# A New Time-Frequency Spectrogram Analysis of FH Signals by Image Enhancement and Mathematical Morphology

Xu Mankun[1], Ping Xijian[1], Li Tianyun[1], Xu Mantian[2]
[1]*Dept. of Information Science, Zhengzhou Information Science and Technology Institute, HeNan, China, 450002*
[2]*Institute of Electronic Science and Engineering, JiLin University, JiLin, China, 130012*
*maggiexmk@163.com*

## Abstract

*A new method is proposed to extract the parameters of frequency hopping (FH) signals. After short-time Fourier transform (STFT), the time-frequency spectrogram of FH signals is treated as a kind of digital image with special contents. The spectrogram analysis is investigated to detect and extract FH parameters by useful image enhancement techniques and mathematical morphology. First, the spectrogram image is enhanced by contrast stretch and binarization. Then, morphological closing and opening cascaded operations are manipulated using rectangular structure elements horizontally and vertically. After morphological image processing, the spectrogram edges are extracted by boundary tracking and extraction. Finally, the important FH parameters, such as hopping carrier frequency, hop timing and hop rate can be estimated, which lay the foundations for later finer hopping frequency location. The experimental results and analysis on the short-wave FH signals show the good performance of the proposed method.*

## 1. Introduction

Frequency hopping (FH) is a kind of spread spectrum communications. Since the middle 20$^{th}$ century, it has become one of the most widely used and effective technologies in military anti-jamming and anti-interception applications because of its low probability of interception, good capability against interference, good ability against fading channel, and facility in networking[1].

To analyze FH signals, including research on FH signal detection, interception, parameter estimation, network classification, de-hopping and demodulation, is hard and hot in signal analysis at present. Especially, it is most difficult to analyze the FH signals in complex short-wave channels.

In recent years, the time-frequency analysis[1,3] is commonly used in FH signal analysis with wide-band sampling, such as short-time Fourier transform (STFT), wavelet transform and Wigner distribution. In the above methods, the STFT has advantages in computational complexity and ability against noise jamming.

In the practical applications of FH signals' parameter estimation, the characteristics of FH signals in the time-frequency spectrogram are too weak to be contaminated by background noise and powerful interference (see Fig.1). To solve this problem, we notice that the time-frequency spectrogram has some similarity to images in vision and matrix forms representation, and so treat them as a kind of image with special contents.

To estimate the FH signals' parameters, we consider both the spectrogram's visual characteristics and the advantages of mathematical morphology in processing images with special shapes, and provide a new method based on image enhancement and mathematical morphology.

In section 1, we introduce FH signals' general conceptions and methods. In section 2, we discuss the STFT technology to acquire the needed time-frequency spectrogram. Section 3 is the most important part. In it, the useful image processing enhancement techniques are introduced and analyzed in detail. First, the characteristics of FH signals are strengthened by image contrast stretch and binarization. Then, we apply morphological closing and opening cascaded operations with rectangular structure elements to wipe off noise and interference. Finally, the spectrogram edges are extracted by boundary extraction. So, the important FH parameters can be estimated, such as hopping carrier frequency, hop timing and hop rate,

0-7695-2929-1/07 $25.00 © 2007 IEEE
DOI 10.1109/ICIG.2007.154

which lay the foundations for later finer hopping frequency location.

## 2. STFT sprectrogram of FH signals

STFT[4,5] is straightforward in describing signals' time-frequency distribution, and is widely used in non-stationary signal analysis. It partitions signals into several segments of short-time signals by shifting the time window. Then, it computes the DFT of these segments to get each local frequency spectrum. In this way, the total of every short-time spectrum construct the signal spectrogram when time varies.

