

Spectrogram Time-Frequency Analysis and Classification of Digital Modulation Signals

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Abstract— A non cooperative communication environment such as in the HF (High Frequency) spectrum is when the signals present are unknown in nature. This is essentially true spectrum monitoring that is an activity in spectrum management and intelligence gathering. An instrument that is used for this purpose is a spectrum surveillance system whose features are: the measurement of signal strength and carrier frequency, the location of transmitters, estimation of modulation parameters and the classifications of signals. This paper describes the design and implement a 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.

Index Terms—digital modulation signals, signal classification, spectrogram, time-frequency analysis.

I. INTRODUCTION

Communication in the HF (High Frequency) spectrum is non cooperative in nature since the communication signals are unknown in nature. Sky wave propagation allows signal to be received within and outside a country national boundaries. The spectrum is used by the aircrafts, ships, broadcasting services, amateur radio, foreign services and military for long range communications. Besides voice and telegraphy, services available today include email, telemetry, short messaging and facsimile. For regulatory organization, monitoring of the spectrum is important to ensure conformance

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to frequency planning. Spectrum monitoring for the military is part intelligence gathering.

A spectrum monitoring system is used for this purpose and its features includes the measurement of signal strength and carrier frequency, the location of transmitters, estimation of modulation parameters and the classifications of signals. The two general methods to analyze and classify digital modulation signals are the likelihood or decision-theoretic method [1][2] and the pattern recognition method [3]-[5]. The decision-theoretic method uses the likelihood function conditioned to a known candidate signals to classify an unknown signal. In the pattern recognition method, the estimated modulation parameters of the signal and are matched to its corresponding type by a classifier such as a linear discriminant function or artificial neural network. Examples of analysis methods used for estimating the modulation parameters includes fractal domain representation [3], wavelets [4] and time-frequency analysis [5]. Unlike decision theoretic approach, the exact signal form is not required and is suitable for a non cooperative environment.

This paper describes 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). The pattern recognition approach is adopted: the analysis method is the spectrogram time-frequency analysis and the classifier is the rules based method.

II. SIGNAL MODEL

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

$$y(n) = x(n) + w(n) \quad (1)$$

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 modelled as a time-varying signal

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

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 1
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	$f_i=2000$	50
ASK1	ASK	$f_i=2000$	100
PSK 1	PSK	$f_i=2000$	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 [2] represents the distribution of the signal power over frequency. From the spectrum, the 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

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

B. Spectrogram Time-Frequency Analysis

Limitation of the periodogram power spectrum estimate is it represents only the frequency content of the signal and does not give any information of its temporal characteristics. This is resolved by representing the signal jointly as a time-frequency representation [3]. For an arbitrary discrete-time waveform of

length N , the spectrogram time-frequency representation is calculated as follows

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

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.

From the time-frequency representation, the instantaneous power can be derived from the time-marginal [7].

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

In addition, the power spectrum is obtained from the frequency marginal.

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

Both marginals derived from the time-frequency representation are used in the system design and implementation.

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]. The following pseudo code describes a rule based classifier of 3 objects A, B, and C.

```
function [z]=rules_based_classifier(x,y)
if (x=xA±0.1xA) & (y=yA±0.1yA)
    z=A;
elseif (x=xB±0.1xB) & (y=yB±0.1yB)
    z=B;
elseif (x=xC±0.1xC) & (y=yC±0.1yC)
    z=C;
else
    z=unknown
end
```

IV. SYSTEM DESIGN AND IMPLEMENTATION

For a given received signal, the system will perform the following set of operations: calculate the spectrogram, estimate the modulation type, estimate the instantaneous frequency, estimate the modulation parameters, and classify the signal

using the rule based approach. The spectrogram time-frequency representation is calculated using Equation (4).

