Identification of Frequency Hopping Communications

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Identification of Frequency Hopping Communications

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Abstract: - A method to detect and characterize a frequency hopping (FH) signal is proposed. The context is Spectrum Surveillance. Hence, no a priori information is available: the parameters of the modulation must be automatically determined. Spread spectrum (SS) modulations are well-known for their low probability of interception (LPI). Nevertheless the aim of this paper is to show that, using a time–frequency representation and ad-hoc eigenanalysis techniques, it is possible to characterize such signal, even in realistic conditions (low SNR). Once characterized, the signal can be demodulated. Many tools are used for this characterization, in particular a precise definition of characteristic parameters and mathematical methods, such as data compression, 3D rotations and principal components analysis (PCA).

Key-Words: - **Digital Communications, Spread Spectrum, Frequency Hopping, Spectrogram, Image Processing, Eigenanalysis Techniques, Identification.**

1 Introduction

Restricted for a long time to the military domain, spread spectrum techniques are now used in more and more non-military applications. They are also proposed as basic techniques for many future digital communication systems. Their noise and echo robustness, as well as their low probability of interception, are interesting for wireless local area networks (WLANs), mobile communications and multiple access systems (cf. [1] and [2]). There are several spread spectrum techniques, the most widely used being direct sequence (DS) and frequency hopping (FH).

Direct sequence techniques use a pseudonoise (PN) sequence which is multiplied by the information signal to directly spread it. As far as FH is concerned, the available channel bandwidth is divided into a large number of contiguous frequency slots, and among them one is chosen for the transmission in any signaling interval. The choice is done by a pseudo-random code. It is such signal we try to detect and characterize in this paper. One originality of the proposed method is to use image processing.

First, we describe what is a FH signal exactly, and how this kind of spread spectrum modulation is produced (Section 2). We also examine the spectrogram (the time-frequency representation) of a FH signal. This particular representation allows an easy view of the different frequency hops, when noise is not too large.

The remainder of the paper is organized as follows. In Section 3 we define precisely the FH parameters, and we show them on the spectrogram. Then, Section 4 shows how to estimate the sequence duration using the autocorrelation of the time-frequency image. Since the image is often very large, we need to reduce it to find the other parameters. This compression and its consequences are explained in Section 5. In Section 6 eigenanalysis techniques, rotations, and model-based sequential search are used to identify the parameters. Our main conclusions are summarized in section 7.

2 FH modulation

The FH modulations are rather simple to produce, and difficult to demodulate. They can be obtained by a frequency synthesizer or by the multiplication of two modulations (at least one Frequency Shift Keying, used for the spreading). As mentioned in the introduction, the principle of FH is based on a division of the available channel bandwidth into many contiguous subchannels. Each subchannel has the same bandwidth, and they are all distributed around a central frequency or carrier frequency. The signal is transmitted at one frequency during a period T_f, then at another frequency during the same period, and so on. The frequencies used are determined by a pseudo-random sequence. These abrupt changes of frequency are called frequency hops.

The only way to see the frequency hops is to use a time-frequency representation (cf. [3]). In our application, we use the spectrogram (fig. 1). For this illustration, we used a simple modulation : only 4 frequencies used, and a PN sequence of length 7. This allows us to see several sequences in the same figure.

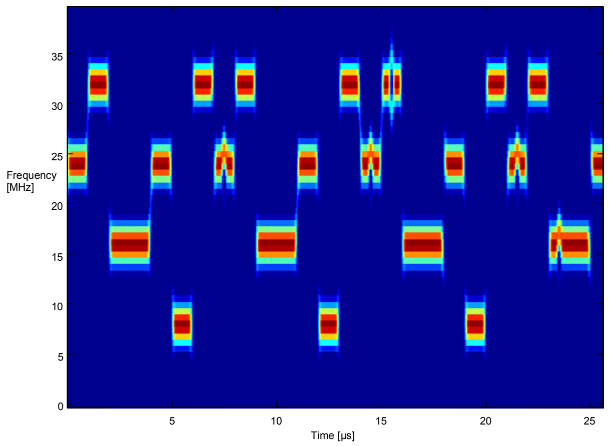

Figure 1: Spectrogram (SNR=10dB)

If a FH signal is simple to modulate, its demodulation is more difficult, especially because the synchronization is not obvious. Usually, the synchronization is divided into two phases: the acquisition phase, and the tracking phase (cf. [4] and [5]).
In the context of spectrum surveillance, the FH signal must be detected and characterized prior to any demodulation tentative.