To compute the FH signals' spectrogram in practice, we adopt a generalized STFT method. The general STFT of signals $s(n)$ is defined as Eq. (1).

$$S(m,k)=\sum_{n=0}^{N-1}s(n+mN')w(n)e^{-j\frac{2\pi}{N}nk},\quad k=0,1,...,N-1 \quad (1)$$

Where $S(m, k)$ denotes the $m$-index time-frequency spectrogram. $N$ represents the time window's width. $N'$ denotes the shifting step of the time window, and is an integer larger than 0. $w(n)$ represents an $N$-point sequence. In this paper, $N$ is set as an integer power of 2 to utilize FFT well. $w(n)$ is usually used as a rectangular time window. When $N'<N$, there is overlapping between time windows of STFT. While when $N'>N$, this overlapping is negative, that is to say, some data between adjacent time windows are discarded. This point is very important in analyzing the FH signals with a low hop rate.

The spectrogram is defined as the magnitude of $S(m, k)$, which is denoted as $A(m, k)$.

$$A(m,k)=\frac{1}{N}\left|S(m,k)\right|^2 \quad (2)$$

When we use STFT in time-frequency analysis, there always exist contradictions in selection of time resolution and frequency resolution, which is determined by uncertainty theory[5]. Narrow time window causes the high time resolution and the low frequency resolution, and vice versa. In practical applications, we should make a compromise with time and frequency resolutions by choosing appropriate $N$ and $N'$.

In computing the STFT spectrogram of FH signals, the selection of $N$ and $N'$ need careful consideration according to FH parameters, especially the hop rate and FH bandwidth. So, we determine the sampling rate by FH signals' bandwidth at first, and then get each FH signal's sampling points by its hop rate. The time window $N$ is flexibly chosen by the needed frequency resolution and the computational complexity. $N$ decides the FH signal's "thickness" in the spectrogram, that is, how many pixels each signal has along the frequency axis in spectrogram. While the shifting step $N'$ decides each signal's "length" in spectrogram, that is, how many pixels each signal has along the time axis.

## 3. Image processing and analysis on FH signals' spectrogram

In the range of FH signals' bandwidth there exists very high and complex background noise jamming of the actual short-wave FH signals, such as the powerful communication signals with constant carrier frequency. The constant frequency behaves as a kind of severe noise jamming in the spectrogram, and interferes the actual signals to cause false judge. So, a technical difficulty is brought, how to remove the background noise while preserving origin shapes of FH signals in the spectrogram? Because of the complexity of disturbance, it is impossible to wipe off all of them. Also, the FH signals' boundaries in the spectrogram will appear partly disjoined after image processing. All the above problems bring a hard and hot nut to FH signals' parameter estimation. To knock out this nut, we utilize the signals' shape characteristics and propose a countermeasure, which is in Fig.1. The detailed processes are discussed in the following steps from 3.1 to 3.6.

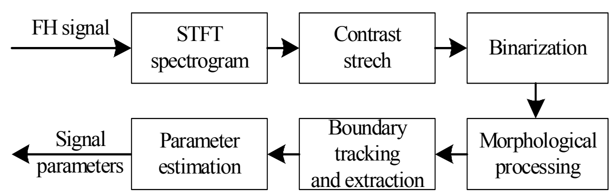


Fig.1. Image processing flow of FH signals' parameter estimation

### 3.1. STFT spectrogram

To show the performance of our method, we select a segment of short-wave FH signals with powerful noise jamming. We use STFT first to get the time-frequency spectrogram of this segment signals, with $N$ set as 1024 and $N'$ set as 2048. The STFT spectrogram is in Fig.2.

