Joint Detection and Hop Parameters Estimation of Slow FHSS/MFSK Signals Using DHWT-AC Technique in Rayleigh Block Fading Channels

S. N. Hosseini , H. Razavi

Abstract—**Frequency hopping spread spectrum (FHSS) has been paid much attention and has been employed by various wireless systems. For the reception of FHSS signals, first of all, we need to detect the presence of signal, and then to estimate hop parameters such as hop timing and hop frequency. In this paper, we propose an efficient algorithm for joint detection and hop parameters estimation of the slow FHSS/MFSK signals using two different methods, namely, the Discrete Haar Wavelet Transform (DHWT) and the autocorrelation (AC) in Rayleigh block fading channels. This algorithm can be used in communication intelligent (COMINT) systems for surveillance issues. The performance and behavior of the proposed algorithm are examined through computer simulations over practical measured data.**

Index Terms—**Autocorrelation function, joint detection and estimation, frequency hopping spread spectrum, discrete Haar-wavelet transform, hop parameters estimation.**

I. INTRODUCTION

Frequency hopping spread spectrum (FHSS) is considered as an efficient technique for secure communications, in satellite systems as well as ambiguity optimization method in MIMO radars [1]. In contrast to direct sequence spread spectrum (DSSS), it is less required to be synchronized. Frequency hopping technique is used commonly for radio transmission in military wireless networks, due to its well-known capabilities such as low probability of detection and interception. Furthermore, this technique can be applied for commercial networks due to its improved performance in fading environments. So, it is widely used in nowadays networks such as FH ad hoc networks, Bluetooth networks and wireless personal area networks (WPAN) [2]-[3]. The combination of DSSS and FHSS, as hybrid DS-FH systems, is also considered and studied in the literatures [4]. Therefore, detection and parameter estimation of FHSS signals is of grate importance and paid much attention for several decades.

Hop timing estimation for noncooperative FH signals is an important problem that feeds into the multiple facets of military communications, from interception of noncooperative communications to interference mitigation [5]. In this paper we assumed that there is no mismatch between the receiver's observation band and the hop bandwidth of the transmitted signals; therefore, there is no model-order variation and fixed model order can be used.

Haar wavelet is one of the most important detection techniques with different applications in detection discontinuities, thanks to its capability for multi-resolution analysis. Since wavelet processing promises computational advantages, in this paper, we employed DHWT technique to estimate the hopping time of the FHSS/MFSK signals through applying it to the phase information of the instantaneous correlation function (ICF) of the signal.

In DHWT technique, detection of signal is performed according to comparing the variance of the detection vector with the predetermined threshold. Whereas, this threshold depends on SNR and informing of variance of detection vector without hopping, then we can not use this method in detection of real signals. Therefore, we can use autocorrelation function in detection, simply. On the other hand, DHWT technique has more accuracy in estimation of hopping times, compared to that of AC technique. Our proposed algorithm works well without having a priori knowledge about hop patterns and rates; therefore, it can be used in the noncooperative networks.

This paper is organized as follows: In section 2, the system model of this paper is introduced. In section 3, detection method based on the AC technique is provided and in Section 4 parameter estimation using the DHWT is described. Joint detection and hop parameter estimation algorithm is presented in section 5. Section 6, contains the simulation results and section 7 concludes the paper.

II. SYSTEM MODEL

The band-pass filtered multiple-hop FHSS signal can be represented by

$$s_{bp}(t) = \sqrt{2P} \cdot \sin\left(\sum_{n=-\infty}^{\infty} \left(2\pi f_n t + \theta_n\right) \cdot I_{\alpha T_H + (n-1)T_H \le t < \alpha T_H + nT_H} \right), \tag{1}$$

in which, *I(.)* is defined as follows,

$$I_{Condition} = \begin{cases} 1 & \textit{condition} \text{ is met,} \\ 0 & \textit{condition} \text{ is not met,} \end{cases} \tag{2}$$

and P is the signal power; f_n and θ_n are the n^{th} hop's carrier

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frequency and phase, relatively; T_H is the hop time; and αT_H $(0 \le \alpha < 1)$ denotes the initial timing offset between the first hop of the signal and the receiver's clock. The band pass noise is a stationary Gaussian process with the standard quadrature representation