3 Parameters definition

Thanks to the time-frequency representation, the FH modulation can be represented by several parameters, as shown on figure 2:

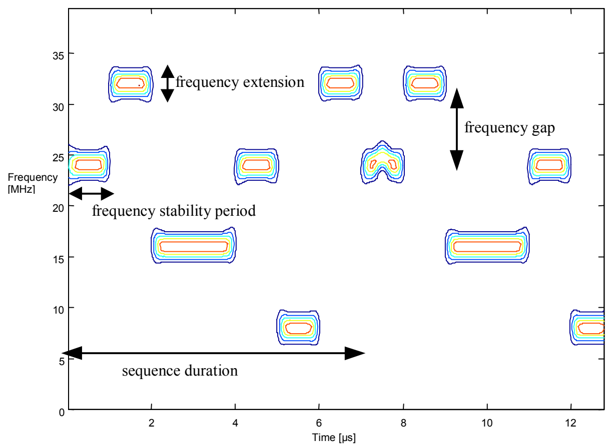

Figure 2: Parameters definition

3.1 Frequency stability period

The frequency stability period, T_f, is the minimal time for the transmission at one frequency (it corresponds to the symbol period used for spreading).

3.2 Sequence duration

A FH modulation is also characterized by the spreading sequence duration D_s. This duration always depends of T_f, but in our application it depends also of the PN sequence length l.
Thus, we can write :

$$D_s = \frac{l * T_f}{n} \qquad (1)$$

with n the power of 2 in the definition of the number M of different symbols used in the spreading modulation: $M = 2^n$.
The number of frequency stages is then defined by :

$$N_s = \frac{D_s}{T_f} \qquad (2)$$

3.3 Symbol period

The symbol period T_s is the symbol period of the data signal (usually, a PSK or FSK modulation is used).
Here, we assume a slow frequency hopping (SFH), i.e. the frequency stability period is larger than the symbol period ($T_f > T_s$). This is the most frequent case. Thus, we can transmit several data symbols for each frequency stage.
The inverse case ($T_f < T_s$) is called fast frequency hopping (FFH).

3.4 Transmission Frequencies

No information is known about frequencies used for the transmission. We must find them automatically, using intermediate parameters, which are :
- The number of transmission frequencies (for a spreading modulation M-FSK, this number is M).
- The central frequency or carrier frequency f_0 of the signal.
- The frequency gap Δf between two adjacent frequencies.
- The frequency extension *ext*, which corresponds to frequency bandwidth around a transmission frequency.

Once we have obtained the above parameters, we are able to provide exactly the spreading sequence used and even to define the modulation type used for data symbols (ex : QPSK,…), and finally demodulate the signal.

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4 Whole image processing: Estimation of the spreading sequence duration

To find the spreading sequence duration, the proposed method consists in calculating the autocorrelation of the whole image. We can clearly observe peaks each time two sequences are superposed and, of course, a maximal peak when the whole image is superposed to itself. The sequence duration is then obtained by calculating the gap between two peaks (they are regularly spaced), and by dividing this gap by the sampling frequency. Figure 3 shows that this method is robust with respect to noise. Even with a negative Signal to Noise Ratio (SNR = -5 dB), we can find the spreading sequence duration.