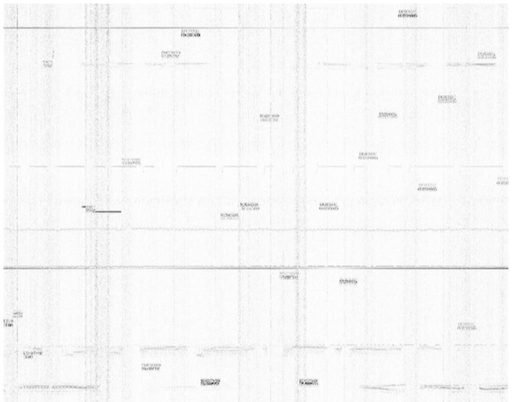

Fig.2. Short-wave FH signals' spectrogram

### 3.2. Spectrogram contrast strech

Contrast is defined as the ratio of maximum grayscale to the minimum grayscale of an image. The higher the contrast is, the larger the dynamic grayscale range is. Contrast enhancement is one way to enhance an image, often used in strengthening some special image contents or characteristics. The spectrogram image is defined as a notation $A(x, y)$, in it $x$=1,2,…,$L_1$ and $y$=1,2,…,$L_2$, where $L_1$ and $L_2$ denote image width and height, and $A(x, y)$ represents the gray value at point $(x, y)$. We apply image contrast strech on the spectrogram to weaken the noise and enhance the FH signals' power at the same time. The effective result can be seen in Fig.3.

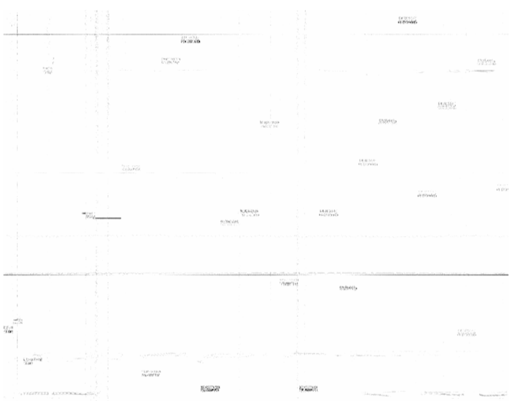

Fig.3. Spectrogram contrast strech

### 3.3. Spectrogram binalization

A binary image is an image with only two gray levels, and so, the lightness and darkness are very easy to be classified. Also binary image has a straightforward merit in convenience of manipulations with low computational complexity. In this way, we apply binarization operation on the gray spectrogram image with only two gray levels to decrease the noise power and reduce computations of the following processing. The binary image is shown in Fig.4.

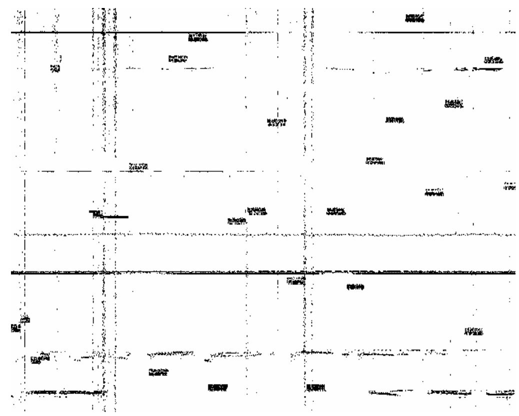

Fig.4. Spectrogram binalization

### 3.4. Morphological image processing

Though the noise in spectrogram image can be removed to a large degree with step 3.2 and step 3.3, there has still some certain background noise hard to be removed clearly, when it's intensity is similar to signals'. So, further noise reduction techniques are needed. Reference to the rectangular shape of FH signals, we apply mathematical morphology to filter the binary image.

Mathematical morphology is successful in processing a binary image with special shapes, especially where the structure of noise differs from the signal's[7,8]. We notice that in the spectrogram of FH signals, the structure of signal and noise are significantly different. So, the rectangular structure element is chosen to run morphological closing and opening cascaded operations. First, horizontal rectangular structure element is used to run closing and opening operations one time, the purpose of which is to remove horizontal noise. Good effects of this manipulation can be seen in Fig.5 and Fig.6. The reason to choose closing operation first and then the opening is for the continuity of signals. But a possible adverse effect could be brought meanwhile, that is signals may be connected to noise. To avoid this adverse circumstance, appropriate structure elements should be chosen. On the basis of horizontal morphological image processing, the vertical rectangular structure element is used to close and open spectrogram image, wiping off vertical noises. This effect is shown in Fig.7. Theoretically, closing and opening cascaded operations can be applied many times, but here, only one time of vertical operation is enough. In our pre-carried experiments, there has no more difference with vertical closing and opening many times.