$$n_{bp}(t) = \sqrt{2}\left[n_I(t)cos(\omega_c t) - n_Q(t)\sin(\omega_c t)\right], \tag{3}$$

where, ω_c is the center angular frequency of the BPF and $n_I(t)$, $n_Q(t)$ are independent, stationary low pass Gaussian process with zero mean and known power spectral density (PSD) $S_{n_I}(f) = S_{n_Q}(f) = N_0 / 2 \cdot I_{-W_{BF/2} \le f \le W_{BF/2}}$, and W_{BF} is the bandwidth of the BPF. Thus, the observed waveform at the receiver can be presented by

$$r_{bp}(t) = h \cdot s_{bp}(t) + n_{bp}(t), \tag{4}$$

where, h is the channel fading gain coefficient which has Rayleigh distribution with the following probability density function

$$p_h(\gamma) = \begin{cases} \dfrac{\gamma}{\sigma^2}\exp\left(-\dfrac{\gamma^2}{2\sigma^2}\right) & \gamma \ge 0, \\ 0 & \gamma < 0, \end{cases} \tag{5}$$

where σ^2 is known as the fading envelope of the Rayleigh distribution.

Various modulation schemes can be used in a FH system, but M-ary frequency shift keying (MFSK) is chosen here for its constant amplitude properties and the ability to easily integrate the modulation and hopping operations into one. In the conventional MFSK system, the data symbol modulates a fixed frequency carrier by sending one of a set of M pre-set tones; while in a FHSS/MFSK system, the data symbols modulate a carrier whose frequency is pseudo randomly determined by a PN sequence. The actual transmitted frequency f_n is determined by the following equation

$$f_n = f_{LO} + f_{Hop} + f_D, \tag{6}$$

Where f_{LO} is the fixed local oscillator frequency of the transmitter, f_{Hop} is the hopping frequency determined by the

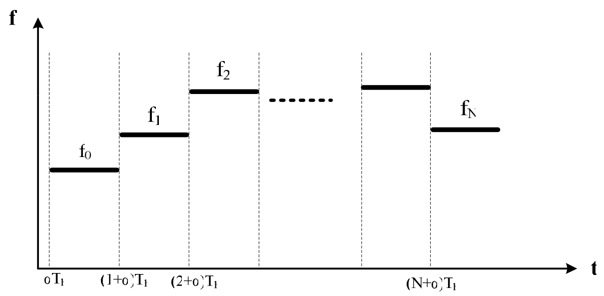

Fig. 1 Spectrogram of a FHSS signal with time offset.

PN sequence, and f_D is one of the M data bearing frequencies of an ordinary MFSK system.

The spectrogram of a FHSS signal with time offset (αT_H) is shown in Fig. 1.

III. FHSS/MFSK DETECTION

This detection process is based on mutual correlation of continuous frames of signal. Block Diagram of the detection technique is presented Fig. 2.

The output of BPF is processed by correlation circuit and is defined as

$$y(\tau) = \int_{\tau}^{T_H} r_{bp}(t) r_{bp}(t-\tau)\, dt = y_{SS} + y_{SN} + y_{NS} + y_{NN}. \tag{7}$$

For high input SNR ($P_S >> P_N$), we can omit y_{SN}, y_{NS} and y_{NN}. The AC function can be estimated as followed

$$\begin{aligned} y(\tau) &= y_{SS} \\ y(\tau) &= S_{bp}(T_H - \tau)\cos(\omega_n \tau). \end{aligned} \tag{8}$$

Power samples of autocorrelation function are defined as

$$W(\tau) = y^2(\tau). \tag{9}$$

Now, we must pass W via LPF (low pass filter) and find Maximum of it. Maximum Power sample of autocorrelation can be defined as follows

$$W_M(k) = \max\left(LPF(W(\tau))\right). \tag{10}$$

The $W_M(k)$, $k = 1, 2, \ldots, N$, are stored in a buffer with size N. This process is continued up to the end of the received frame. According to Fig. 4, the output of the correlation function is decreased in the end of each hop. In order to recognize the presence of signal, the FH selected frame must have at least 4 hops, since making decision is adaptive and is specified by standard deviation of buffer output. If the input signal is not FH signal (e.g. AM), standard deviation of buffer output will be a constant value. Else, it must be compared to specified threshold. The flag of FH detection must be set if standard deviation of buffer output exceeds some threshold value.

