Automatic Analysis and Classification of Digital Modulation Signals Using Spectrogram Time-Frequency Analysis

Tan Jo Lynn* and Ahmad Zuri Sha'ameri†
Faculty of Electrical Engineering
Universiti Teknologi Malaysia, Skudai 81300, Johor, Malaysia
Tel: +60-7-5534516, Fax: +60-7-55
E-mail: * tjolynn82@yahoo.co.uk, † ahmadzs@yahoo.com

***Abstract*— Automatic analysis and classification of signals is important for spectrum monitoring. It enables the system to monitor the conformance of frequency planning from the users. Spectrogram time-frequency analysis can be used to extract useful information from time-varying signals. The information can be used for signal classification. This paper describes the design and implement an automatic system to analyze and classify the basic types of digital modulation signals such as Amplitude Shift-Keying (ASK), Frequency Shift-Keying (FSK) and Phase Shift-Keying (PSK). Analysis method is based on the spectrogram time frequency analysis and a rules based approach is used as a classifier. From the time-frequency representation, the instantaneous frequency is estimated which is then used to estimate the modulation type and its parameters. This information is further used as input to the rules based classifier. The robustness of the system is tested in the presence of additive white Gaussian noise. On the average, the classification accuracy is 90 percent for signal-to-noise ratio (SNR) of 2 dB. Thus, the results show that the system gives reliable analysis and classification of signals in an uncooperative communication environment even if the received signal is weak.**

I. Introduction

Spectrum monitoring is an important activity for regulatory organizations to ensure conformance to frequency planning from the users. From the military perspective, spectrum monitoring is part of intelligence gathering. Among the features in spectrum monitoring are signal strength measurement, carrier frequency and modulation parameters estimation, location of transmitters and classification of signals [1].

The digital modulation signals such as ASK, FSK and PSK are time-varying signals due to the time variation in the transmitted information that is represented either in the amplitude, frequency or phase. Traditional spectrum estimation method based on the Fourier transform assumed signals as time-invariant and does not represent the temporal signal characteristics. Time representation indicates how the amplitude of the signals varies in time and the frequency representation indicates the frequency content of the signal. The individual representation by themselves does not give sufficient information represent and classify of time-varying signals. One of the popular methods that have been used to analyze time-varying signals is time-frequency analysis. Spectrogram is the most common time-frequency analysis method that can be used to estimate parameters of signal of interest [2]. Information that can be estimated from the time-frequency representation (TFR) are the instantaneous energy/power and instantaneous frequency (IF). From the IF, modulation parameters such as subcarrier frequencies and bit duration can be obtained. These information are then used as input to a classifier.

This paper describes an improvement to the design and implementation of a system for analysis and classification of the class of digital communication systems such as ASK (Amplitude Shift-Keying), FSK (Frequency Shift-Keying) and PSK (Phase Shift-Keying) in [1]. The method used to differentiate the ASK signals from FSK/PSK signals is modified to get better parameters estimation and noise robustness. The same pattern recognition approach is adopted: the analysis method is the spectrogram time-frequency analysis and the classifier is the rules based method.

II. Signal Models

The received signal when expressed in discrete-time form is defined as follows

$$y(n) = x(n) + w(n) \tag{1}$$

where $x(n)$ is the signal of interest and $w(n)$ is the interference due to additive white Gaussian noise with zero mean and variance σ_w^2. The signal of interest is a digital modulation signal that can be modeled as a time-varying signal

1-4244-0977-2/07/$25.00 © 2007 IEEE

$$x(n) = a(n)\cos(2\pi \sum_{\lambda=-\infty}^{n} f_i(\lambda) + \phi(n)) \quad (2)$$

where $a(n)$, $f_i(n)$ and $\phi(n)$ are the instantaneous amplitude, frequency and phase respectively. The basic class of digital modulation signals is defined as follows

i) ASK : $f_i(n)$ and $\phi(n)$ constant while $a(n)$ varies with time.
ii) FSK : $a(n)$ and $\phi(n)$ constant while $f_i(n)$ varies with time.
iii) PSK : $a(n)$ and $f_i(n)$ constant while $\phi(n)$ varies with time.

To verify the performance of the system, the modulation type and parameters of a set of test signals are shown in Table 1.

TABLE I
MODULATION TYPE AND PARAMETERS OF TEST SIGNALS USED IN SIMULATIONS

Signal Name	Modulation Type	Subcarrier Freq (Hz)	Bit-rate (bits/sec)
FSK0	FSK	f_0=2125 f_1=2295	50
FSK1	FSK	f_0=2125 f_1=2295	100
FSK2	FSK	f_0=2125 f_1=2525	50
FSK3	FSK	f_0=2125 f_1=2525	100
ASK0	ASK	f_1=2000	50
ASK1	ASK	f_1=2000	100
PSK	PSK	f_1=2000	100

III. THEORY

The various analysis and classification technique relevant to this paper is described in this section.

