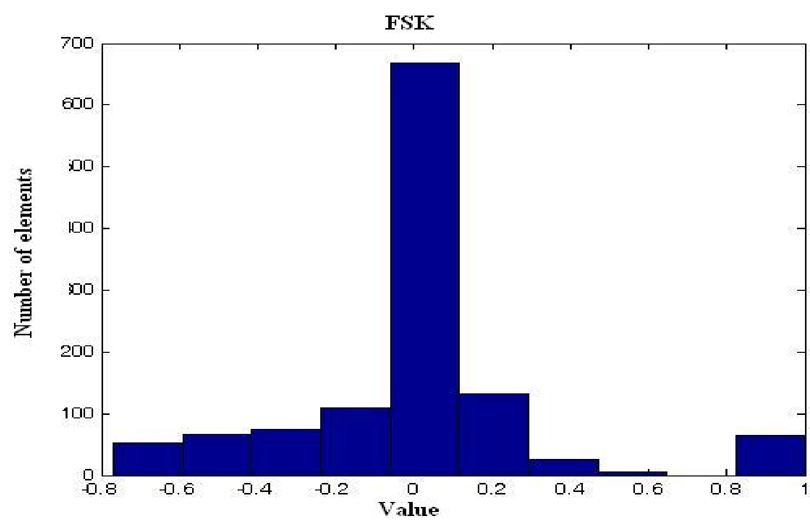

Figure 3.11: The centered normalized instantaneous amplitude histogram for BFSK signal

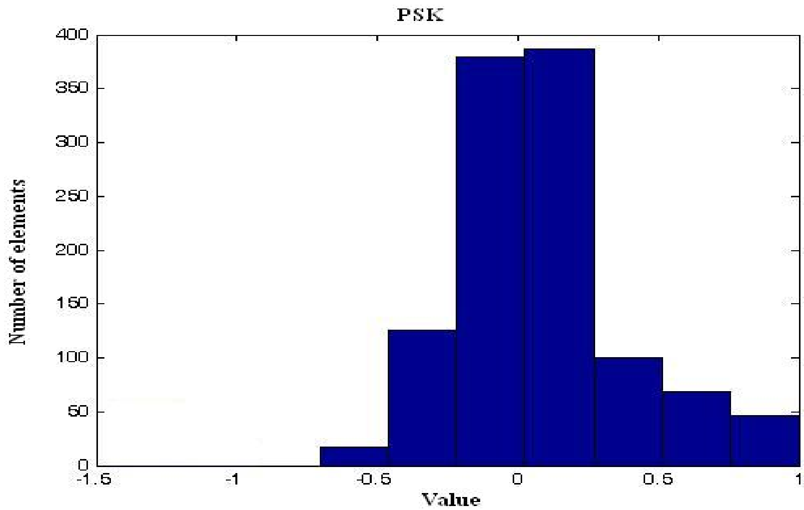

Figure 3.12: The centered normalized instantaneous amplitude histogram for BPSK signal

- Power of centered instantaneous amplitude(P):

The power of the centered instantaneous amplitude is calculated as follows:

$$P = \frac{1}{N_s} \sum_{i=1}^{\infty} a_c(i)^2 \tag{3.7}$$

Where a_c is the centered instantaneous amplitude, N_s is the total number of samples.

- Variance of the instantaneous phase(σ^2):

The variance is a measure of the amount of variation within the values of that variable. In this case the variable is the centered instantaneous phase.

- Standard deviation of the absolute value of the centered non-linear component of the instantaneous phase(σ_{ap}):

This feature is defined by [1], [2]

$$\sigma_{ap} = \sqrt{\frac{1}{C}(\sum_{a_n(i)} \Phi_{NL}^2(i)) - \frac{1}{C}(\sum_{a_n(i)} |\Phi_{NL}^2(i)|)^2} \tag{3.8}$$

Where $\Phi_{NL}(i)$ is the value of the centered non-linear component of the instantaneous phase, C is the number of samples in $\{\Phi_{NL}\}$. $\Phi_{NL}(i)$ are the values of phase characteristic without the contribution of the carrier frequency and it is defined by:

$$\Phi_{NL}(i) = \Phi_{uw}(i) - \frac{2\pi f_c}{f_s} \tag{3.9}$$

Where $\Phi_{uw}(i)$ is the unwrapped phase sequence, f_c is the carrier frequency and f_s is the sampling frequency.

3.3 Decision making and threshold determination

This section consists of two parts. First the reasons of choosing the key features are explained. Then how the decision is made about the recognition of any of the four signals of interest is explained in the same order as that of the algorithm. The second part shows how the threshold is determined. All the values of the graphs shown in this section are the average value of the feature in question for 100 different realization for each signal type.

3.3.1 Decision Making

The first signal classified in the algorithm is the CW signal. The recognition of the CW signal depends on two key features. These two key features are the number of negative elements of the centered normalized instantaneous amplitude and the variance of the instantaneous phase.

The number of negative elements of the centered normalized instantaneous amplitude is used mainly to distinguish between BASK and CW signals. A centered normalized instantaneous amplitude histogram of CW and BASK signals e are shown in Figure 3.13 and 3.14 respectively. It is clear that the number of elements that has the value less than -0.3 is much more in BASK signal than that of the CW signal. This is the point in which the decision about distinguishing between BASK and CW depends on.

The aim of using the variance of the instantaneous phase in this part of the algorithm is to differentiate between CW and both BPSK and BFSK. Figure 3.15 represents the variance of instantaneous phase of CW, BPSK and BFSK signals. A semi log scale for the y axis of the graph is used for making all the the values of the three signals fit in one graph since the value of the instantaneous phase variance of the BFSK signal is much more than that of the CW and BPSK signals. By observing Figure 3.15, it is clear that the value of instantaneous

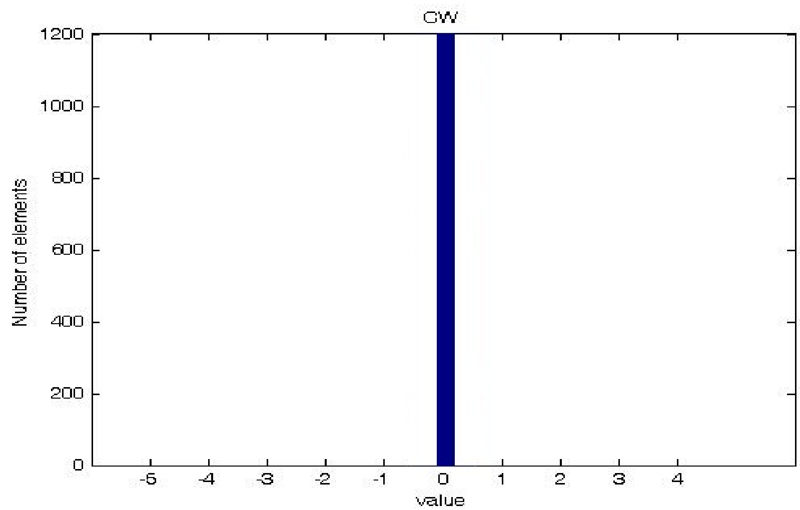

Figure 3.13: Histogram of the centered normalized instantaneous amplitude of CW without channel impairments

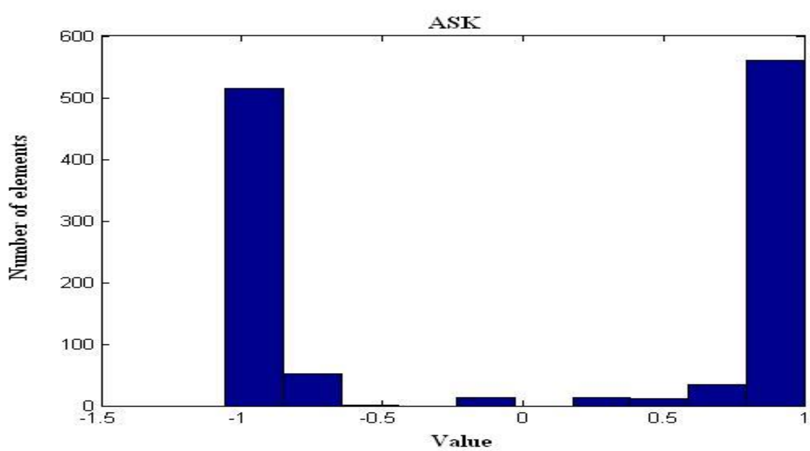

Figure 3.14: Histogram of the centered normalized instantaneous amplitude of BASK without channel impairments

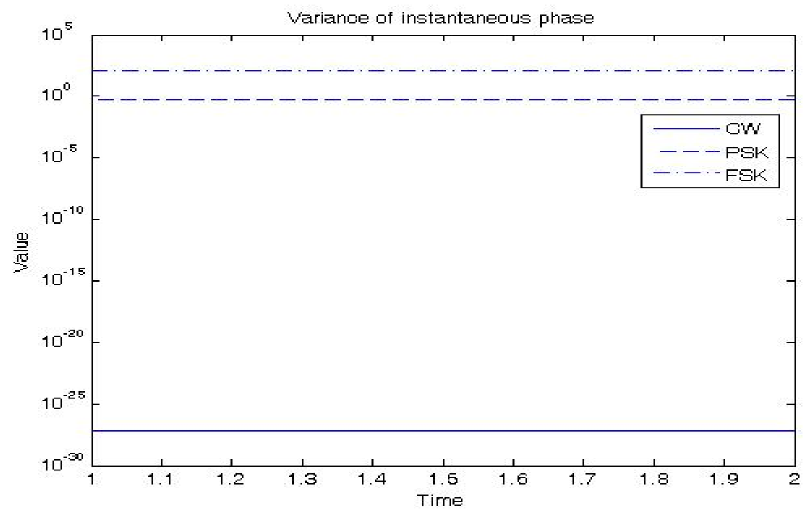

Figure 3.15: Variance of instantaneous phase for CW, BPSK and BFSK without channel impairments

phase variance of the BFSK and BPSK signals are higher than that of the CW .

The number of negative elements of the centered normalized instantaneous amplitude is compared with a predefined threshold, and if it is less than the threshold so the probability of the signal being BASK is eliminated. At the same time the variance of the instantaneous phase is also compared with a different predefined threshold, if it is less than the threshold BPSK and BFSK signals are also eliminated. Both conditions must be satisfied to conclude that the signal is CW.

BASK signal is the second signal to be classified. If this part of the algorithm is reached this means that the signal is definitely not a CW signal. Hence to test for the BASK signal distinguishing only between BASK, BPSK and BFSK is needed. To do so the use of two key features are required which are the power of centered instantaneous amplitude and the number of negative elements of the centered normalized instantaneous amplitude. In this case both features perform the same task which is differentiating between BASK and the rest of the signals (BPSK and BFSK).