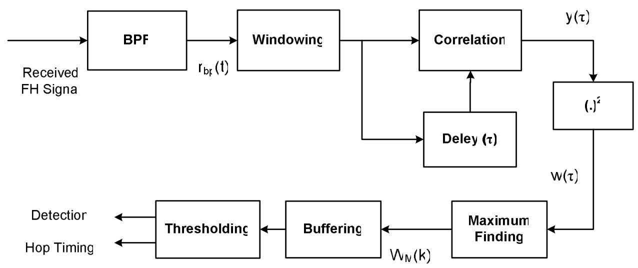

Fig. 2: Block diagram of FHSS/MFSK detection method using AC technique.

IV. FHSS/MFSK ESTIMATION

In this section, a method is presented for parameter estimation of FHSS signals (without MFSK modulation) [6]-[8]. In this method, the ICF of the FH signal is calculated and then the coefficients of wavelet are used to estimate the discontinuities caused by hopping. This method does not need any information about hopping pattern and does not set any presumption about hopping time such as being deterministic or fixed; however, lowest epoch time in each frequency hopping is specified. The aforementioned algorithm has good performance even when the signal level is below the noise level, as will be shown in the next sections.

The instantaneous correlation function (ICF) of signal r_{bp} is defined as follows

$$R_x^i(t,\tau) = r_{bp}\left(t+\frac{\tau}{2}\right) r_{bp}^*\left(t-\frac{\tau}{2}\right) \tag{11}$$

where i stands for instantaneous feature, t is the time and τ is the time delay (lag). The ICF is conjugate symmetric with respect to the time delay, i.e. $R_x^i(t,\tau) = R_x^{i*}(t,-\tau)$. Also, at $\tau = 0$ $R_x^i(t,0) = \left|r_{bp}(t)\right|^2$, the instantaneous power of r_{bp} at time t. It is noteworthy that the ICF is even symmetry with respect to τ. The ICF of a real signal may has interference terms. So, in order to compute the ICF of a real signal, we use analytical form of that signal.

If we consider the following analytical frequency hopping signal

$$\begin{aligned} x_a(t) &= e^{2\pi j f_1 t}\left[u(t)-u(t-T_{hop})\right] + \\ & e^{2\pi j f_2 t}\left[u(t-T_{hop})-u(t-T)\right], \\ & where \\ & T_{hop} < T \le 2T_{hop} \end{aligned} \tag{12}$$

Then ICF of signal (11), is as follows

$$\begin{aligned} ICF(t,\tau) = {} & e^{j2\pi f_1\tau}\left[u(t+\frac{\tau}{2})\left[u(t-\frac{\tau}{2})-u(t-\frac{\tau}{2}-T_{hop})\right]\right. \\ & \left. + u(t+\frac{\tau}{2}-T_{hop})\left[u(t-\frac{\tau}{2}-T_{hop})-u(t-\frac{\tau}{2})\right]\right] + \\ & e^{j2\pi f_2\tau}.\left[u(t+\frac{\tau}{2}-T_{hop})\left[u(t-\frac{\tau}{2}-T_{hop})-u(t-\frac{\tau}{2}-T)\right]\right. \\ & \left. + u(t+\frac{\tau}{2}-T)\left[u(t-\frac{\tau}{2}-T)-u(t-\frac{\tau}{2}-T_{hop})\right]\right] \\ & + e^{j2\pi\left[(f_2-f_1)+\frac{f_1+f_2}{2}.\tau\right]} \times \left[u(t+\frac{\tau}{2}-T_{hop})\left[u(t-\frac{\tau}{2})-\right.\right. \\ & \left.\left. u(t-\frac{\tau}{2}-T_{hop})\right] + u(t+\frac{\tau}{2}-T)\times\right. \\ & \left.\left[u(t-\frac{\tau}{2}-T_{hop})-u(t-\frac{\tau}{2})\right]\right] \\ = {} & ICF_1(t,\tau)+ICF_2(t,\tau)+ICF_{12}(t,\tau). \end{aligned} \tag{13}$$

The ICF contains 3 terms; 2 terms in relation to frequencies f_1 and f_2 (ICF_1 and ICF_2), and one interference term (ICF_{12}).