A. Periodogram Spectrum Analysis

The periodogram power spectrum estimate [3] represents the distribution of the signal power over frequency. This frequency representation is essentially averaged over the values of the time representation at all times [4]. From the spectrum, frequency content of the signal can be estimated directly from the frequency sample value that corresponds to the peak value. It is calculated based on the frequency representation of the discrete-time waveform. The periodogram calculated for a signal $x(n)$ is as follows

$$S_{xx}(k) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi kn}{N}}\right|^2 ,\ 0 \le k \le N-1 \quad (3)$$

However, this method is unable to give the temporal characteristics of time-varying signals. To resolve this, time-varying signals can be represented in both time and frequency concurrently as TFR [5].

B. Spectrogram Time-Frequency Analysis

For an arbitrary discrete-time waveform of length N, the spectrogram TFR is calculated as follows

$$\rho_x(n,k) = \frac{1}{M}\left|\sum_{m=0}^{M-1} g(m-n)x(m)e^{-j\frac{2\pi km}{M}}\right|^2 ,0 \le n \le N-1 \quad (4)$$

where $x(n)$ is the discrete-time waveform, $g(n)$ is the window function of length M, and M is chosen to be less than N. Any one of the popular window functions such as Hamming, Hanning or Blackman can be used in the spectrogram.

The instantaneous power can be derived from the summation of the TFR over frequency which is also known as time-marginal [4].

$$P_x(n) = \sum_{k=0}^{M-1} \rho_x(n,k) \quad (5)$$

In addition, the energy spectrum is obtained from the summation over time which is known as frequency marginal.

$$S_{xx}(k) = \sum_{n=0}^{N-1} \rho_x(n,k) \quad (6)$$

Both marginal derived from the TFR are used in the system design and implementation. Although spectrogram does not actually satisfy the marginal [4], the information derived from the marginal can assist in the classification process.

C. Rule Based Classifier

This is one of the basic classification techniques where the different classes of objects are segregated based on a set of rules [6]. For this paper, the set of rules for the different class of signals are derived from the signal parameters.

IV. SYSTEM DESIGN AND IMPLEMENTATION

For a given received signal, the system as described in the flow chart in Figure 1 will perform the following set of operations: calculate the spectrogram, estimate the modulation type, estimate the IF, estimate the modulation parameters, and classify the signal using the rule based approach. Spectrogram TFR is calculated using (4).

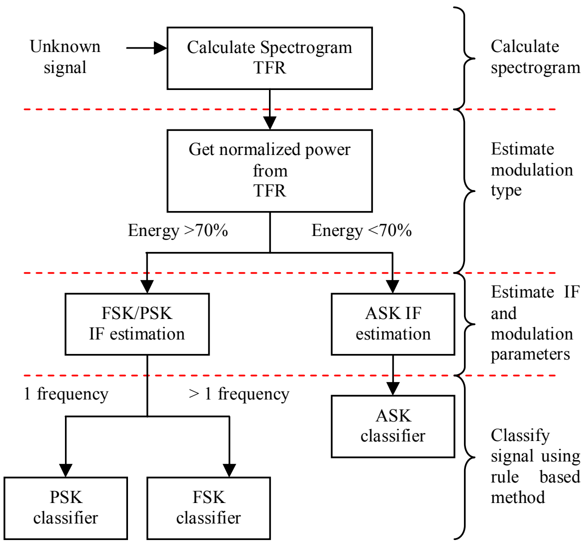

Figure 1: Flow chart of the analysis and classification system

A. Modulation Type Estimate (ASK or FSK/PSK)

The instantaneous power is calculated from the time marginal of the time-frequency representation as defined in (4). It is then normalized to the maximum value of the instantaneous frequency

$$P_{x,norm}(n) = \frac{P_x(n)}{P_{x,\max}} \tag{7}$$

The instantaneous power is summed such that

$$P_x = \frac{1}{N}\sum_{n=0}^{N-1} P_{x,norm}(n), \text{ for } P_{x,norm}(n) \geq P_{thd} \tag{8}$$

where P_{thd} is the threshold value that is obtained experimentally with a value of 0.3. The threshold is needed to differentiate a signal from noise at a given time instant. If P_x is greater than 0.7, the signal is either PSK or FSK since these signals have constant amplitude. Else, the observed signal is ASK. The value 0.7 is also obtained experimentally. Next, the instantaneous frequency will be estimated from the time-frequency representation.