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

From the time-frequency representation, the function will get the normalized instantaneous power of the signal. Then, the function will search for the lowest magnitude in the instantaneous power estimation. If the magnitude is below 0.02, then the modulation type is ASK. This is because ASK signal has time intervals with zero magnitude. As a result, the lowest magnitude in power of ASK signals is generally lower than 2% of the peak. If the magnitude is higher than 0.02, the function will consider the signal as FSK/PSK. The threshold is set from the experimental results using signals in the presence of noise. Next, the instantaneous frequency will be estimated from the time-frequency representation. The threshold for instantaneous frequency estimate will be set according to the modulation type; either ASK or FSK/PSK. The procedure is described by the following pseudo code.

```
function [mod, threshold]=function mode type( $f_i(n)$ )

% To estimate the power from time-frequency representation
 $P_x(n)$ =power estimation( $\rho_x(n,k)$ )

% To normalized the estimated power to the peak
 $P_x(n)$ =  $P_x(n)$ /max[ $P_x(n)$ ]

[N,M]=size( $\rho_x(n,k)$ )

for n=0:N-1
    if min[ $P_x(n)$ ]<0.02
        mod=ASK
        go to ASK instantaneous frequency estimate

    else mod=FSK/PSK
        go to FSK/PSK instantaneous frequency estimate
    end
end
```

B. Instantaneous Frequency Estimation

From the time-frequency representation $\rho_x(n,k)$, the instantaneous frequency is estimated from the frequency based on the peaks in the time-frequency plane evaluated for all time instants. 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. For ASK signal, the threshold is set to 0.3. The procedure is described by the following pseudo code.

```
function [ $f_i(n)$ ]=function ASK IF estimate( $\rho_x(n,k)$ )
```

```
[N,M]=size( $\rho_x(n,k)$ )
```

```
% Search for the peak values for all time
for n=0:N-1
     $f_i(n)$ =max[ $\rho_x(n,k)$ ]

    if max[ $\rho_x(n,k)$ ]< 0.3
         $f_i(n)$ =  $f_i(n-1)$ 
    end
end
```

For FSK/PSK signal, the threshold is set to 0.6. From the IF estimate, the function will check for the frequencies that exist in the signal. The function will check from the frequency histogram if there is a single or multiple frequencies present. A signal frequency will indicate that the signal is PSK and FSK if more frequencies are present. The procedure is described by the following pseudo code.

```
function [ $f_i(n)$ ]=function FSK/PSK IF estimate( $\rho_x(n,k)$ )
```

```
[N,M]=size( $\rho_x(n,k)$ )
```

```
% Search for the peak values for all time
for n=0:N-1
     $f_i(n)$ =max[ $\rho_x(n,k)$ ]

    if max[ $\rho_x(n,k)$ ]< 0.6
         $f_i(n)$ =  $f_i(n-1)$ 
    end
end
```

```
[freq]=frequencies in time-frequency representation
```

```
[A]=size(freq)
```

```
if A=1
    mod=PSK
else
    mod=FSK
end
```

C. Modulation Parameters Estimate

Once the modulation type is determined, the next step is to estimate the frequency content and bit-rate. The procedure for estimating the frequency content is similar to the first part of the modulation type estimate that was described in the pseudo code in Section 4A. The last part is ignored since the modulation type is already known.

The bit-rate is estimated from the bit duration since the relationship is the inverse of each other. The function begins with the search for the minimum continuous duration for a given frequency estimate. Once obtained, this is the estimated

bit-duration. The pseudo code to estimate the bit-rate is as follows.

```
function [bit-rate]=function bit-rate estimate(f(n))

for n=0:N-1
    [nd]=continuous duration estimate(f(n))
end

Tb=min(nd); % bit-duration is the minimum continuous duration
Bit-rate=1/Tb; % bit-rate is the inverse of the bit-duration
```