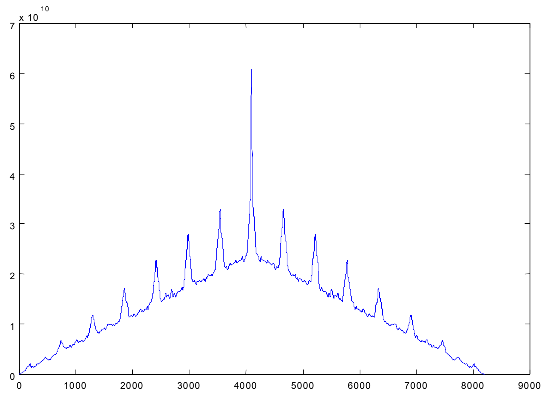

Figure 3: Image autocorrelation (SNR=-5dB)

To avoid edge effects and to obtain better precision, the image to process must be rather large, but the processing becomes quickly costly in calculation time.

5 Image compression

The spreading sequence can be very long. Thus it is necessary to reduce the image before processing it, because at least two whole sequences are required to obtain the characteristic parameters. To compress the image, we propose to project it in a new orthogonal functions base, for example cosine functions.

A matrix Φ, built with cosine functions, is used to transform the original image into its representation in this new base. The matrix entry at row n and column i is :

$$\phi_n(i) = \cos\left(n\pi \frac{2i+1}{2N_e+2} \right) \qquad (3)$$

with $1 \le i \le N_e$ where N_e is the number of columns of the image, and $1 \le n \le N$ where N is its number of rows.

The image in the cosine functions base is represented by a matrix, noted C, the size of which is N*N. This size is considerably smaller than the original size, because usually $N_e >> N$. To reconstruct the image, we only have to perform the computation below:

$$\begin{bmatrix} \vec{l_1}^T \\ \vdots \\ \vec{l_N}^T \end{bmatrix} = \begin{bmatrix} c_{1,1} & \cdots & c_{1,N} \\ \vdots & \ddots & \vdots \\ c_{N,1} & \cdots & c_{N,N} \end{bmatrix} * \begin{bmatrix} \vec{\phi_1}^T \\ \vdots \\ \vec{\phi_N}^T \end{bmatrix} \qquad (4)$$

reconstructed image = *C* * *transform matrix*

The expression of a reconstructed row of the image is:

$$\begin{aligned} \vec{l_1}^T &= c_{1,1}\vec{\phi_1}^T + \ldots + c_{1,N}\vec{\phi_N}^T \\ \vec{l_1} &= c_{1,1}\vec{\phi_1} + \ldots + c_{1,N}\vec{\phi_N} \end{aligned} \qquad (5)$$

Thus the ith row of C contains the components of the ith row of the reconstructed image in the new base.

The image in the new base C is representative of the original image, and the loss of information due to the compression is very low (fig. 4)

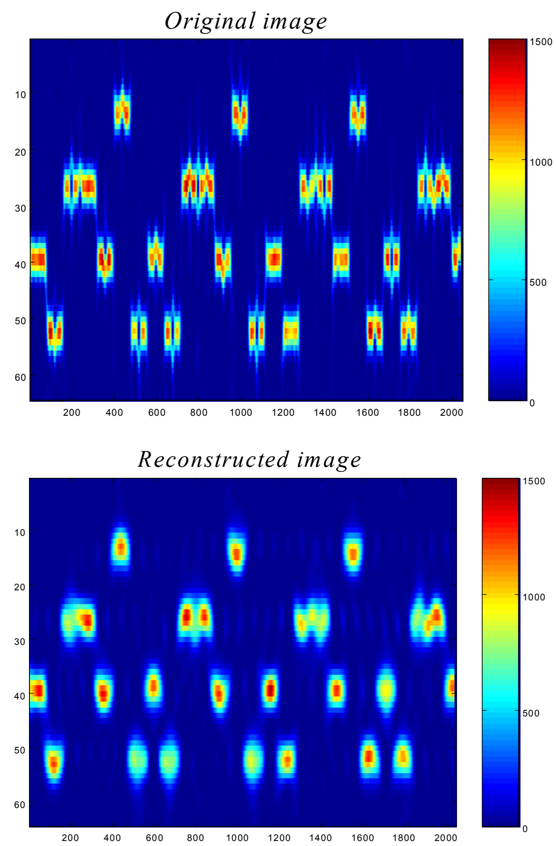

Figure 4: Original and reconstructed images

This compression method consists in suppressing the highest image frequencies. When we look at C (fig. 5), we can see that the main energy is at the left of the image, where the low frequencies are located. This explains the low loss of information.

