A Novel Digital Frequency De-hopper using Bandpass Sampling Technique

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Abstract

In military and defense communication systems, frequency hopping technique is considered one of the most effective electronic protective measurements to avoid jamming. Frequency hopping is performed by rapidly changing carrier frequencies during the communication. With the rapid growth of frequency hopped wireless networks, frequency detection and jamming has become a challenging task. In this paper, we propose a novel algorithm for frequency detection in a frequency hopping system, by using bandpass sampling technique. Bandpass sampling downsamples the signal below the Nyquist frequency as a result of which, copies of signal are received at frequencies around carrier frequency which are integral multiple of the sampling frequency. The resulting copies are then used to detect the carrier frequency. The performance of the proposed algorithm is analyzed in Stanford University Interim (SUI) channel models. The proposed technique provides fast frequency detection with low probability of error and low computational complexity.

1. Introduction

Frequency-hopping is a technique to transmit radio signals by switching the carrier frequency rapidly among different frequencies. This is sometimes done by using a pseudo-random sequence, which is known to both the transmitter and receiver. The reason to introduce frequency hopping was to counter unintentional interferences like multiple access interferences and to avoid frequency jamming as it was considered harder to find the hopping characteristics. Military radios use cryptographic techniques for the generation of channel sequence. It is controlled by secret transmission security key, which is shared by the sender and receiver in advance.

In today's world, frequency hopping (FH) is no more a complete protective technique against jamming. Different algorithms for the frequency de-hopping have been developed. The efficiency of these algorithms is computed on the basis of high measurement resolution, large dynamic range and fast frequency detection. Hence, frequency identification plays a key role in frequency jamming. A process to detect and characterize a frequency hopping signal is known as frequency identification. Thus research on effective estimation of FH parameters is a challenging task. Frequency Identification is a key step of frequency de-hopping, once a carrier frequency is identified and the hopping pattern is traced, it is no more a big deal to block or jam the frequency.

Different algorithms and methods for frequency analysis are present in the literature. Some of them were based on initial random guesses or reference signals, but some extra bandwidth is required for reference signals. So, to keep the bandwidth efficiency high, no reference signal is used and blind estimation is made. Generally, maximum likelihood based algorithms perform well but ML-estimation faces difficult non-linear numerical problem. So, iterative methods are followed because direct greedy search method has large computational cost. A reversible jump Markov chain Monte Carlo based algorithm for the identification of frequency is proposed in [2]. It uses two hop model with unknown dwell time. For a frequency hopped signal, original Bayesian model is formulated. However, it requires the advance knowledge of hyper parameter which is not always possible.

In [3], expectation maximization algorithm and an antenna array for the estimation and blind hop timing of multiple FH signals are used, with possible mismatch of bandwidth. The initialization of this algorithm was given by data spectrogram. It was considered to perform better even at low SNR but it is computationally very extensive. The method of matching pursuit is followed in [4] for frequency detection. In this method, the signal is decomposed into linear expansion of time-frequency components. For practical implementation of this algorithm, selection of discrete subset out of possible dictionary functions was required. A joint frequency and hop-time estimation method is proposed in [5]. It is based on dynamic programming coupled with 2-D harmonic retrieval by using antenna arrays. It works even with unknown hop rates, asynchronous environment.

A blind maximum likelihood based iterative algorithm for the estimation of frequency is proposed in [6], by using two hop model. The first order Taylor expansion was used as approximation and for reduction of computational complexity. However, the initial estimates were required to start the iterations and method to obtain those estimates was not discussed by authors. It is indicated in [3] that this approach would not guarantee the frequency estimation. It would propose more than one solution hence the problem of convergence to correct solution would raise. Another blind estimation scheme for assessment of frequency and estimation of transition time without utilizing reference indicators is proposed in [7]. The scheme is robust as it can avoid unbalanced sampling block problem which was faced in previous maximum ML-based schemes, which causes failures in estimates of frequency. An efficient method for frequency detection is given in [8] that can converge to global maximum without any requirement of initial guesses. It was based on divide and conquer' approach. Iterative disassemble and assemble (IDNA) algorithm was proposed to show a unique global maximum for proposed objective function. This scheme disassembles a higher order objective function polynomial into several simple monomial functions. The solutions to those monomial functions are computed iteratively and then assembled to get final result.

Time frequency analysis was considered to be a powerful tool for the analysis of signals with time-varying content. Frequency Hopping signal is a non-stationary signal, whose parameters can be obtained by this method. In this technique a signal is being studied in both time and frequency domain simultaneously [9]. An Algorithm was introduced in [10] to estimate the signal's hopping characteristics named Winger-Ville distribution (WVD). This distribution in particular was supposed to be efficient for the estimation of FH signals. But In multi-component signals, the frequencies change non-linearly along time axis. So WVD leaded to serious cross-term interference. A Smoothed Pseudo Winger Ville Distribution is proposed in [11] to get fewer interference terms and high resolution. Hence localization of frequency hopping signal components is improved. The proposed method does not assume any initial value for hopping frequency, hopping duration or synchronization. The paper emphasizes on joint estimation of signal parameters including the modulation type as well. By introducing the first and second moments of SPWVD, estimation of hopping frequencies, hopping sequence and hopping rate is done. The method basically includes two main steps. In first step by utilizing time frequency estimation, joint signal parameters are estimated which include hopping frequency, hopping rate and hopping sequence. In second step maximum likelihood (ML) method is adopted to recognize MSFK modulation type. So, for frequency hopping signal parameters we used reassigned SPWVD within Cohen's class of time-frequency distribution. For recognition of MFSK and modulation type, ML method was used by recognizing the likelihood function.