D. Rules Based Classifier

The modulation type and parameters are input 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 defined for the classifier based on the estimated signal type and parameters from the instantaneous frequency. The following pseudo code demonstrates the function of the classifier.

```
function rule based classifier(mod type, mod param)

if mod type=ASK % Classify signal as ASK

    if mod param=mod param 0
        signal=ASK0
    else if mod param=mod param 1
        signal=ASK 1
    else
        signal=unknown ASK
    end

else if mod type=FSK % Classify signal as FSK

    if mod param=mod param 0
        signal=FSK0
    else if mod param=mod param 1
        signal=FSK1
    else if mod param=mod param 2
        signal=FSK2
    else if mod param=mod param 3
        signal=FSK3
    else
        signal=unknown FSK
    end

else % Classify signal as PSK

    if mod param=mod param 1
        signal=PSK1
```

```
else
    signal=unknown PSK
end
end
```

V. RESULTS

The results will initially discuss on the signal classification followed by bias in the bit-rate and frequency estimation. The performance of the classifier is evaluated using test signals at SNR range of 0dB to 12dB. The performance is calculated on 100 realizations of each test signal. Table II and figure 1 shows the percentage of correct classification for each test signals. It is shown that the classification for all test signals is above 80% for signals at SNR ≥ 2dB and ASK0 has 100% correct classification for all SNR. It is observed that ASK1 and PSK have almost perfect classification as well.

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 [7]. Due to the compromise in time and frequency [7], the spectrogram cannot estimate high bit-rate data accurately. Reducing the window length is a solution but at the cost of reduced frequency resolution. The problem can be observed in figure 2.

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	99
6	100	99	100	100	100	100	100
4	98	97	100	95	100	100	100
2	92	82	94	84	100	99	99
0	75	49	62	55	100	97	97

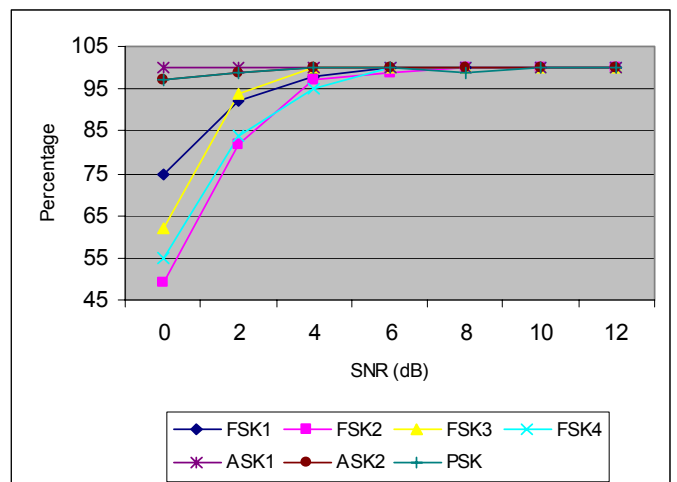


Figure 1. Percentage of correct classification vs SNR

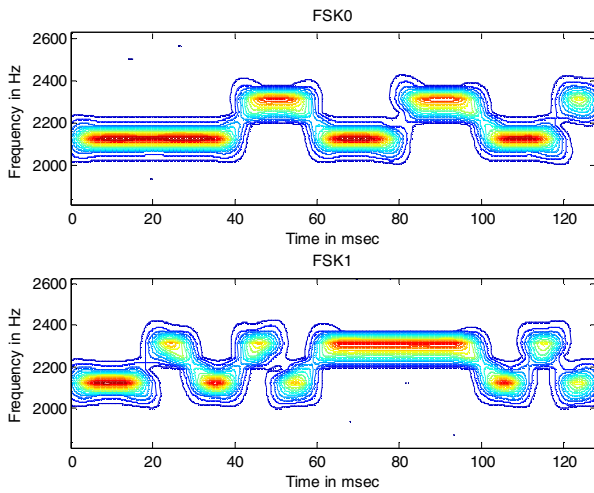


Figure 2: Time-Frequency representation of FSK0 and FSK1 at SNR=12dB

Table III shows the bias in bit-rate estimation for the test signals used. Ideally, the bias should be as low as possible. Results for PSK are not presented in the table because spectrogram time-frequency representation does not show phase changes. It is observed that the bias in bit-rate increases as the noise level increases. This is because at low SNR, the bit-rate cannot be estimated accurately.