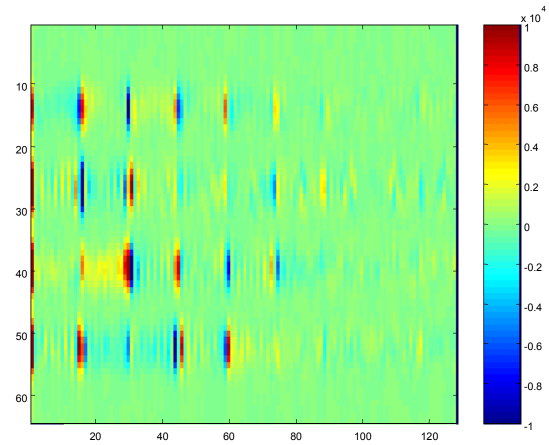

Figure 5: Representation of C

6 Determination of the parameters

Eigenanalysis techniques are useful to determine the principal directions in a large set of vectors. In the sequel, we show that, combined with other techniques, they are of great help for determination of the FH parameters.

6.1 Rows analysis

As far as the noise is weak, the frequency stability period is clearly visible on a time frequency representation, and its value could be determined by a human operator. Nevertheless he could not obtain a precise value. Furthermore, as soon as the noise becomes important, this approach does not work any more. For example, on figure 6 we show the spectrogram of the same transmitter as in §2, but with SNR=-5dB.

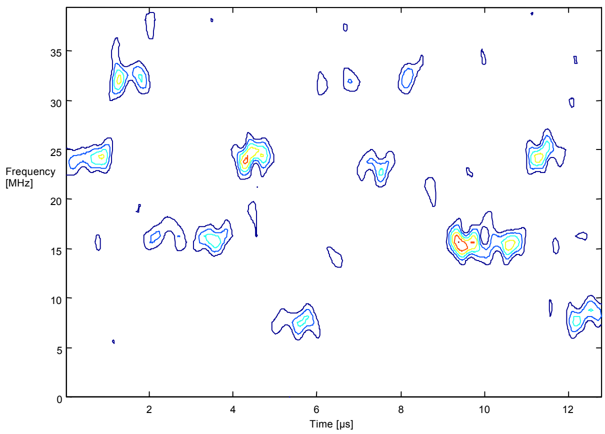

Figure 6: Spectrogram with SNR=-5dB

The method we developed consists in calculating the autocorrelation matrix of the rows of matrix C. We can observe the eigenvalues of the autocorrelation matrix $R_l = C^T C$ on figure 7.

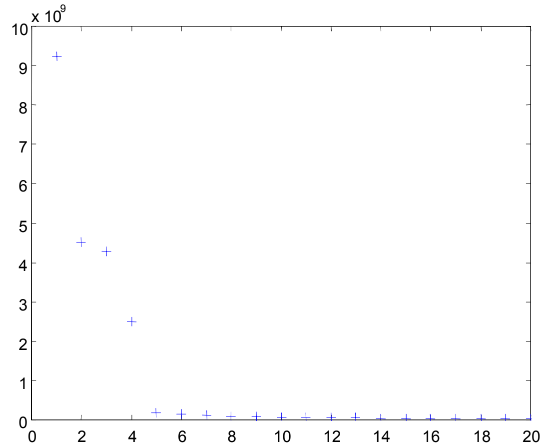

Figure 7: Rows analysis eigenvalues (20 first ones)

Four large eigenvalues, each one corresponding to one of the transmission frequencies, are clearly observed. The corresponding eigenvectors are transformed back to the initial domain using matrix Φ. The result is shown on figure 8.