The main feature in this part is the power of centered instantaneous amplitude. As shown in Figure 3.16 there is a wide gap between the value of the power

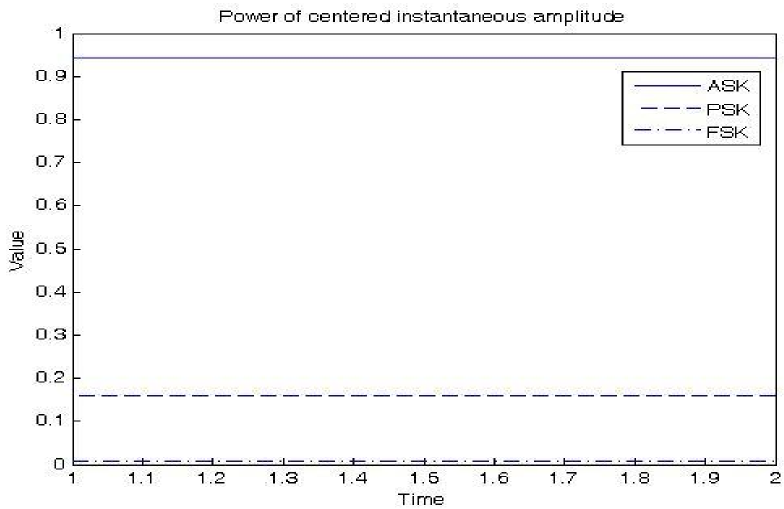

Figure 3.16: Power of centered instantaneous amplitude of BASK, BPSK and BFSK without channel impairments

of centered instantaneous amplitude of the BASK and the values of BPSK and BFSK signals.

A centered normalized instantaneous amplitude histogram of BASK, BPSK and BFSK signals without any channel impairments are shown in Figure 3.17, 3.18 and 3.19. By observing the three figures it is noticed that there is a big difference between the number of elements that has the value less than -0.3 of the BASK signal which is more than that of the BPSK and BFSK signals.

The power of centered instantaneous amplitude and the number of negative elements of the centered normalized instantaneous amplitude are compared with two different predefined thresholds. If they exceed the threshold value then the condition is satisfied. Since both features perform the same task which is differentiating between BASK and the rest of the signals (BPSK and BFSK) not both conditions must be satisfied, only one of the conditions must be satisfied to classify the received signal as an BASK signal.

Finally, the last part of the algorithm is to decide whether the received signal is BPSK or BFSK. At this point of the algorithm the probability of the signal being CW or BASK signal is eliminated. The key features used in this part are standard deviation of the absolute value of the centered non-linear component of the instantaneous phase and variance of the instantaneous phase.

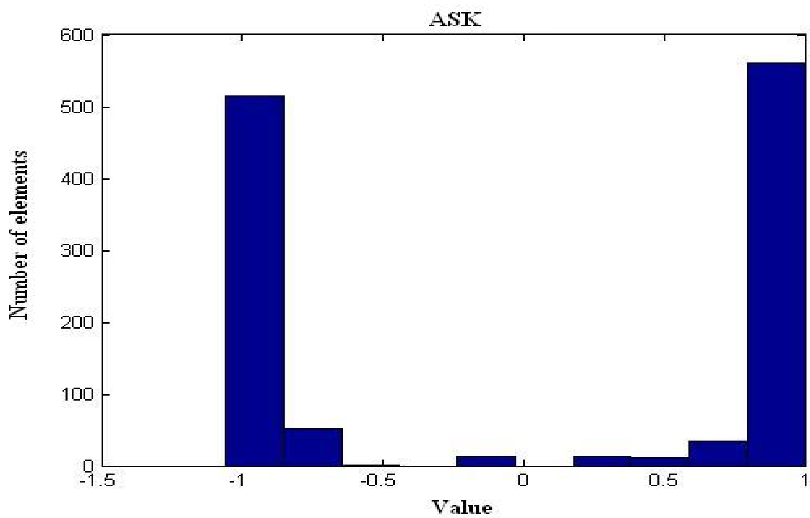

Figure 3.17: Histogram of the centered normalized instantaneous amplitude of BASK without channel impairments

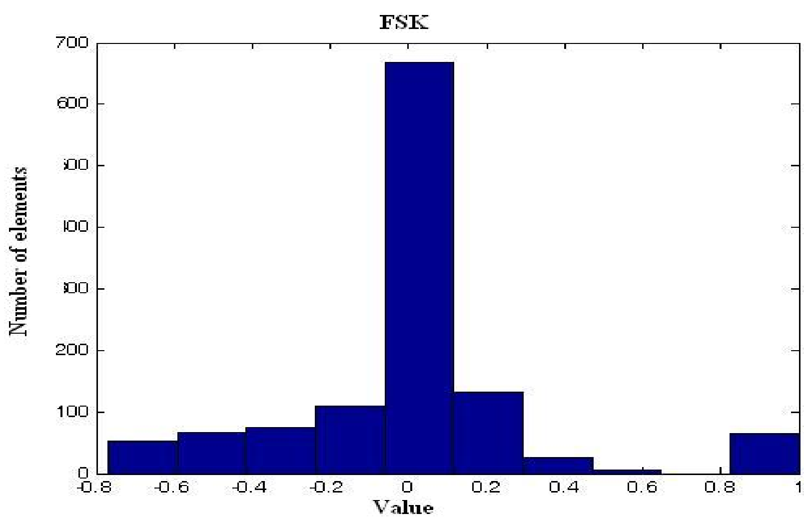

Figure 3.18: Histogram of the centered normalized instantaneous amplitude of BFSK without channel impairments

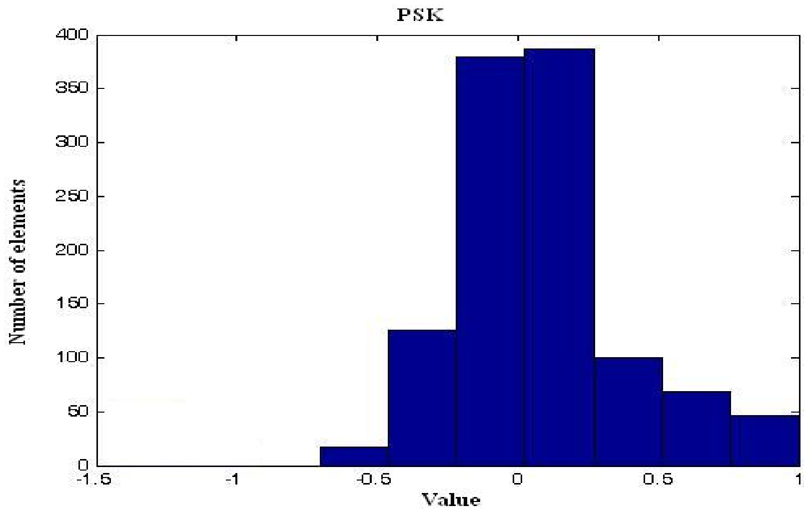

Figure 3.19: Histogram of the centered normalized instantaneous amplitude of BPSK without channel impairments

The variance of the instantaneous phase of BPSK and BFSK is shown in Figure 3.20. It is clear from the figure that the difference between the value of the variance of the instantaneous phase of BPSK and BFSK is not comfortably large, so another key feature must be used to decrease the percentage of misclassification.

Therefore standard deviation of the absolute value of the centered non-linear component of the instantaneous phase is introduced in this part. Figure 3.21 shows the standard deviation of the absolute value of the centered non-linear component of the instantaneous phase of BPSK and BFSK signals. A semi log scale for the y axis is used so that the signals appear clearly on the graph since the difference between the signals is large.

Both the standard deviation of the absolute value of the centered non-linear component of the instantaneous phase and variance of the instantaneous phase are compared with two different predefined thresholds. If they are less than the threshold then the condition is satisfied. If one or both of the conditions is satisfied the received signal is BPSK. For the received signal to be BFSK both conditions must fail.

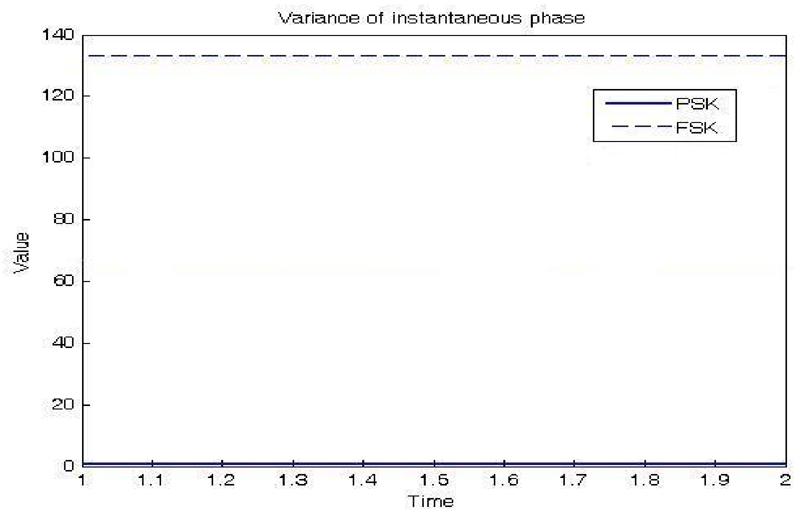

Figure 3.20: Variance of the instantaneous phase of BPSK and BFSK without channel impairments

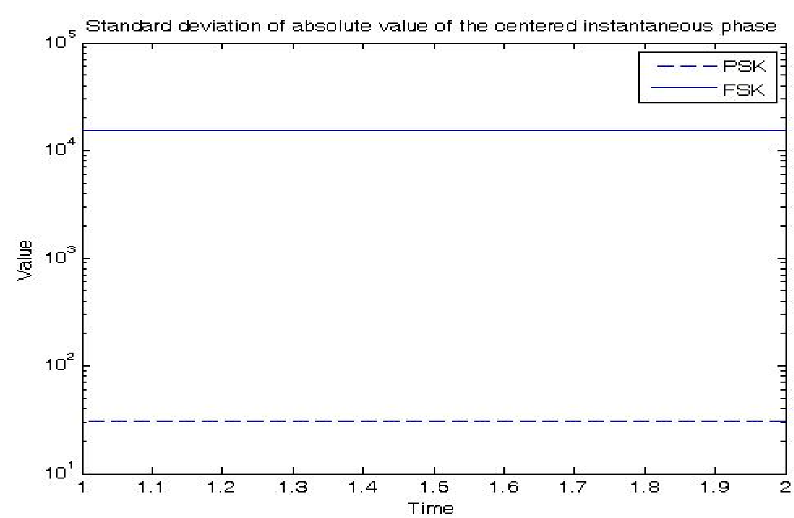

Figure 3.21: standard deviation of the absolute value of the centered instantaneous phase of BPSK and BFSK without channel impairments

3.3.2 Threshold Determination

Threshold determination is derived from 100 realization for each signal of interest. The following steps shows how a suitable threshold is obtained taking the variance of instantaneous phase as a feature to differentiate between BPSK and BFSK signals as an example:

- Step one is to obtain 100 readings of the feature of interest for each signal as shown in Table 3.1 .