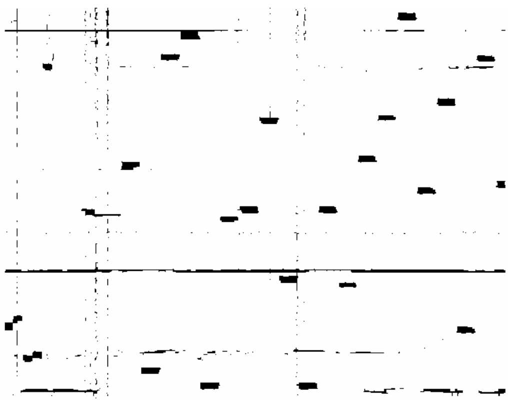

Fig.5. Spectrogram by horizontal closing operation

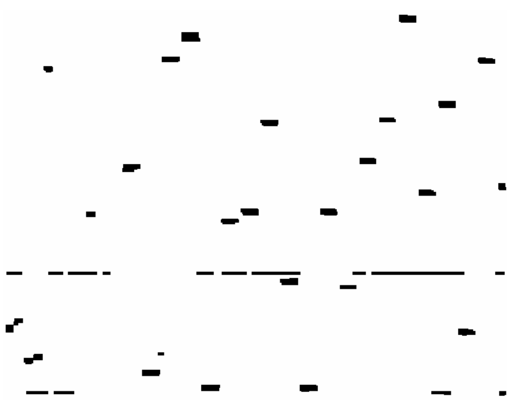

Fig.6. Spectrogram by horizontal opening operation

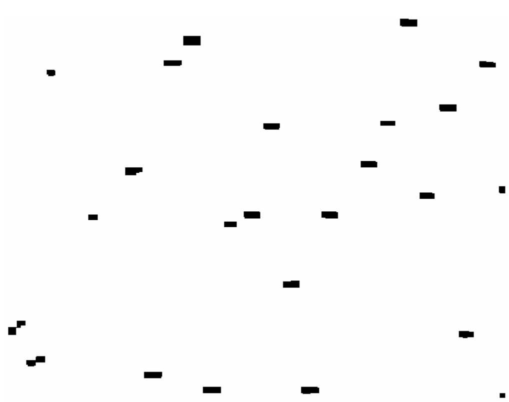

Fig.7. Spectrogram by vertical closing operation

### 3.5. Boundary tracking and extraction

For the convenience of extracting signals' parameters, we use boundary tracking and extraction operations after step 3.4 to simplify the following process. The edges of each FH signal behaves like closed blocks, which can be seen in Fig.8.

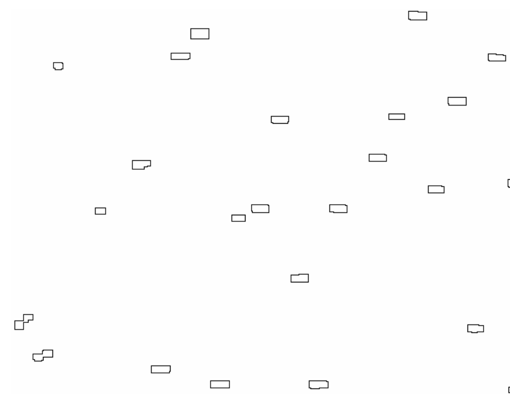

Fig.8. spectrogram by boundary tracking and extraction

### 3.6. Parameter extraction

The above steps 3.1 to 3.5 lower the noise and strengthen the signals, but will also bring distortion inevitably at the same time, causing certain errors in extracting parameters. For examples, it is known that each FH signal is exclusive at one time, but in Fig.8 we can see that there has overlapping in the furthest right two blocks. Compared with the original signals, the lowest one is noise in fact. When the noise is similar to signals not only in shape and size but also in power, to remove it will be very hard. Also, in Fig.8, the furthest left block is very irregular, because it is distorted severely by noise jamming (see Fig.2). All of these adverse factors make the practical parameter extraction difficult. In our work, every vertical length of signal blocks is estimated and averaged as hopping carrier frequency, each horizontal length corresponds to the FH signal's lasting time, and the hop timing is the value in time axis when each signal ends.