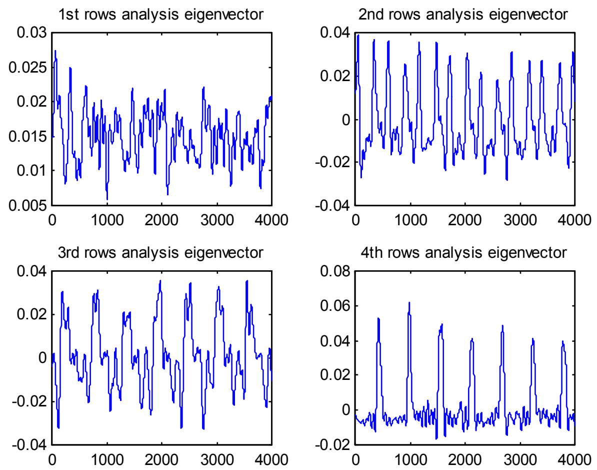

Figure 8: Rows analysis eigenvectors

Each vector represents the temporal sequence of one of the transmission frequencies or is a linear combination of two or more sequences. Hence, in order to remove linear combinations, we must rotate the set of vectors until a criteria is minimized. Since we know that two transmission frequencies cannot be present at the same time, the criteria is built in order to reach a minimum when the following condition is true: "for each i, if the ith component of a vector is non-zero, then the ith component of the other vectors must be zero". When the system works in interactive mode, a human operator can decide to fix some vectors, which seem already correct. This can help to reduce the search time. In our example, if we fix the 4th vector (which seems to be the most significant one), the rotation is restricted to the three remaining vectors. In order to do this rotation, we use a conventional 3D rotation matrix R, defined by:

$$R = \begin{pmatrix} \cos\varphi\sin\theta & \sin\varphi\sin\theta & \cos\theta \\ \cos\varphi\cos\theta & \sin\varphi\cos\theta & -\sin\theta \\ -\sin\varphi & \cos\varphi & 0 \end{pmatrix}, \qquad (6)$$

where $0 \leq \varphi \leq 2\pi$ and $0 \leq \theta \leq \pi$.

The results are shown on figure 9.

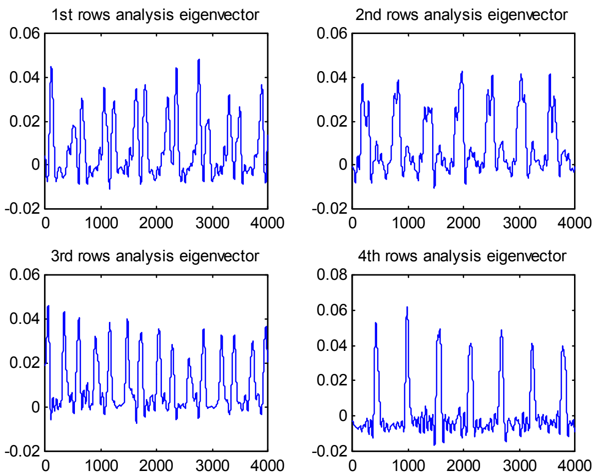

Figure 9: rows analysis eigenvectors after 3D-rotation

After the rotation, each vector corresponds clearly to the temporal sequence of one of the transmission frequencies. As we know the sequence duration D_s (§3), we can easily count the number of peaks in one sequence (note that it corresponds to the number of frequency stages N_s seen in §3).
Thus, by dividing D_s by N_s we directly obtain the frequency stability period.

6.2 Columns analysis

The original image has the same number of rows as the image C in the cosine functions base, so it is not necessary to compress it for columns analysis.
Computing the columns autocorrelation matrix $R_c = image * image^T$, and performing eigenanalysis, we obtain the number of frequencies used by the spreading sequence, because it is also the number of significant eigenvalues of this matrix (fig.10).