Table 3.1: Readings of instantaneous phase variance

BPSK	BFSK	BPSK	BFSK	BPSK	BFSK	BPSK	BFSK
0.605	261.93	0.609	105.06	0.606	370.05	0.605	108.35
0.582	61.92	0.604	22.83	0.598	80.73	0.615	67.37
0.590	81.84	0.609	76.34	0.605	37.44	0.609	127.10
0.605	111.19	0.612	73.82	0.598	57.75	0.612	134.48
0.606	364.82	0.616	60.99	0.604	46.94	0.598	66.61
0.603	133.11	0.605	156.96	0.604	35.66	0.609	181.58
0.605	157.03	0.603	53.56	0.517	40.75	0.605	18.88
0.591	173.13	0.598	109.73	0.605	62.39	0.604	90.06
0.555	294.11	0.599	171.28	0.614	76.72	0.614	138.23
0.571	97.74	0.609	77.99	0.609	150.48	0.609	63.80
0.604	247.92	0.605	591.14	0.598	130.63	0.606	18.41
0.605	146.84	0.598	48.32	0.560	37.08	0.571	72.43
0.598	136.74	0.609	94.19	0.606	48.98	0.612	80.44
0.591	72.62	0.602	123.84	0.604	176.77	0.609	21.69
0.607	42.35	0.604	63.39	0.605	63.22	0.547	123.62
0.604	94.10	0.615	268.68	0.598	124.29	0.604	37.45
0.609	133.10	0.598	44.95	0.608	48.90	0.609	42.78
0.604	83.95	0.602	86.25	0.591	92.64	0.603	33.50
0.612	99.39	0.582	46.34	0.598	130.26	0.606	102.57
0.598	182.39	0.613	400.54	0.601	161.71	0.604	34.91
0.591	121.27	0.612	171.53	0.604	34.81	0.605	110.54
0.613	94.87	0.603	45.09	0.605	42.37	0.582	97.17
0.602	184.18	0.547	27.63	0.609	177.99	0.603	143.08
0.615	48.48	0.615	20.86	0.591	225.17	0.605	109.15
0.612	117.43	0.591	35.39	0.612	49.39	0.609	108.05

- Step two is to take the average value of the 100 readings for each signal as shown in Table 3.2.

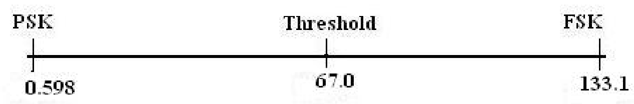

Figure 3.22: Threshold determination

Table 3.2: Signal average values

Signal	average
BPSK	0.598
BFSK	133.1

- Step three is getting the threshold which is the median value between successive values obtained from step two as shown in Figure 3.22.

Figure 3.23 shows the graph of the number of negative elements of the centered normalized instantaneous amplitude and Figure 3.24 shows the graph of the variance of instantaneous phase. Both figures shows the threshold determination of the two key features. These two key features are used in classifying the CW signal with the threshold

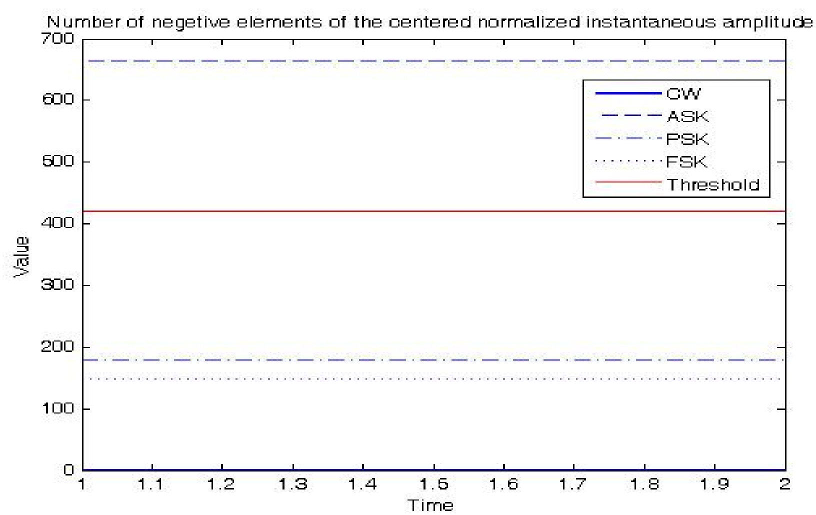

Figure 3.23: Number of negative elements of the centered normalized instantaneous amplitude

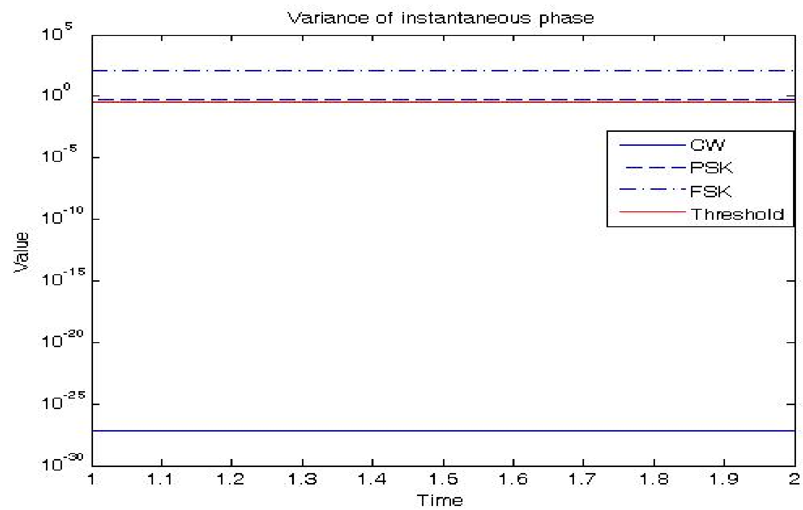

Figure 3.24: Variance of instantaneous phase

value 423, 0.15 for the number of negative elements of the centered normalized instantaneous amplitude and the variance of the instantaneous phase respectively. In the variance of the instantaneous phase graph the threshold appears closer to BPSK and BFSK signals than BASK signal this is due the log scale of the y axis.

Figure 3.25 shows the power of the centered instantaneous amplitude graph with the threshold determination for the BASK, BPSK and BFSK signals and the threshold value of 0.55.

Figure 3.26 represents the graph of the standard deviation of absolute value of the centered instantaneous phase and Figure 3.27 shows the variance of instantaneous phase. Both of the figures shows the threshold determinations of the two key features. These two key features are needed to differentiate between BPSK and BFSK signals with the threshold values of 7400 and 69 for the standard deviation of absolute value of the centered instantaneous phase and the variance of instantaneous phase respectively. In the standard deviation of absolute value of the centered instantaneous phase graph the threshold appears closer to BFSK signal than the BPSK signal as mentioned previously this is due the semi log scale of the y axis.

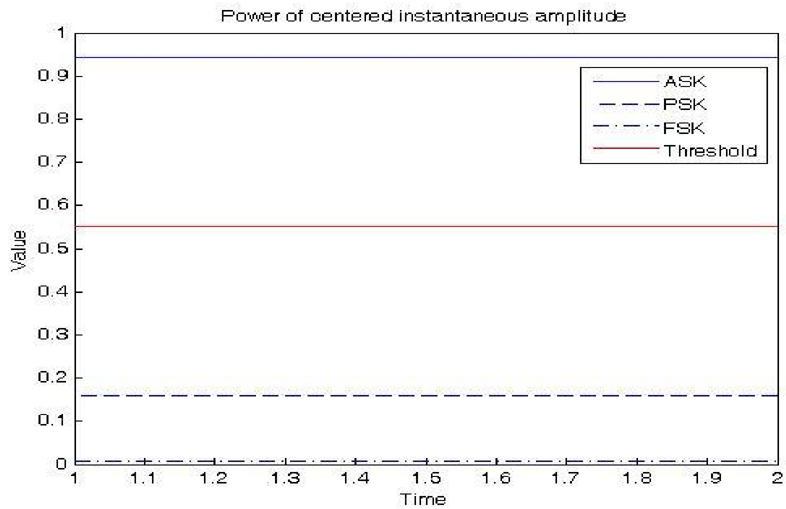

Figure 3.25: The power of the centered instantaneous amplitude

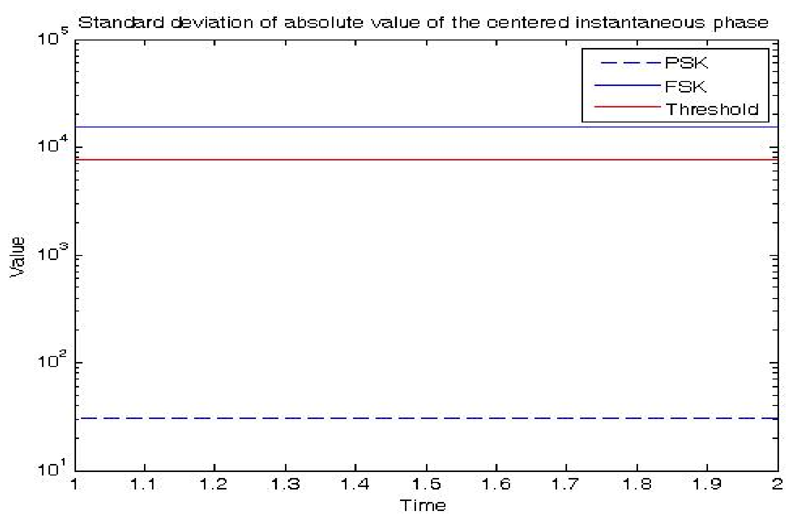

Figure 3.26: The standard deviation of absolute value of the centered instantaneous phase

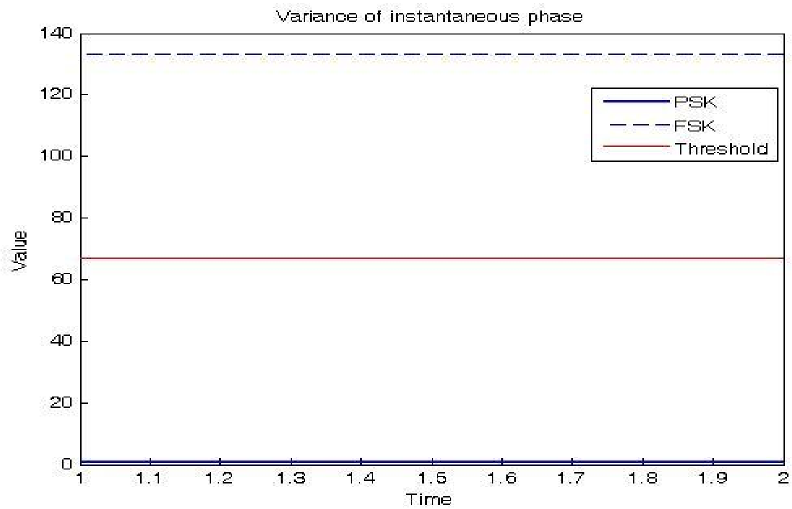

Figure 3.27: The variance of instantaneous phase

3.4 Introducing Channel Impairments

In this section, channel impairments are applied to the algorithm these channel impairments are additive white Gaussian noise (AWGN) and Flat fading. First the AWGN was added, as a result of that all the previous parameters and key features values mentioned in the above sections will change. Hence the threshold values must be re-evaluated. After adjusting the threshold values, Flat fading was added to the channel as a final step in the algorithm, but with no further threshold adjustments.

The received signal will be defined as follows:

$$r(t) = s(t) + w(t) \tag{3.10}$$

Where w(t) is an AWGN.