Different steps of DHWT algorithm are as follows:

1) Convert FH signal to analytical form using Hilbert transform, or creating I and Q components.
2) Divide the samples of the signal into frames with length shorter than T_{hop_min} (the minimum dwelling time in one hop). So, in each frame there will be one hop. If the signal has no data modulation, T_{hop_min} is equal to the inverse of maximum hopping rate. However, if there is MFSK modulation and if the hopping rate is less than symbol rate, T_{hop_min} will equal to one period of symbol. Therefore, the upper limit of the symbol rate must be specified or be estimated.
3) Calculate ICF in each frame and obtain the phase information using *angle(.)* function.
4) Unwrap the phase of the ICF along t axis. This causes the deletion of discontinuities due to periodicity in phase and reduction of accidental strikes due to noise in the phase of the ICF. Phase unwrapping is defined as

$$unwp(p(t)) = \begin{cases} p(t) & if\ \left|p(t)-p(t-1)\right| \le \pi \\ p(t)+2\pi & if\ (p(t)-p(t-1)) < -\pi \\ p(t)-2\pi & if\ (p(t)-p(t-1)) > \pi \end{cases} \tag{14}$$

5) Apply median filter along t axis to the phase of the ICF. (In simulations, the order of this filter is 5). Use of median filter prior to the differentiation causes the reduction of noise effects.
6) Differentiate the phase information along the t axis. This step changes the profile of phase from gradient to semi rectangular which is concentrate on the milieu of hopping time.
7) Use another median filter at output of the differentiator. The selection of the orders of the median filters depends on the T_{hop_min} which is used. The application of this filter reduces the noise effects.
8) Use discrete DHWT along t axis. The use of the DHWT results in detection of defined edges of interfered terms.
9) Add the wavelet coefficients associated with two first scales (d_1 and d_2 of DHWT). Apply 45°/135° addition to all values of τ in order to obtain one detection vector. The index of the detection vector shows different time samples. This stage is caused to reinforce edges of defined region TCF_{12} and its detection.
10) Compare variance of detection vector with predetermined threshold. If the variance is greater than the threshold, hopping is occurred in the selected frame. If there is a hop, the time instant that associated with the maximum value of the detection vector, will be the hop time instant.

V. JOINT DETECTION AND PARAMETER ESTIMATION OF FHSS/MFSK

In spite of high accuracy in hopping time estimation of the wavelet transform algorithm, it is not suitable for detection of the frequency hopping signal in practical environment because its required threshold is equal to multiplication of two parameters; one of them is variance of detection vector without noise and the other is depended on SNR. In real signals, not only it is impossible to have frame without hop, but also estimation and determining the SNR require separate processing. Therefore, it is better to use the AC technique as detector and the DHWT as hop parameter estimator for its accuracy.

Flowchart of the aforementioned joint algorithm is shown in Fig. 3. As mentioned earlier, the wavelet transform algorithm, for hop timing estimation of the modulated signal, requires the information about upper limit of the symbol rate. The simple and reliable method for bit rate estimation is the *cyclic autocorrelation function* method which is proposed in [9].

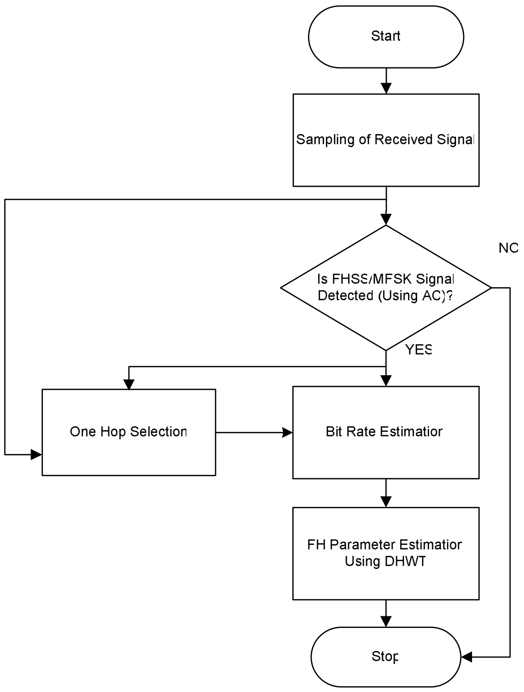

Fig 3: Flowchart of the DHWT-AC algorithm.