TABLE III
BIAS IN BIT-RATE ESTIMATION OF VARIOUS SIGNALS USED

SNR (dB)	FSK0	FSK1	FSK2	FSK3	ASK0	ASK1
12	6.953	15.19	1.916	6.963	2.415	8.973
10	6.938	15.34	2.045	7.317	2.553	9.134
8	6.961	14.65	2.123	8.317	2.647	9.659
6	7.310	13.76	2.527	9.499	2.877	10.09
4	8.015	13.34	3.336	9.633	3.070	11.09
2	11.33	18.60	7.918	12.89	3.215	11.35
0	16.79	25.66	18.98	19.66	3.738	11.29

Next, comparison is made between FSK signals with smaller frequency difference between the subcarrier frequencies (FSK0 and FSK1) and with the ones with bigger frequency difference (FSK2 and FSK3). It shows that the performance of the latter is better than the former. It is shown that the percentage of correct classification is higher and the bias in bit-rate estimation is lower. This is because at smaller frequency difference, there are overlaps between the bits with different carrier frequencies. It is observed in figure 3 where the comparison between FSK1 and FSK3 is done in terms of the time-frequency representation. The FSK1 has overlaps between the bit '0' and bit '1'. At low SNR, these overlaps cause error in the IF estimate that consecutively contributes to the error in bit-rate estimation. Thus it is observed that the classifier is worse for FSK with smaller frequency difference.

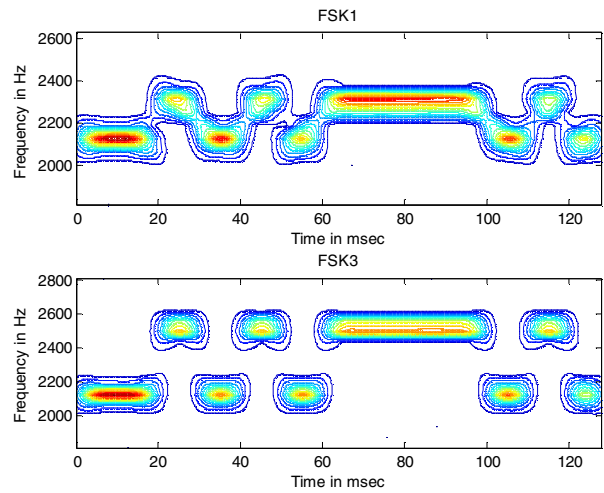


Figure 3: Time-Frequency representation for FSK1 and FSK3 at SNR=12dB

Next, the bias in frequency estimation is compared among all the test signals used. It is shown in Table IV that all the signals have almost the same bias in frequency estimation. Thus, the bias in frequency estimation does not affect the performance of the classifier. In general, the bias increase for all signals as the SNR reduced.

TABLE IV
BIAS IN FREQUENCY ESTIMATION OF VARIOUS SIGNALS USED

SNR (dB)	FSK0	FSK1	FSK2	FSK3	ASK 0	ASK 1	PSK
12	62.50	62.50	62.50	62.50	62.50	62.50	62.50
10	62.50	62.50	62.50	62.50	62.50	62.50	62.50
8	62.50	62.50	62.50	62.50	62.50	62.50	63.13
6	62.50	62.50	62.50	62.50	62.50	62.50	62.50
4	63.75	63.75	62.50	65.00	62.50	62.50	62.50
2	65.00	73.75	65.00	75.00	62.50	62.50	63.13
0	81.25	83.75	77.50	86.25	62.50	62.50	64.38

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 [1],[3],[4]. 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.

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