Since the received signal changed thus the instantaneous amplitude and instantaneous phase will differ. Figures 3.28, 3.29, 3.30 and 3.31 shows the instantaneous amplitude of the four signals of interest after adding noise,

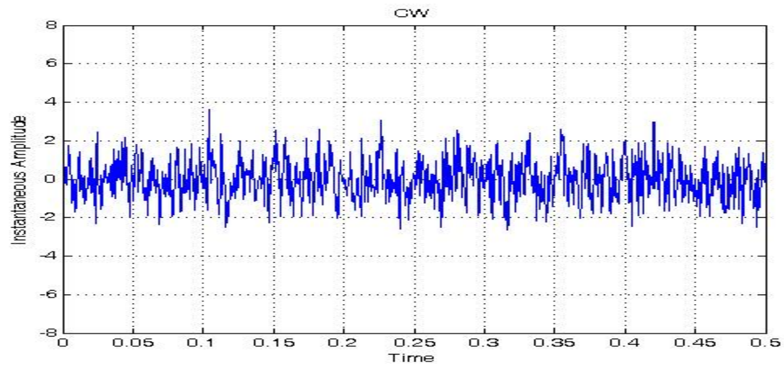

Figure 3.28: CW instantaneous amplitude at SNR=15 dB

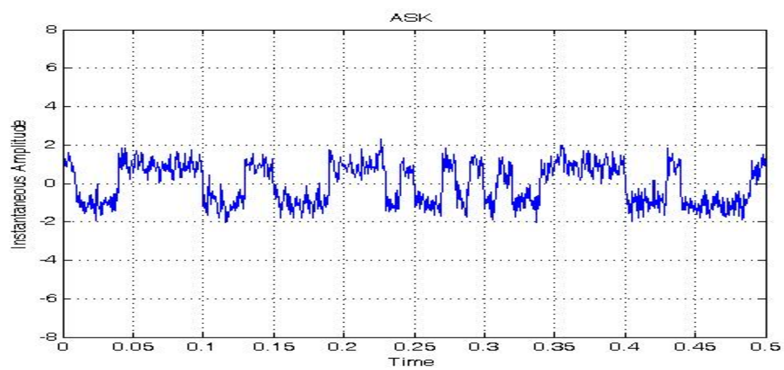

Figure 3.29: BASK instantaneous amplitude at SNR=15 dB

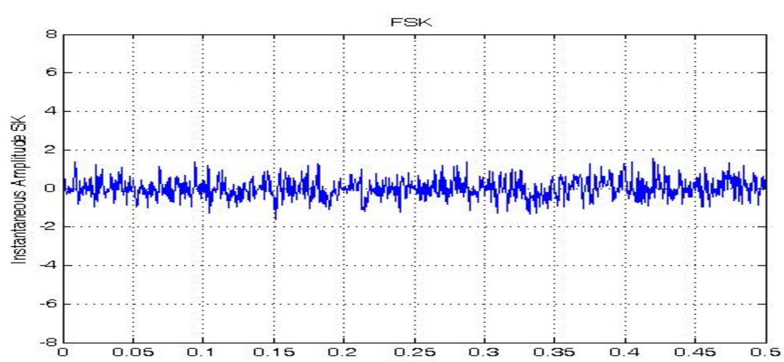

Figure 3.30: BFSK instantaneous amplitude at SNR=15 dB

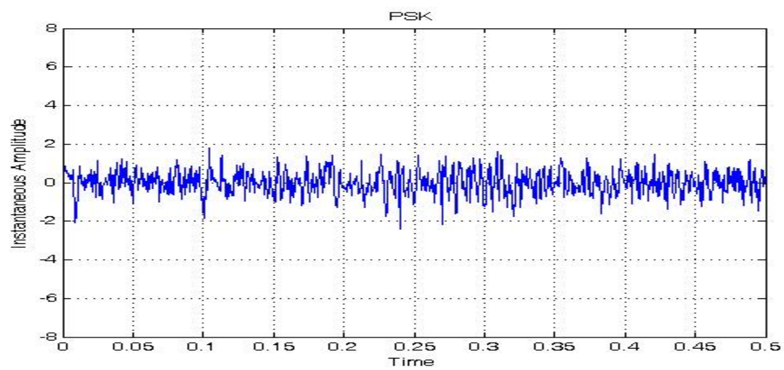

Figure 3.31: BPSK instantaneous amplitude at SNR=15 dB

As Figures 3.32, 3.33, 3.34 and 3.35 shows the instantaneous phase of the same signals after adding noise. All the graphs are computed at SNR=15 dB.

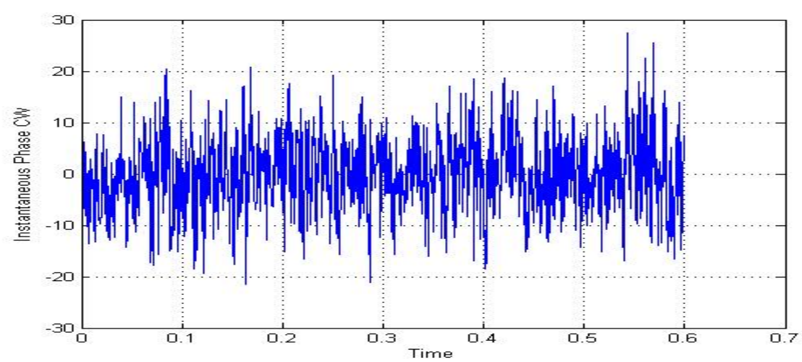

Figure 3.32: CW instantaneous phase at SNR=15 dB

The values of the key features changed as a result of changing the values of the main parameters. Hence the threshold determination must be re-evaluated using the same procedure explained before in section 3.3.2.

Figures 3.36, 3.37, 3.38, 3.39 and 3.40 shows graphs of all the key features values after adding noise to the signals and the signals they distinguish between. The graphs are generated after taking the average value of 100 different signal realization and at a SNR=7.5 dB.

The optimum threshold is the value of the threshold that gives the highest probability of success at the lowest SNR as possible it doesn't have to be the median value. The graphs showing the determination and optimization of the

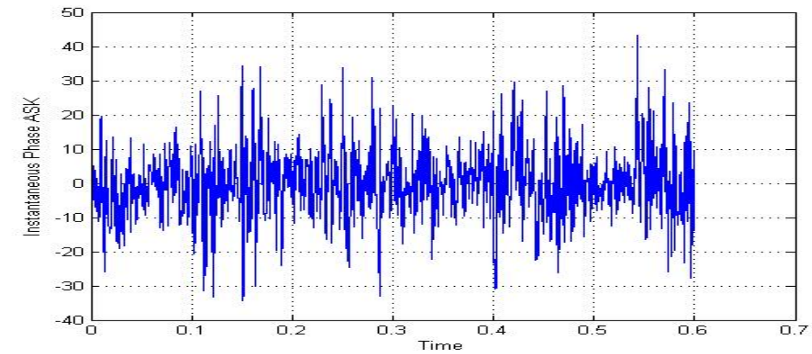

Figure 3.33: BASK instantaneous phase at SNR=15 dB

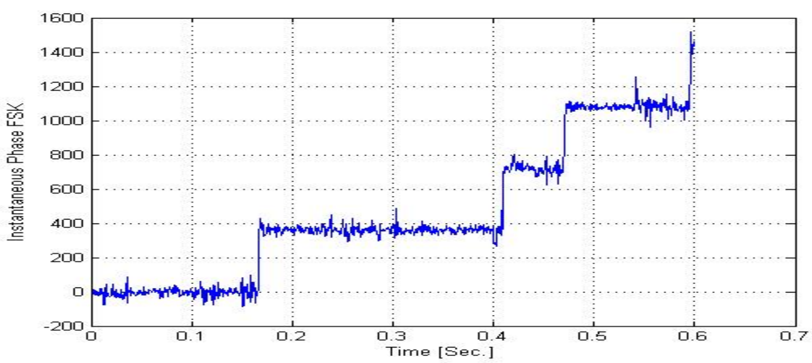

Figure 3.34: BFSK instantaneous phase at SNR=15 dB

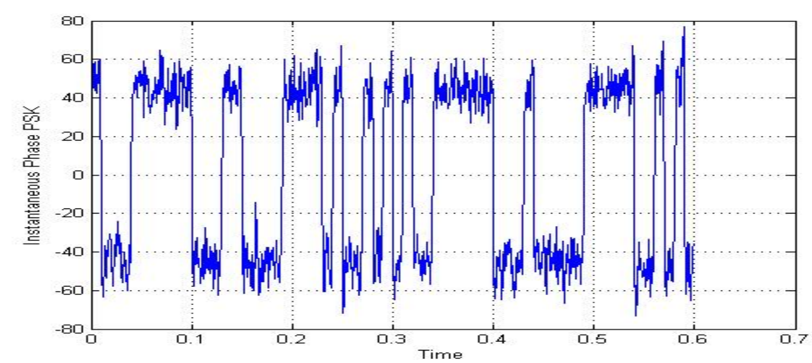

Figure 3.35: BPSK instantaneous phase at SNR=15 dB

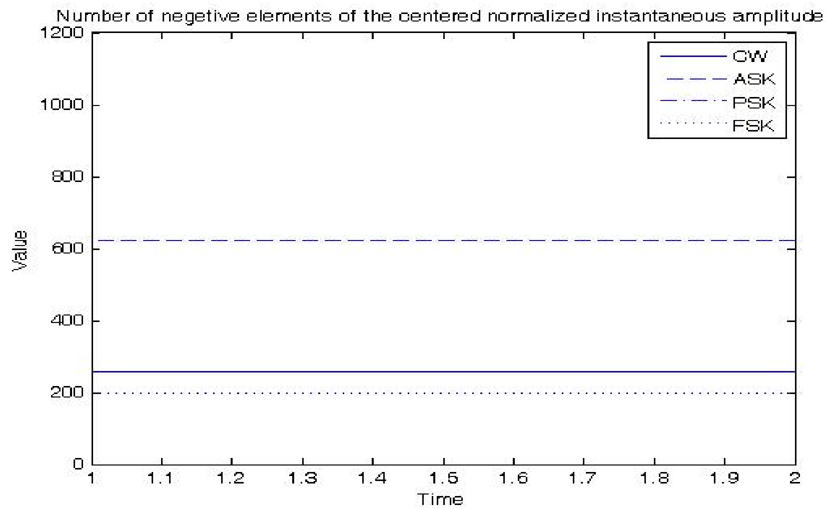

Figure 3.36: Number of negative elements of the centered normalized instantaneous amplitude at SNR=7.5 dB