## 4. Results and analysis

Author names and affiliations are to be centered beneath the title and printed in Times 12-point, non-boldface type. Multiple authors may be shown in a two- or three-column format, with their affiliations italicized and centered below their respective names. Include e-mail addresses if possible. Author information should be followed by two 12-point blank lines.

### 4.1. Extraction results

We set the spectrogram' left and upper point as the beginning point (0,0). The horizontal direction is time axis x, and the vertical one is frequency axis y. In the order of FH signals' hopping carrier frequency (x, y), lasting time and hop timing, the parameter extraction is carried out on closed signal blocks in Fig.8. In original spectrogram (see Fig.2), there appear 24 FH signals all together, where the 24th signal does not appear entirely. Our method detects 23 signals and the parameters are listed in table 1.

Table 1. Estimation results of FH signals' parameter extraction

| parameters / indexed signals | hop frequency | lasting time | hop timing |
|---|---|---|---|
| 1 | （6，398） | 24 | 29 |
| 2 | （29，441） | 26 | 54 |
| 3 | （55，74） | **13** | **67** |
| 4 | （108，258 | **14** | **121** |
| 5 | （155，199 | 24 | 178 |
| 6 | （179，458 | 25 | 203 |
| 7 | （204，62） | 25 | 228 |
| 8 | （229，33） | 24 | 252 |
| 9 | （254，477 | 25 | 278 |
| 10 | （281，267 | 18 | 298 |
| 11 | （306，255 | 23 | 328 |
| 12 | （331，142 | 23 | 353 |
| 13 | （356，343 | 23 | 378 |
| 14 | （379，478 | 25 | 403 |
| 15 | （405，255 | 23 | 427 |
| 16（lost） | — | — | — |
| 17 | （455，190 | 23 | 477 |
| 18 | （480，138 | 21 | 500 |
| 19 | （505，10） | 24 | 528 |
| 20 | （530，230 | 21 | 550 |
| 21 | （555，119 | 24 | 578 |
| 22 | （580，407 | 21 | 600 |
| 23 | （606，63） | 23 | 628 |
| 24 | （631，223 | **10** | **640** |

### 4.2. Result analysis

In Fig.2, each FH signal lasts about 24 pixels in time axis. Most of the extracted parameters in table 1 in our method tally with original signals. By the influence of noise jamming and noise-reduction processing, there are 3 signals' lasting time obviously smaller than the average one, which affect the corresponding hop timing. These signal parameters are marked with bold typeface. To analyze the abnormal results, the 3rd signal is shorter than average block in itself by noise jamming, and can be only extracted with smaller block. Likewise, the 4th signal is distorted, second half of which is something like constant frequency, and so is removed by morphological processing (see Fig.5 and Fig.6). By comparison with the average and most normal values, these errors can be corrected as 23, and their hop timing will be corrected correspondingly. We notice that in table 1, the 16th signal is lost (marked in the circle of Fig.9). It is removed by vertical close and open operations because its bandwidth is smaller than the rectangular element in the spectrogram (see Fig.7). In this condition, it can be modified by adjusting structure elements' size.

Fig.9. spectrogram with lost signal

Anyway, in such bad conditions of complex and powerful noise jamming, experimental results in table 1 show good performance of our method. When the noise jamming is not severe and signals are clear, our method will perform better.

## 5. Conclusions and future work

From the above experimental results and analysis, it can be seen that the proposed method can extract FH hopping parameters effectively. It can eliminate the complex interference of short-wave channels, including constant frequency signals' jamming of broadcasting radios, atmospherics, noise of ionosphere sudden changing, etc, while these adverse conditions are very hard to deal with by common communications means. Also, the STFT time-frequency analysis, image enhancement processing, and binary morphological processing are easy to be implemented with low computational complexity, so the proposed method can process real-time FH signals at high wide-band sampling rate.

As for the errors in experimental results, we could correct them with the common sense that each FH signal lasts the same time. Further, we will employ finer spectrogram analysis to achieve more accurate parameter estimation based on the experimental results.

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