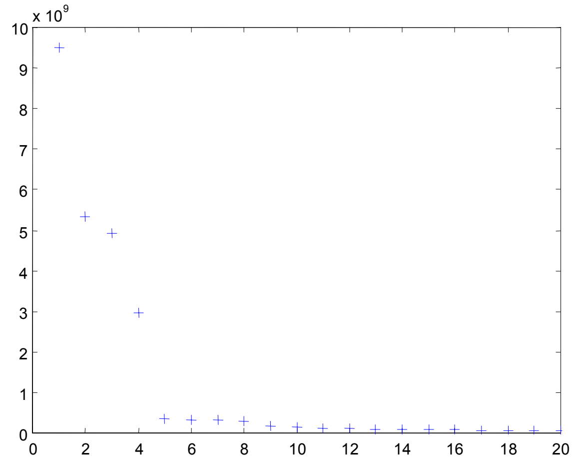

Figure 10: columns analysis eigenvalues (20 first ones)

Four large eigenvalues are clearly seen. They correspond to the transmission frequencies. The corresponding eigenvectors are displayed on figure 11.

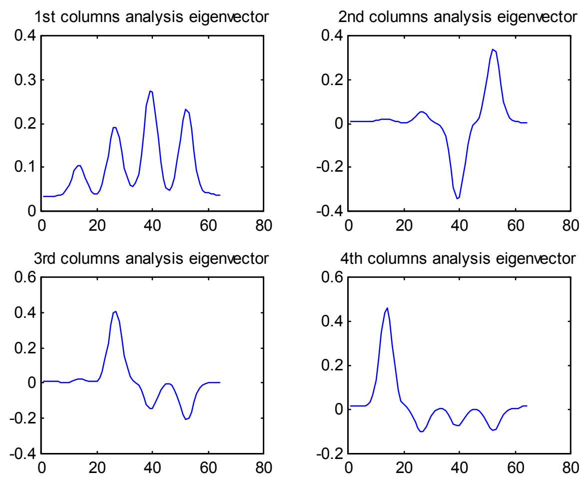

Figure 11: Columns analysis eigenvectors

In fact, these eigenvectors are linear combinations of eigenvectors centered on each transmission frequency, and which would allow us to find the modulation carrier frequency, the frequency gap and the frequency extension as well.
The best way to find these vectors is to perform a sequential search, based on Hamming windows (weigthing windows). We make these 3 parameters vary and we keep the vectors whose projection on the initial eigenvectors give us the minimal error .

We obtain finally the vectors represented on figure 12.

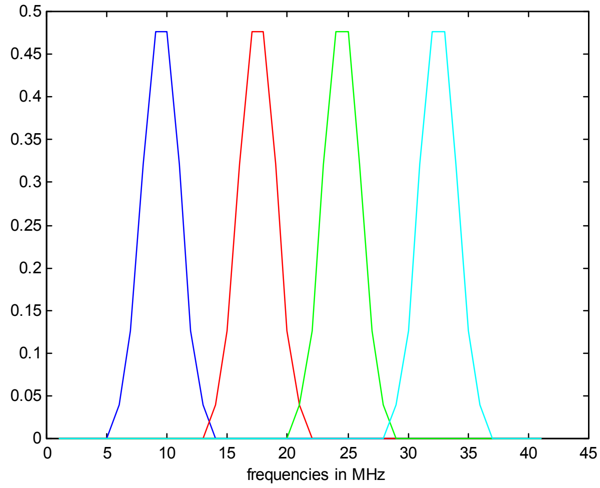

Figure 12: Vectors providing the minimal projection error

These vectors are only defined by the central frequency, the frequency gap and the frequency extension, so they allow us to determine these 3 parameters.

7 Conclusion

The spread spectrum systems, and consequently Frequency Hopping systems, are very difficult to intercept. It is the main reason for which they are used for many years for military applications. In this paper we show that, by combining various analysis techniques, it is really possible to characterize such signals.
This new approach starts from a time-frequency representation, and requires a precise definition of the parameters, as well as the use of mathematical tools. The method is able to demodulate signals in realistic conditions, and even in bad conditions (SNR=-5dB).
Some techniques used could probably be adapted to other digital modulations identification problems, and this is part of our further work.

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