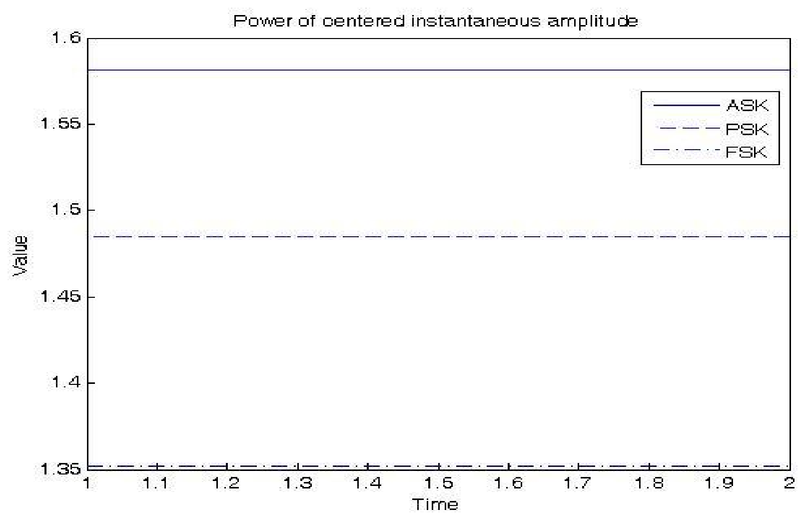

Figure 3.37: Power of centered instantaneous amplitude at SNR=7.5 dB

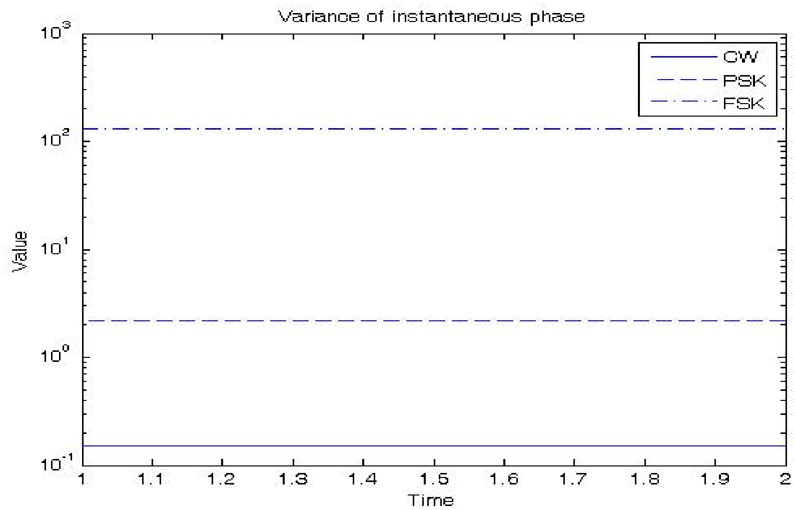

Figure 3.38: Variance of instantaneous phase at SNR=7.5 dB

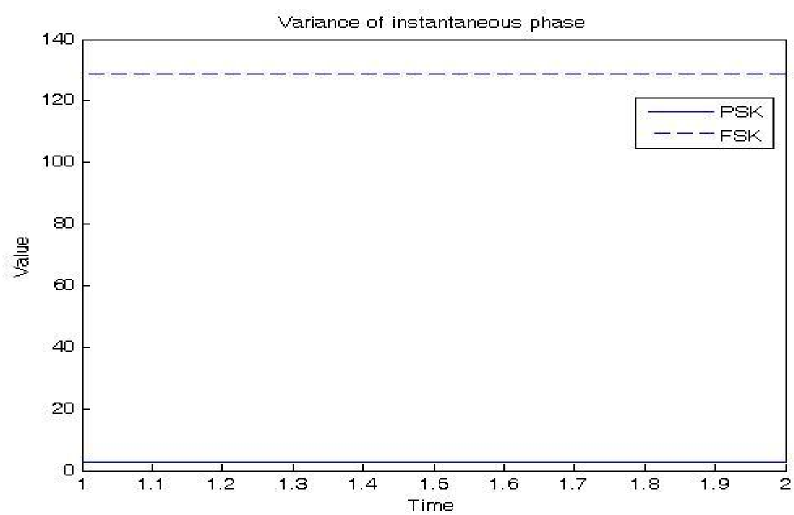

Figure 3.39: Variance of instantaneous phase at SNR=7.5 dB

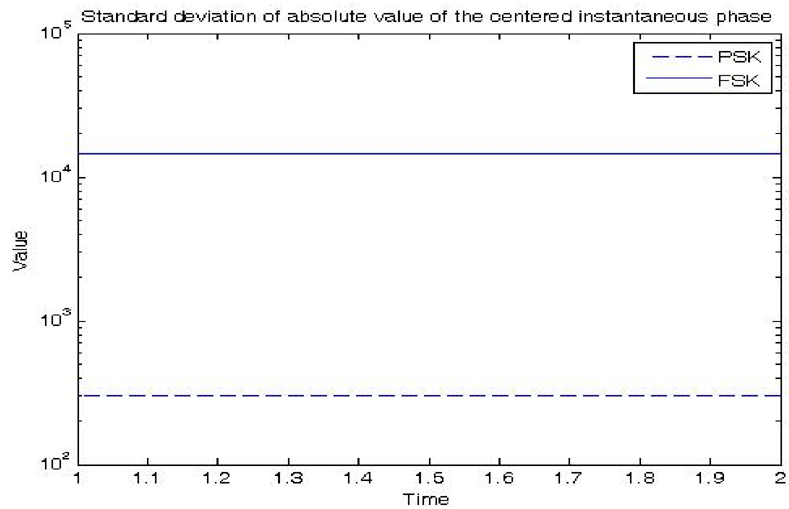

Figure 3.40: Standard deviation of absolute value of the instantaneous phase at SNR=7.5 dB

threshold of the key features over different SNR are shown from Figure3.41 to Figure 3.44.

Figure 3.41 shows the number of negative elements of the centered normalized instantaneous amplitude values for CW, BASK, BPSK and BFSK signals against different SNR. From Figure 3.41 it is concluded that the optimum threshold of the number of negative elements of the centered normalized instantaneous amplitude to differentiate between BASK signal and any other signal is about 275.

Figure 3.42 shows the instantaneous phase variance values for CW, BPSK and BFSK signals against different SNR. From Figure 3.42 two instantaneous phase variance thresholds is obtained threshold 1 and threshold 2. Threshold 1 is the threshold used to distinguish between CW signal and both BFSK and BPSK signals, threshold 2 is used to differentiate between BPSK and BFSK. The optimum value of threshold 1 and threshold 2 obtained from the figure is 0.3 and 6 respectively.

Figure 3.43 shows the power of the centered instantaneous amplitude of BASK, BPSK and BFSK signals against different SNR. From Figure 3.43 it is concluded that the optimum threshold of power of centered instantaneous amplitude needed to distinguish between BASK and BPSK,BFSK signals is 0.85.

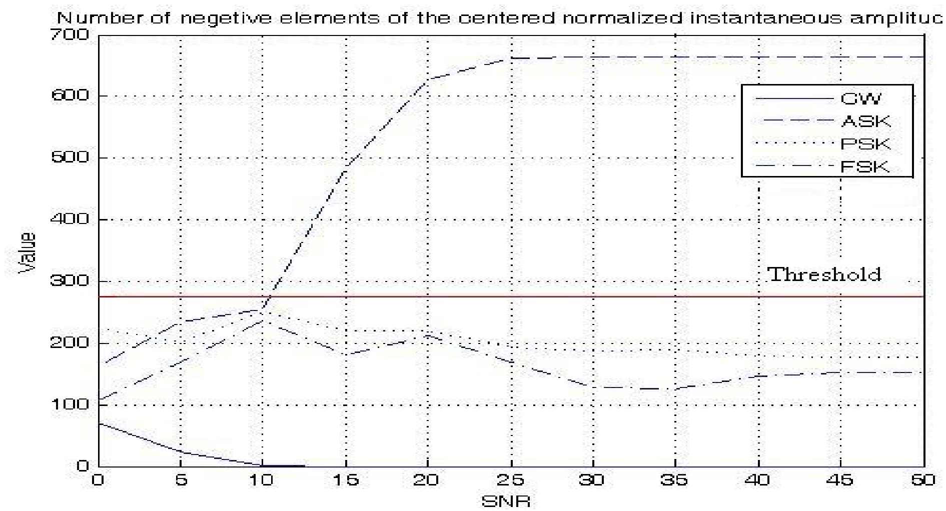

Figure 3.41: The number of negative elements of the centered normalized instantaneous amplitude

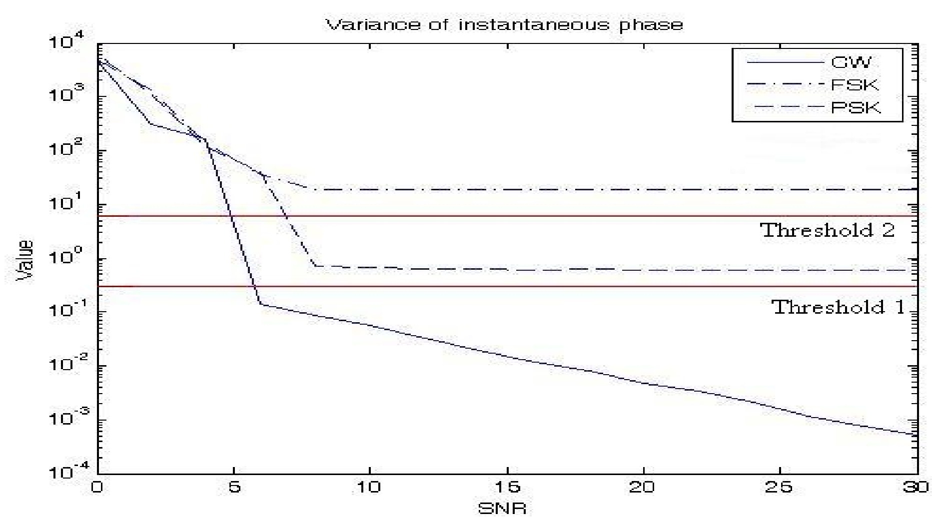

Figure 3.42: Variance of instantaneous phase

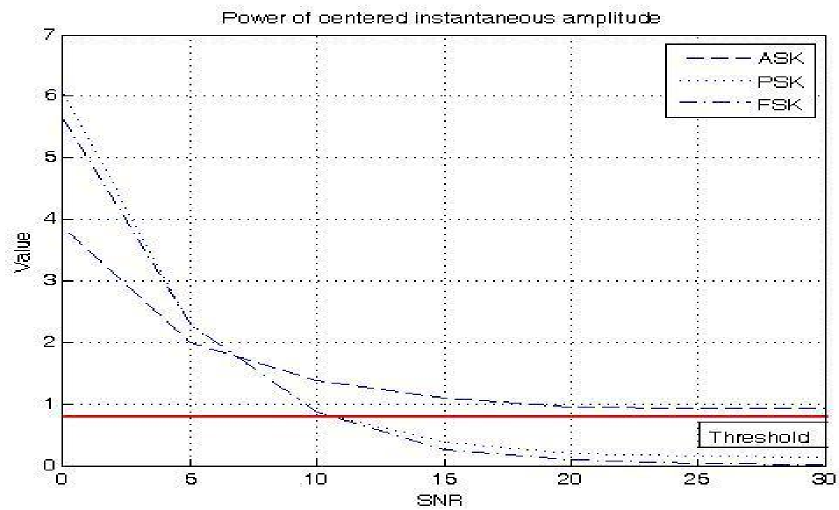

Figure 3.43: The power of centered instantaneous amplitude

Figure 3.44 shows the standard deviation of the absolute value of the centered non-linear component of the instantaneous phase of BPSK and BFSK signals against different SNR. From Figure 3.44 it is concluded that the optimum threshold of power of Standard deviation of the absolute value of the centered non-linear component of the instantaneous phase needed to distinguish between BPSK and BFSK signals is 350.

Finally, after adding the AWGN and then new values of the threshold was determined Flat fading was added to the channel changing the received signal to be defined as follows:

$$r(t) = F\ s(t) + w(t) \tag{3.11}$$

Where F is the interference due to fading and w(t) is AWGN. The interference due to fading is defined by:

$$F = Ge^{j\theta} \tag{3.12}$$

Where G is the gain of the channel which has Rayleigh distribution and $\theta$is the phase of the channel which is uniformly distributed from 0 to 2π.