VI. Simulation Results

In this section, we compare the detection and hop timing estimation capabilities of the two aforementioned algorithms, namely, the DHWT and the AC technique, for the FHSS/MFSK waveforms through computer simulations. We consider the same condition for two algorithms in order to fairly compare them with each other. The parameters which are used in the simulations are presented in Table 1.

Fig. 4 shows the spectrogram of simulated FH signal and the output of the autocorrelation function. It is obvious that the amount of the autocorrelation decreases in the edge of each hop. Also, it is compared with the threshold that is adapted to the power of the FH signal. We compare the two algorithm's capability in detection of FHSS/MFSK signals in Fig. 5 and Fig. 6. Fig. 5 shows the probability of detection (P_d) of two algorithms for different SNR values and Fig. 6 compare the probability of false alarm (P_{fa}) for two algorithms for different SNR values.

TABLE 1: The simulation parameters

Sampling Frequency	50 MHZ
Data modulation	BFSK
Bit Rate	16 Kbps
Number of Hopping Channels	256
Channel Spacing	25 KHz
Sequence of Hop Rates	{100,200,300 } Hop /Sec
Bandwidth of Hopping	10 MHz
First Hopping Frequency	400 KHz
Length of Processed Signal	1 Sec

Both algorithms show acceptable performance even in low SNR. As can be seen, the AC algorithm has better detection performance than DHWT as it has the higher probability of detection and the lower probability of false alarm compared to that of the DHWT. For example, the P_d of the AC is 5×10^{-2} higher than that of the DHWT and also the P_{fa} of the AC is 4×10^{-4} lower than that of the DHWT at SNR= 0 dB.

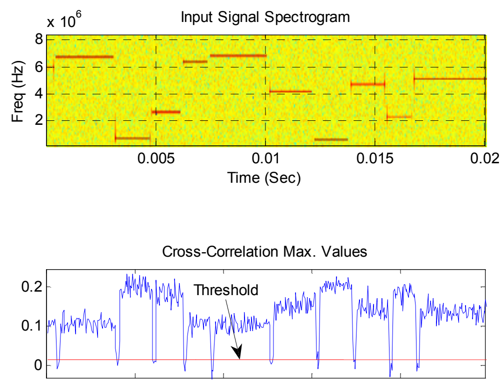

Fig 4: The spectrogram of FH signal and the output of the autocorrelation function.

Fig. 7 compares the hop edge error of the DHWT algorithm with that of the AC algorithm in estimation of hopping times, versus SNR. As we can see in this figure, the DHWT is more accurate than the AC in estimation of hopping edges and therefore it is more suitable for hop timing estimation of FHSS/MFSK signals.

Fig. 8 compares the Probability of hop edge Estimation of the DHWT algorithm and the AC algorithm in estimation of hopping times, versus SNR. As we can see in this figure, the DHWT is more accurate than the AC in estimation of hopping edges. For example, Probability of hop edge estimation of DHWT is 0.057 higher than that of the AC at SNR= 0 dB and the allowed edge deviation = 50 %.

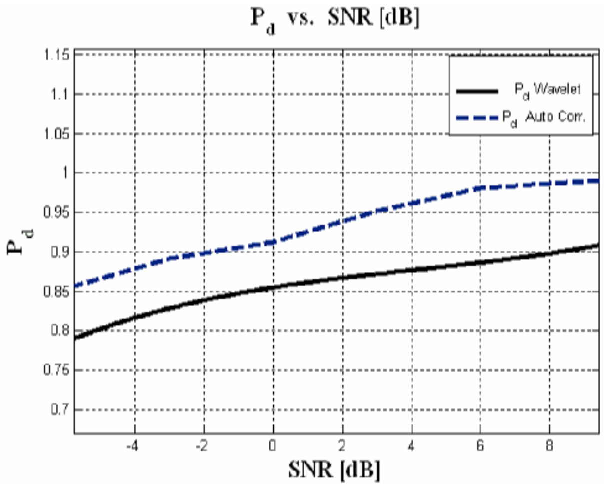

Fig 5: Comparison of P_d for the AC and the DHWT algorithms.