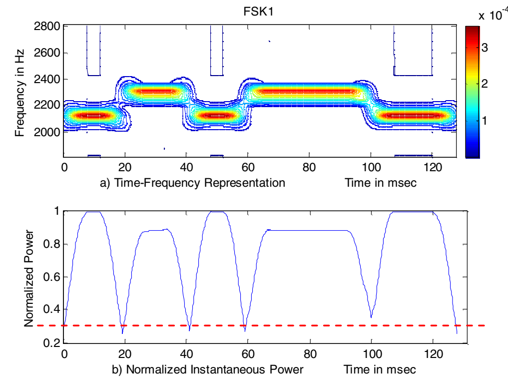

Figure 2: TFR and normalized instantaneous power of FSK1 without noise. The red line is the threshold that has been set for energy ratio calculation.

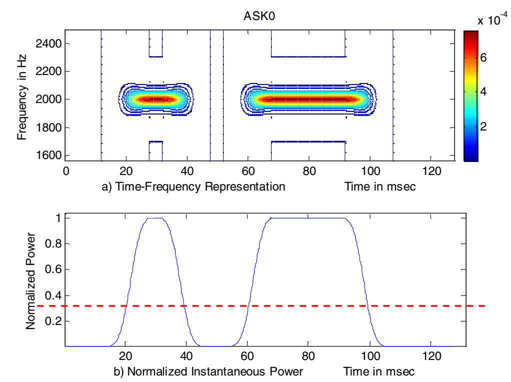

Figure 3: TFR and normalized instantaneous power of ASK0 without noise. The red line is the threshold that has been set for energy ratio calculation.

B. Instantaneous Frequency Estimation

The instantaneous frequency is estimated based on the peaks of the TFR at all time instants

$$\hat{f}_i(n) = \max_k \left[\rho_x(n,k)\right], \quad 0 \leq n \leq N-1 \tag{9}$$

Similar to the modulation estimation in the previous section, a threshold value is used to differentiate between actual signal and noise in the TFR. In order to increase its robustness in noise, a threshold for the instantaneous frequency estimation is set according to the modulation type. Similar to modulation type estimate in Section 4A, the threshold is set according to the experimental result on signals in the presence noise. Any frequency with the instantaneous power below the threshold will not be considered. The threshold of ASK signal is set as 0.3 while for FSK/PSK signals, it is set as 0.6.

The FSK and PSK signals are differentiated by checking for the frequencies that exist in the signal and plots a histogram from the IF estimate. A single frequency will indicate that the signal is PSK and FSK if more frequencies are present.

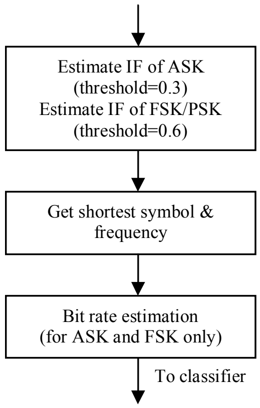

Figure 4: Flow chart of IF estimation of signals

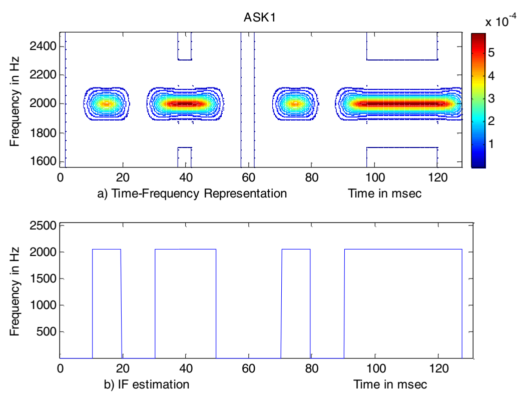

Figure 5: TFR and IF estimation of ASK1 without noise

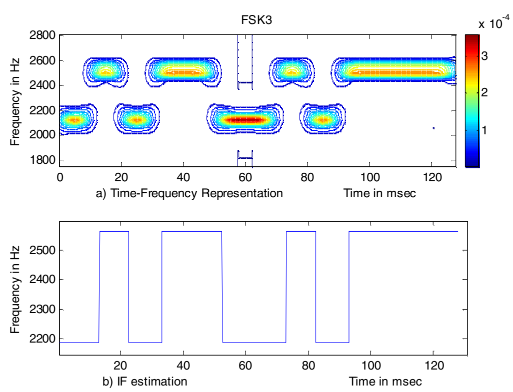

Figure 6: TFR and IF estimation of FSK3 without noise

C. *Modulation Parameters Estimate*

Once the IF estimate is obtained, the next step is to estimate the modulation parameters: subcarrier frequencies and bit-rate. The frequencies and bit-rate are obtained from the IF estimation. For bit-rate estimation, the minimum continuous duration is searched for a given frequency estimate. This duration is the estimated bit-duration and bit-rate is obtained from its inverse.