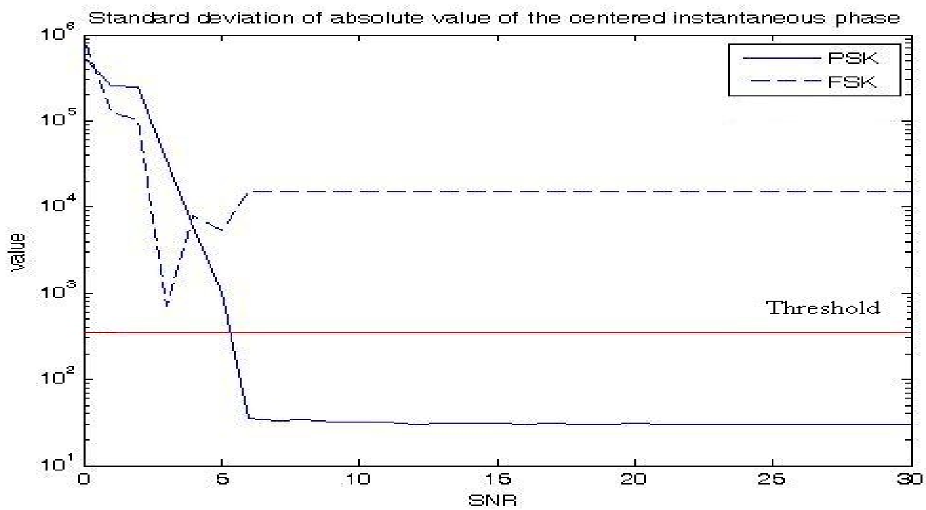

Figure 3.44: The Standard deviation of the absolute value of the centered instantaneous phase

3.5 Flow Chart

Figure 3.45 shows the flow chart of the classification algorithm. From the flow chart it is clear that three operations are executed through out the algorithm. All the operations depend on the result of the previous operation which means that the operation will not be executed unless all the previous operations fail, except for the first operation. Each operation either choose or exclude a specific signal.

Table 3.3 shows the symbols definition and the threshold values used in the flow chart.

Table 3.3: Symbols used in flow chart

Symbol	Definition	Value
ζ	Number of negative elements of the centered normalized instantaneous amplitude values	Calculated
tζ	Number of negative elements of the centered normalized instantaneous amplitude values threshold	275
σ^2	Variance of instantaneous phase	Calculated
tσ^2	Variance of instantaneous phase threshold	Calculated
P	Power of centered instantaneous amplitude	0.3, 6 respectively
tP	Power of centered instantaneous amplitude threshold	0.85
σ_{ap}	Standard deviation of the absolute value of the centered instantaneous phase	Calculated
tσ_{ap}	Standard deviation of the absolute value of the centered instantaneous phase threshold	350

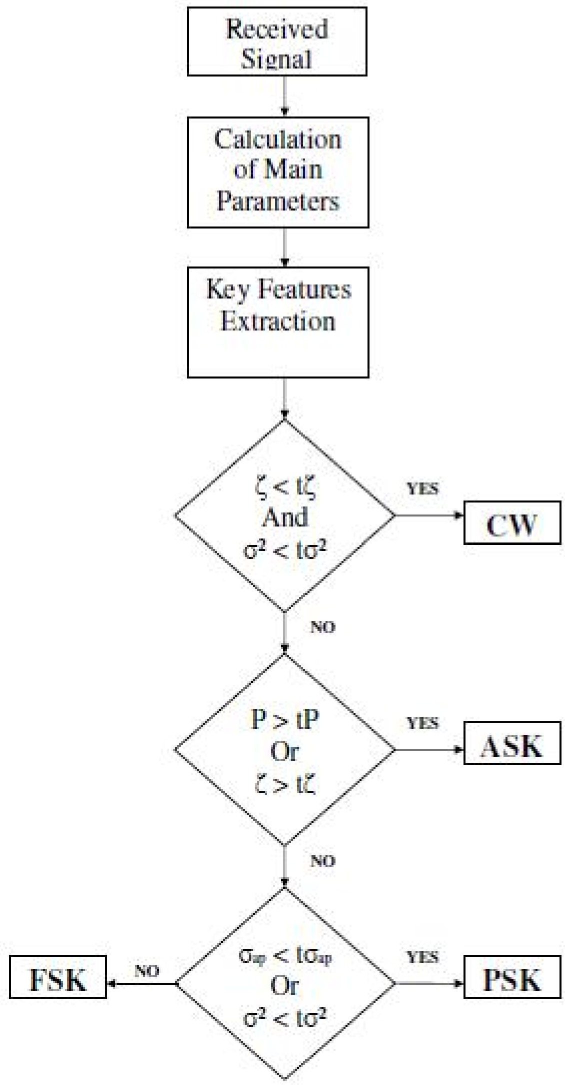

Figure 3.45: Flow chart

Chapter 4

SIGNALS GENERATION AND PERFORMANCE EVALUATION

This chapter is divided into two parts. In the first part computer simulations and signal generation is discussed taking into consideration the channel impairments. While in the second part the performance evaluation of the classification algorithm is shown.

4.1 Computer Simulations

In this section the generation of the four signals is presented in the presence of the channel impairments. The signals are generated and analyzed using MATLAB software. A uniformly distributed random sequence of 0 and 1 are generated representing the message bits. The parameters used in the simulation are 60 bits per frame, 20 samples per bit and the carrier frequency used is 200 KHz. Figure 4.1 shows an example of a random generated message.

- Continuous wave (CW) which is the carrier wave and is defined as follows:

$$CW(t) = A\cos(2\pi f_c t) \tag{4.1}$$

Where A is the signal amplitude which in this case is equal to 1 and f_c is the carrier frequency. Figure 4.2 shows the generated CW signal.

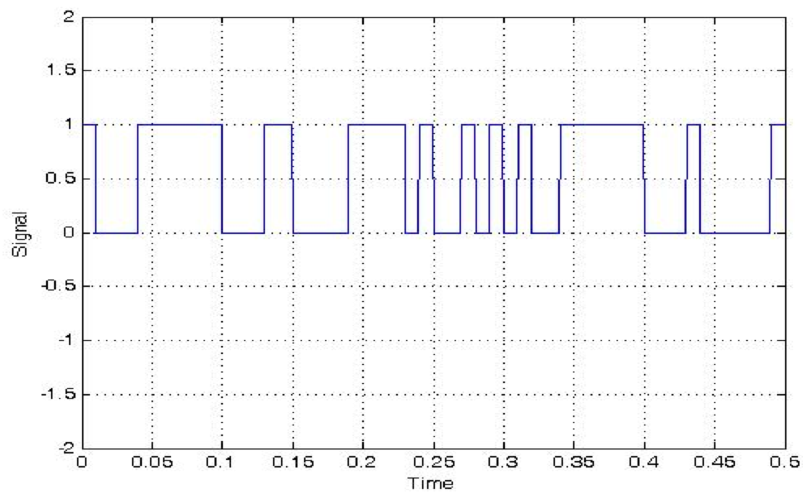

Figure 4.1: Random message

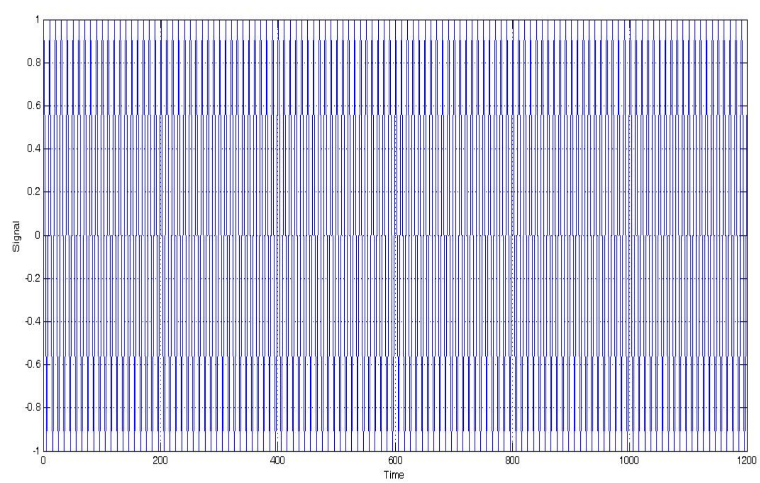

Figure 4.2: CW signal

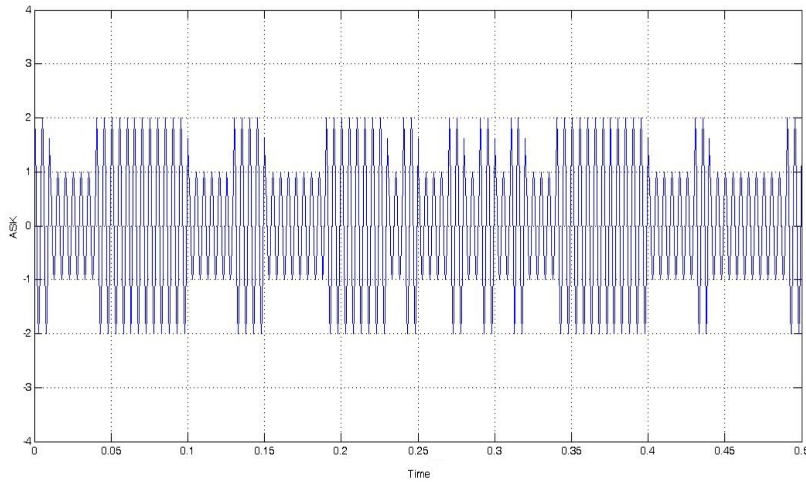

Figure 4.3: without channel impairments BASK signal

- In binary amplitude shift keying (BASK) signal, the amplitude of the carrier signal changes in response to the message, while the frequency and the phase remains the same. If bit 1 is transmitted a value of 2 is given to the amplitude, but if bit 0 is transmitted the amplitude is set to a value of 1. BASK signal is defined by:

$$ASK(t) = A\, m(t) \cos(2\pi f_c t) \tag{4.2}$$

Figure 4.3 shows a generated BASK signal without channel impairments. Figure 4.4 shows BASK signal in presence of noise, while Figure 4.5 shows the BASK signal in presence of both noise and fading.

- In binary frequency shift keying (BFSK) signal, the frequency of the carrier signal changes in response to the message, while the amplitude and phase remains constant. If bit 0 is transmitted the frequency is set to f_1, but if bit 1 is transmitted the frequency is set to the f_2. These frequencies are calculated as follows:

$$f_1 = f_c - \Delta f$$

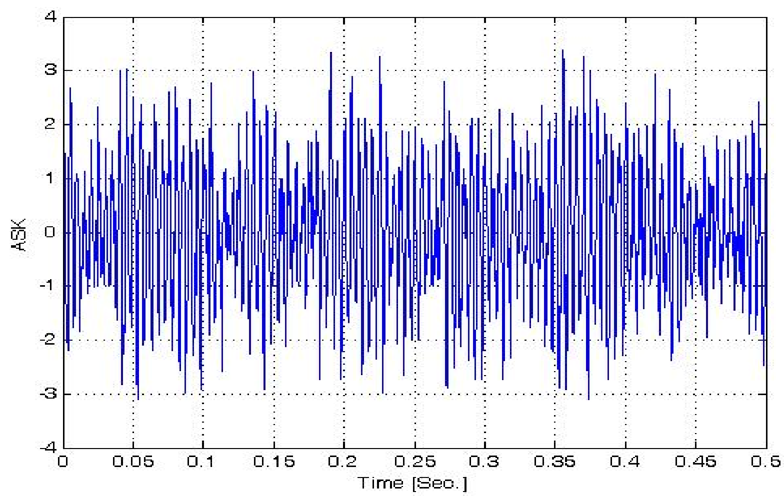

Figure 4.4: BASK signal in presence of noise

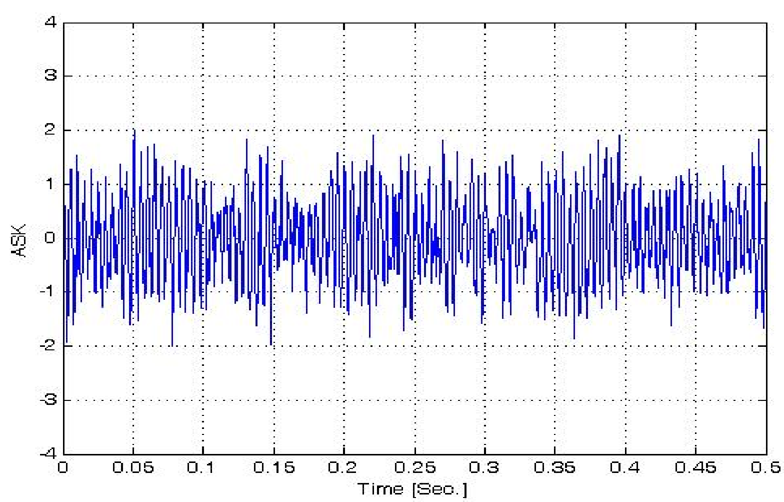

Figure 4.5: BASK signal in presence of noise and fading

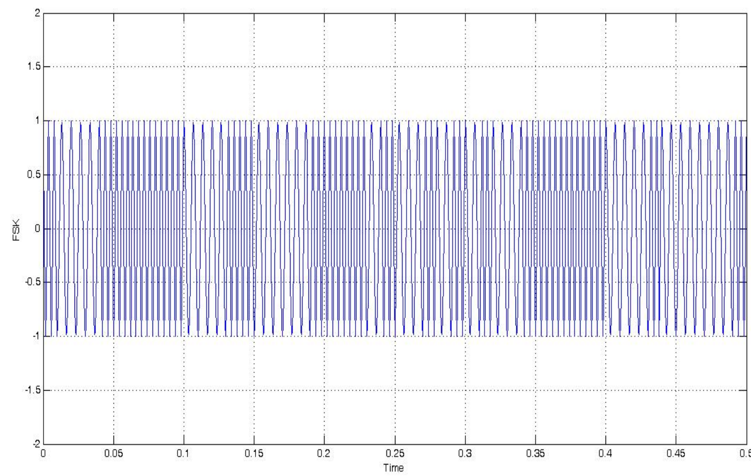

Figure 4.6: BFSK signal without channel impairments

$$f_2 = f_c + \Delta f$$

Where f_c is the carrier frequency and Δf has the value of 50 Hz. As a result f_1 is equal to 150 Hz and f_2 is equal to 250 Hz. The BFSK signal is defined as follows:

$$FSK(t) = A\cos(2\pi f_c t + 2\pi \triangle f) \quad (4.3)$$

Figure 4.6 shows a generated BFSK signal without channel impairments. Figure 4.7 shows BFSK signal in presence of noise, while Figure 4.8 shows the BFSK signal in presence of both noise and fading.

- In binary phase shift keying (BPSK) signal, the phase of the signal changes in response to the message, while the amplitude and the frequency remains constant. if bit 0 is transmitted the phase is set to 0°, but if bit 1 is transmitted the the phase changes to 180°. The BPSK is defined as follows:

$$PSK(t) = A\cos(2\pi f_c t + \theta m(t)) \quad (4.4)$$

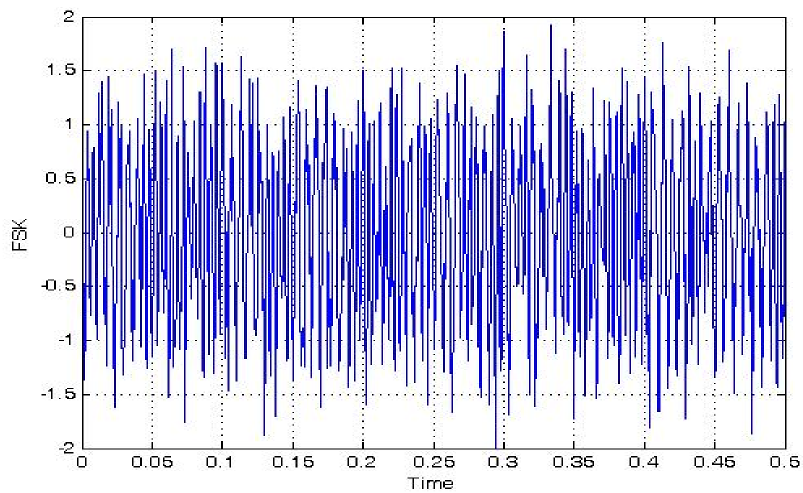

Figure 4.7: BFSK signal in presence of noise

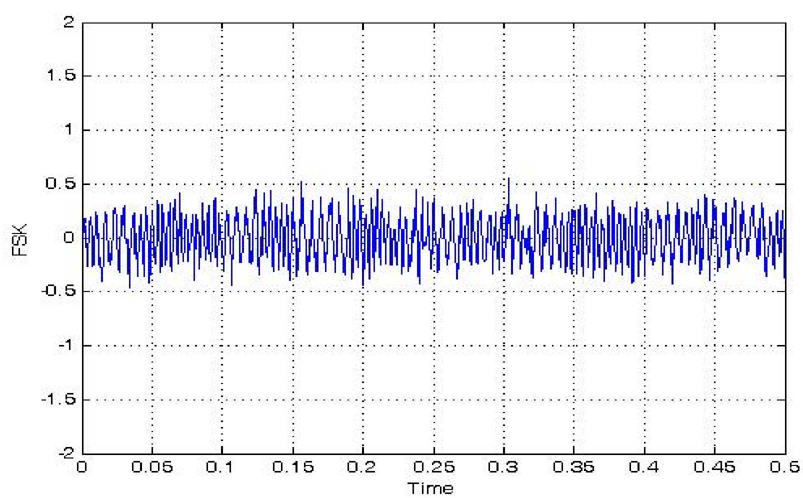

Figure 4.8: BFSK signal in presence of noise and fading

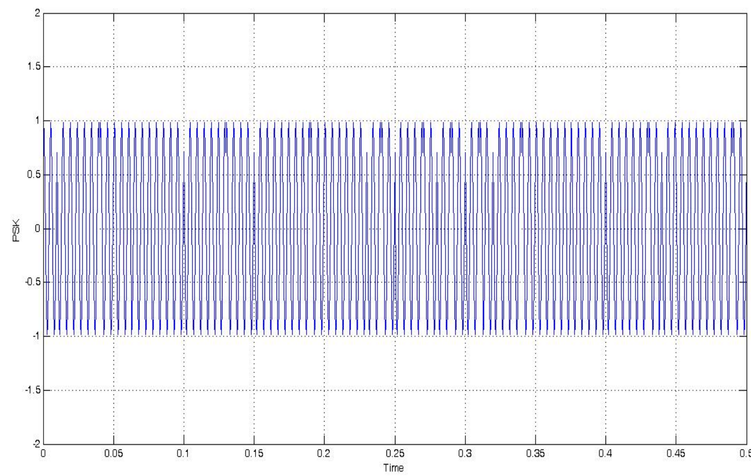

Figure 4.9: BPSK signal without channel impairments

Figure 4.9 shows a generated BPSK signal without channel impairments. Figure 4.10 shows BPSK signal in presence of noise, while Figure 4.11 shows the BPSK signal in presence of both noise and fading.

4.2 Performance Evaluation of the Classification Algorithm

The classification algorithm classifies between signals in the presence of channel impairments such as AWGN and Flat fading. In this section the performance evaluation of the algorithm is introduced in terms of its confusion matrices, once in the presence of noise only and another in the presence of noise and fading as channel impairments.

4.2.1 Performance Evaluation in Presence of AWGN

Figure 4.12 shows the percentage of correct classification of the four signals of interest CW, BASK, BPSK and BFSK against different SNR . From Figure 4.12 it can be concluded that all of the four signals are 100% correctly classified at SNR of about 12.5 dB.

Table 4.1 shows the confusion matrix at SNR of 0 dB. It is clear that all the

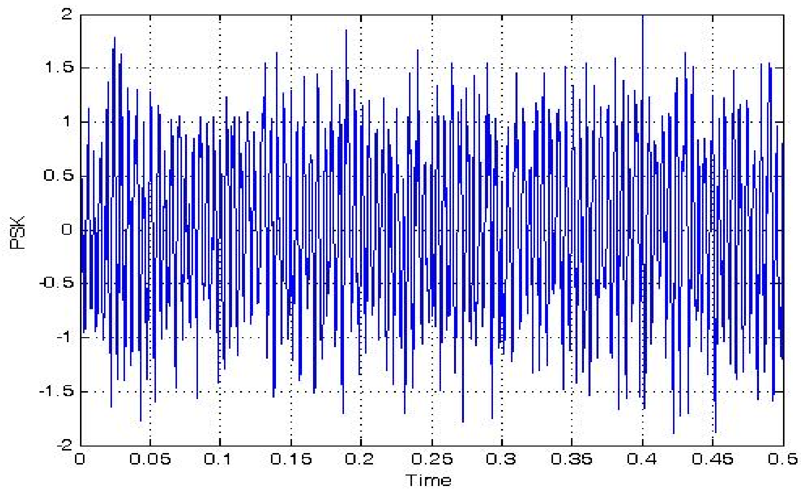

Figure 4.10: BPSK signal in presence of noise

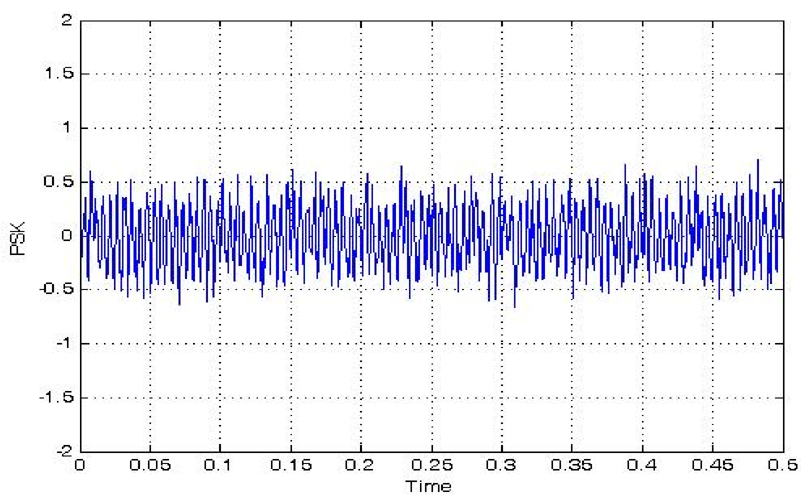

Figure 4.11: BPSK signal in presence of noise and fading

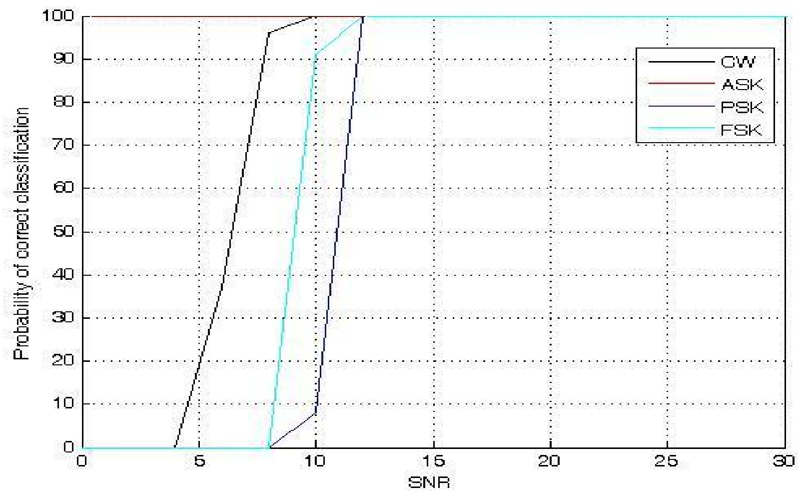

Figure 4.12: percentage of correct classification in presence of noise

received signals are classified as BASK signals

Table 4.1: Confusion matrix at SNR=0 d**B**

	CW	BASK	BFSK	BPSK
CW		100%		
BASK		100%		
BFSK		100%		
BPSK		100%		

Table 4.2 shows the confusion matrix at SNR of 5 dB. It is clear that 18% of the CW signal starts to be classified correctly. BPSK and BFSK signals are still 100% misclassified as BASK signals.