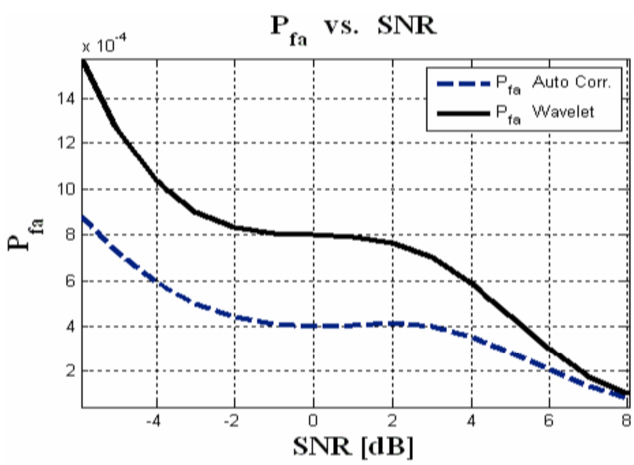

Fig 6: Comparison of P_{fa} for the AC and the DHWT algorithms.

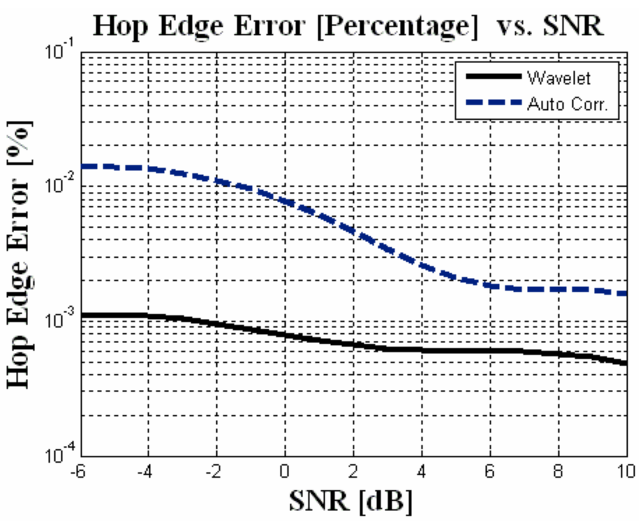

Fig 7: Comparison of the Percentage of Hop Edge Error of the AC and the DHWT algorithms.

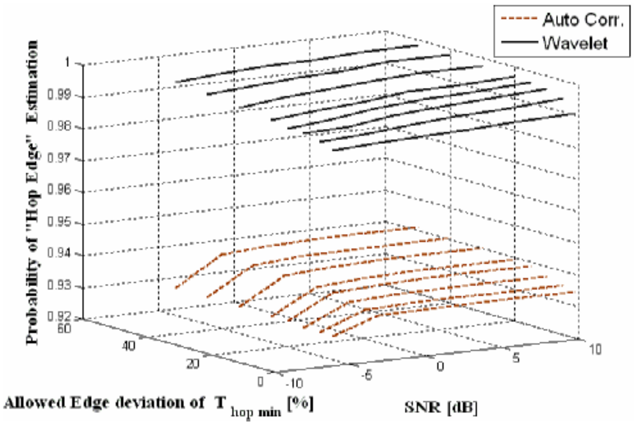

Fig 8: Comparison of the Probability of Hop Edge Estimation.

VII. Conclusion

In this paper, we compared two algorithms for detection and hop timing estimation of slow FHSS signals with MFSK modulation. In wavelet transform based algorithm, we need to know the lowest dwelling time in each hop. Also, we need to know the SNR and the variance of the detection vector without hopping, in order to determine the thresholds that are used for detection using this algorithm; however, these information are not available in real world. So, it is better to use the AC technique for detection of the FHSS signals. On the other hand, accuracy in estimation of hopping times by wavelet transform based algorithm is more than that of the AC technique and this makes this algorithm as an efficient candidate for hop timing estimation of the FHSS signals. Thus, we conclude that the joint detection and hop timing estimation technique which uses the DHWT-AC is more efficient than using two techniques individually for detection and estimation of the FHSS/MFSK signals.

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