For PSK signals, bit-rate cannot be determined as this information is embedded in the phase. Spectrogram is unable to represent this information in the TFR since the TFR represents the signal power as a function of time and frequency. Alternative approaches needs to be considered for phase modulated signals.

D. *Rules Based Classifier*

The modulation type and parameters are then sent as inputs to the classifier. All the possible signal candidates are defined as rules in the classifier. If the input signal is not defined in the classifier, then the received signal is classified as unknown. However, the modulation type and parameters of the signal can be redefined for the classifier based on the estimated signal type and parameters from the instantaneous frequency.

V. RESULTS

The system is tested using the signal models in section II in the presence of additive white Gaussian noise at SNR range of 0dB to 12dB. The performance is calculated on 100 realizations of each test signal.

Table II shows the percentage of correct classification for each test signals. It is shown that the classification for all test signals is above 84% for signals at SNR $\geq$ 2dB and ASK0 has 100% correct classification for all SNR. It is observed that ASK1 and PSK have almost perfect classification as well. ASK and PSK signals have good classification because there is only one frequency in the signals. The probability of wrong classification due to the estimated frequency is half of the FSK signals. As for PSK signal, classification is done solely based on the frequency as the bit-rate cannot be determined using spectrogram. It is assumed that only three types of digital modulation signals, as discussed in section II, are received by this system.

Comparison among the FSK signals shows that signals with bit-rate 50bits/s (FSK0 and FSK2) have better performance than the ones with bit-rate 100bits/s (FSK1 and FSK3). This is because at higher bit-rate, the spectrogram has time resolution problem [4]. Due to the compromise in time and frequency [4], the spectrogram cannot estimate high bit-rate data accurately. The problem can be observed in figure 6 where there are overlapping in time from one bit to another. This results in higher estimated bit-duration. Reducing the window length is a solution but at the cost of reduced frequency resolution.

TABLE II
PERCENTAGE OF CORRECT CLASSIFICATION

SNR (dB)	FSK0	FSK1	FSK2	FSK3	ASK 0	ASK 1	PSK
12	100	100	100	100	100	100	100
10	100	100	100	100	100	100	100
8	100	100	100	100	100	100	100
6	100	100	100	100	100	100	100
4	97	97	98	98	100	100	100
2	90	87	84	91	100	99	100
0	78	48	64	76	100	94	97

VI. CONCLUSIONS

The classifier suggested in this paper is capable of classifying ASK, FSK and PSK signal correctly. It is found that the threshold SNR for correct classification is about 2dB, which is an improvement in the reduced SNR threshold from previous papers [6],[7],[8]. There is no further improvement in terms of bias and variance from [1] but the changes made in modulation differentiation of ASK and FSK/PSK signals eliminate the need threshold in that function. Besides, they reduce the probability of wrong classification due to wrong modulation type estimation. It is shown that due to the resolution limitation of spectrogram, signals with high bit-rate and/or small frequency difference between the carrier frequencies have lower performance at low SNR. The bit-rate of PSK signal cannot be estimated from the spectrogram time-frequency representation.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Agilent Foundation for supporting this research and to Universiti Teknologi Malaysia for providing the resources for this research.

REFERENCES

[1] Sha'ameri, A.Z., Tan, J. L., "Spectrogram time-frequency analysis and signal classification of digital modulation signals," *ICT-MICC 2007*, 14-17 May 2007.

[2] Cohen. L., *Time-Frequency Analysis*, Upper Saddle River, NJ: Prentice-Hall, 1995.

[3] Hong, L, Ho, KC, "Modulation classification of BPSK and QPSK Signals using a Two Element Antenna Array Receiver", IEEE Milcom 2001, 28-31 October 2001, pp 118-122.

[4] B. Boashash, Time-Frequency Signal Processing: A comprehensive Reference, Amsterdam: Elsevier, 2003.

[5] Hippenstiel, R. El-Kishky, H. Radev, P., "On time-series analysis and signal classification - part I: fractal dimensions", 38th Asilomar Conference on Signals, Systems and Computers 2004, 7-10 Nov 2004, pp 2121-2125..

[6] Rich, E, Knight, K, Artificial Intelligence, McGraw Hill, Singapore, 1991.

[7] Kadame, S, Jiang, Q, "Classifications of Modulation of Signals of Interest", 11th IEEE Digital Signal Processing Workshop 2004, 1-4 August 2004, pp 226-230.

[8] Jiang Yuan Zhang Zhao-Yang Qiu Pei-Liang, "Modulation Classification of Communication Signals", IEEE Milcom 2004, 31 Oct-3 Nov 2004, pp 1470-1476.