Table 4.2: Confusion matrix at SNR=5 dB

	CW	BASK	BFSK	BPSK
CW	18%	82%		
BASK		100%		
BFSK		100%		
BPSK		100%		

Table 4.3 shows the confusion matrix at SNR of 7.5 dB. It is clear that most of the CW signals with a percentage of 79 % is classified correctly, but the BPSK and BFSK signals are still 100% misclassified as BASK signals which will change at SNR of 10 dB as shown in Table 4.4.

Table 4.3: Confusion matrix at SNR=7.5 dB

	CW	BASK	BFSK	BPSK
CW	79%	21%		
BASK		100%		
BFSK		100%		
BPSK		100%		

Table 4.4: Confusion matrix at SNR=10 dB

	CW	BASK	BFSK	BPSK
CW	100%			
BASK		100%		
BFSK		8%	92%	
BPSK		92%		8%

From Table 4.4 it is shown that 100% of the CW signal is correctly classified. As for the BFSK signal 92% is classified correctly, while 92% of the BPSK signals are still misclassified as BASK signals.

The confusion matrix at SNR=12.5 dB is shown in Table 4.5. It is clear from the table that all of the four signals are 100% correctly classified. The confusion matrices at SNR of 15, 20, 30 and 50 dB was computed and all gave the same result as at SNR of 12.5 dB.

Table 4.5: Confusion matrix at SNR=12.5 dB

	CW	BASK	BFSK	BPSK
CW	100%			
BASK		100%		
BFSK			100%	
BPSK				100%

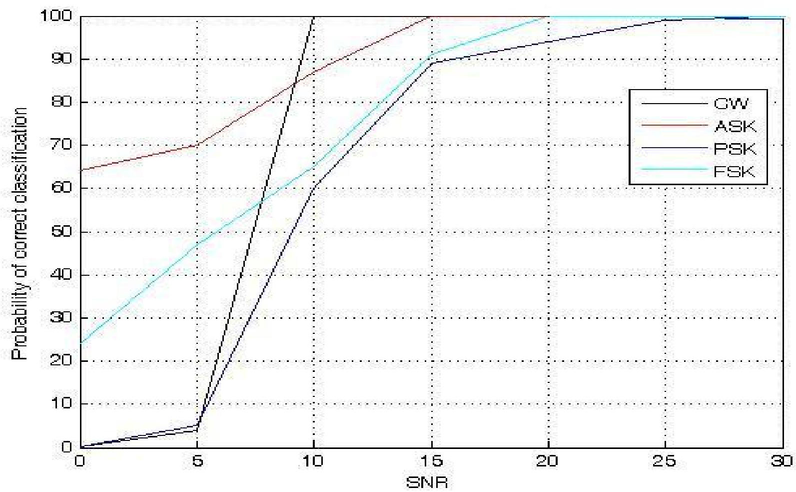

Figure 4.13: percentage of correct classification in presence of noise and fading

Table 4.6 shows the overall success rate of the proposed algorithm in the presence of AWGN channel at SNR of 0, 5, 7.5, 10, 12.5 dB.

Table 4.6: Overall success rate in presence of noise

SNR (dB)	Overall success rate
0	25%
5	29.5%
7.5	44.75%
10	75%
12.5	100%

4.2.2 Performance Evaluation in Presence of both AWGN and Flat fading

Figure 4.13 shows the percentage of correct classification of CW, BASK, BFSK and BPSK signals against different SNR. From Figure 4.13 it can be concluded that all the signals except for the BPSK signal reaches 100% correct classification at SNR of 20 dB, as for the BPSK signal it never reaches 100% correct classification instead it reaches a percentage of 98% at SNR of 30 dB.

Table 4.7 shows the confusion matrix at SNR of 0 dB. It is clear that all of the signals are classified either as BASK signal or BFSK signal, with a percentage to be classified as BASK signal higher than to be classified as BFSK.

Table 4.7: Confusion matrix at SNR=0 dB

	CW	BASK	BFSK	BPSK
CW		76%	24%	
BASK		64%	36%	
BFSK		75%	25%	
BPSK		68%	32%	

Table 4.8 shows the confusion matrix at SNR of 5 dB. It is found that the CW can be classified as any of the four signals with higher probability of being classified as BASK signal. BASK and BFSK signals situation stays the same but with a bit higher probability of being classified correctly, as for the BPSK signal 5% only is classified correctly.

Table 4.8: Confusion matrix at SNR =5 dB

	CW	BASK	BFSK	BPSK
CW	4%	59%	31%	6%
BASK		70%	30%	
BFSK		52%	48%	
BPSK		54%	41%	5%

The confusion matrix at SNR of 7.5 dB is shown in Table 4.9. It is clear from the table that still none of the signals reached a 100% correct classification.

Table 4.9: Confusion matrix at SNR=7.5 dB

	CW	BASK	BFSK	BPSK
CW	62%	15%	21%	2%
BASK	1%	76%	19%	4%
BFSK		46%	54%	
BPSK		59%	9%	32%

Table 4.10 shows the confusion matrix at SNR of 10 dB. It is clear that CW

reached 100% correct classification, as for the rest of the signal has a higher probability of being classified correctly than being misclassified.

Table 4.10: Confusion matrix at SNR=10 dB

	CW	BASK	BFSK	BPSK
CW	100%			
BASK	10%	87%	1%	2%
BFSK		25%	75%	
BPSK		40%		60%

Table 4.11 represents the confusion matrix at SNR of 15 dB. As shown in the table the BASK signal reaches 100% correct classification. While BFSK reaches a percentage of 92 % and BPSK reaches a percentage of 88%.

Table 4.11: Confusion matrix at SNR=15 dB

	CW	BASK	BFSK	BPSK
CW	100%			
BASK		100%		
BFSK		8%	92%	
BPSK		12%		88%

From Table 4.12 which represent the confusion matrix at SNR of 20 dB it is shown that BFSK signal reaches 100% correct classification, while still the BPSK signal has a percentage of 94%.

Table 4.12: Confusion matrix at SNR=20 dB

	CW	BASK	BFSK	BPSK
CW	100%			
BASK		100%		
BFSK			100%	
BPSK		6%		94%

Table 4.13 shows the confusion matrix at SNR of 30 dB. It is clear from the table that BPSK signal reached a percentage of 98%. Confusion matrices at

SNR of 35, 40, 45 and 50 dB was computed and all gave the same result as at SNR of 30 dB.

Table 4.13: Confusion matrix at SNR=30 dB

	CW	BASK	BFSK	BPSK
CW	100%			
BASK		100%		
BFSK			100%	
BPSK		2%		98%

The overall success rate is shown in Table 4.14 for SNR of 0, 5, 7.5, 10, 15, 20 and 30 dB. The overall success rate never reaches 100% this is due to the BPSK signal that has a maximum percentage of correct classification of 98%.

Table 4.14: Overall success rate in presence of noise and fading

SNR (dB)	Success Rate
0	22.25%
5	31.75%
7.5	56%
10	80.5%
15	95%
20	98.5%
30	99.5%

Chapter 5

CONCLUSIONS AND FUTURE WORK SUGGESTIONS

This chapter consists of two main sections. The first section is a brief summary of the work discussed previously in the thesis, while the second section is some suggestions about future work that could be carried out.

5.1 Conclusions

An automatic modulation classification algorithm for digitally modulated signals based on decision theoretic approach has been presented. The algorithm took into account the effect of some channel impairments such as AWGN and Flat fading. Four key features was used in the algorithm, these key features are the number of negative elements of the centered normalized instantaneous amplitude, standard deviation of the absolute value of the centered non-linear component of the instantaneous phase, the power of centered instantaneous amplitude and the variance of the instantaneous phase. All of the four key features were extracted from two instantaneous parameters which are the instantaneous amplitude and instantaneous phase.

Many simulations for three digital modulated signals which are the BASK, BFSK and BPSK in addition to the CW signal has been carried out at different

SNR. The simulation results are in good agreement with the theoretic case. Thresholds for the different key features were calculated by taking the median between the values of the key feature which is the average of 100 realization for each signal of interest for the ideal channel without channel impairments and then adjusted for the case of the presence of AWGN.

The performance evaluation of the classification algorithm has been performed using confusion matrices once for the presence of AWGN and once in the presence of both AWGN and Flat fading at different SNR. For the case of the presence of AWGN only, the algorithm has been tested at SNR of 0, 5, 7.5, 10, 12.5, 15, 20, 30 and 50 dB. It was found that an overall success rate of 25% was the case at SNR of 0 dB, it became 29.5% at 5 dB and then increased to 44.75% at SNR of 7.5 dB, then increased to 75% at SNR of 10 dB until finally it reaches 100% at a SNR of 12.5 dB. The BASK signal is 100% correctly classified at any SNR starting from 0 dB, CW starts to be correctly classified at SNR of 5 dB and reaches 100% correct classification starting at SNR of 10 dB as for the BFSK signal starts to be correctly classified at SNR of 8 dB while the BPSK signal starts to be correctly classified at 10 dB, but both signals are 100% classified correctly at SNR of 12.5 dB. The algorithm was tested at SNR of 15, 20, 30 and 50 dB to ensure the 100% correct classification.

In the presence of AWGN and Flat fading the algorithm was tested at SNR of 0, 5, 7.5, 10, 15, 20, 30, 35, 40, 45 and 50 dB. It has been found that an overall success rate of 22.25% at 0 dB. It reached 31.75% at SNR of 5 dB, then it continued to increase to be 56, 80.5, 95, 98.5% at SNR of 7.5, 10, 15, 20, 30 dB respectively until it reaches 99.5% at SNR of 30 dB. It never reaches 100% due to the BPSK signal were it's maximum percentage of correct classification never exceeds 98%. The BASK signal was classified correctly with a percentage of 64% starting at SNR of 0 dB and continues to increase until reaching 100% at SNR of 15 dB. The CW starts to be correctly classified with a percentage of 4% at SNR of 5 dB then increases to reach 100% correct classification at SNR of 10 dB. The BFSK signal was classified correctly with a percentage of 25 % at SNR of 0 dB until it reaches 100% at SNR of 20 dB. Finally the BPSK signal starts to be correctly classified at SNR of 5 dB with a percentage of 5% until it reaches it's maximum percentage of 98% at SNR of 30 dB. The algorithm was tested at SNR of 35, 40, 45 and 50 dB to confirm the previous results.

It is concluded that the overall success rate in presence of noise only reaches 100% at SNR of 12.5 dB while in the presence of noise and Flat fading it reaches an overall success rate of 95% at SNR of 15 dB and reaches it's maximum value of 99.5% at SNR of 30 dB.

5.2 Future Work Suggestions

The following points are suggested by the author for future work.

- Extend the algorithm to include more types of modulation such as MASK, MFSK and MPSK.
- Extend the algorithm to add more channel impairments such as more types of fading.
- Experimental evaluation of the classification algorithm.

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