This paper proposes a novel scheme for the detection of the frequencies in a frequency hopped system, by using band-pass sampling technique. Bandpass sampling downsamples the signal below the Nyquist frequency as a result of which, copies of signal are received at $f_c \pm n * f_s$, where f_c is the carrier frequency, f_s is the sampling frequency and $n = 0, 1, 2, 3, ...$ The resulting copies are then used to detect the carrier frequency. It provides fast frequency detection with low probability of error and low computational complexity.

2. Bandpass Sampling

According to the Nyquist criteria, the reconstruction of original signal is possible if the sampling frequency of the signal is greater than or equal to twice the maximum frequency in the signal spectrum [12].

$$f_s \geq 2f_H \tag{1}$$

where, f_s is the Nyquist rate and f_H is the maximum frequency of the signal. Bandpass sampling allows the band limited signal to be sampled at a rate below the baseband Nyquist rate, and still allow the signal reconstruction.

The bandwidth B can be defined as

$$B = f_H - f_L \tag{2}$$

According to the bandpass sampling theory, the sampling rate should be greater than twice analog bandwidth B.

$$f_s > 2B \tag{3}$$

Bandpass sampling allows us to reduce the sampling rate significantly and still avoid aliasing. To achieve this alias free spectrum, certain limits have to be applied on f_s, which are given as

$$\frac{2f_H}{n} \leq f_s \leq \frac{2f_L}{n-1} \tag{4}$$

Where,

$$1 \leq n \leq \frac{f_H}{B} \tag{5}$$

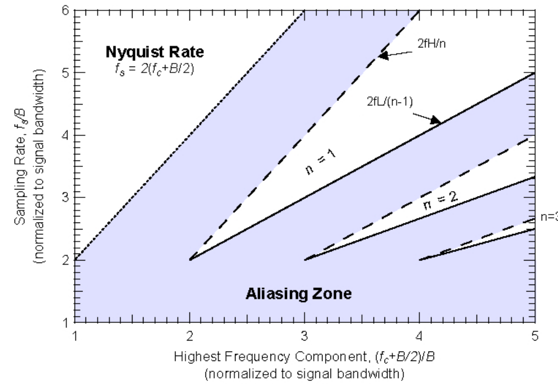

Figure 1. Aliasing and alias free zones

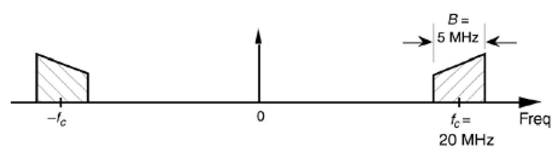

Figure 2. An Example Band-pass Signal Spectrum

So, for different values of n, we get different ranges of possible sampling frequencies f_s. The acceptable and unacceptable sets of sampling frequencies are shown in the figure 1. Figure 1 clearly shows that the allowable sampling frequencies lie between the shaded regions. So, the signals existing in these regions will be recovered back without distortion/aliasing.

After downsampling the received signal, the copies of original signal are generated at

$$f_{new} = f_c \pm (n * f_s) \tag{6}$$

Where n is a positive integer. The copies will be received at $f_c + f_s, f_c - f_s, f_c + 2f_s, f_c - 2f_s$ and so on. Let us consider a band-limited signal with carrier frequency, $f_c = 20MHz$, and bandwidth, $B = 5MHz$, as shown in figure 2. We can see that

$$f_H = f_c + \frac{B}{2} = 22.5MHz$$

and

$$f_L = f_c - \frac{B}{2} = 17.5MHz$$

To fulfill the Nyquist criteria, we must choose

$$f_s \geq 2 * f_H = 45MHz$$

and to fulfill Band-pass sampling criteria,

$$f_s \geq 2 * B = 10MHz$$

is sufficient. Let us now set the sampling frequency $f_s = f_L = 17.5MHz$, which fulfills 3 and 4. The resulting Spectrum is shown in figure 3. Hence, we can still get alias free results without fulfilling Nyquist criteria.

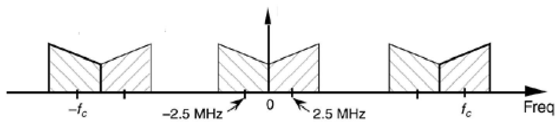

Figure 3. Signal spectrum with sampling rate fs=17.5MHz

3. Proposed Algorithm

3.1. Computation of New Sampling Frequency

The first step of the proposed frequency identification algorithm is the computation of sampling frequency. The received signal is then required to be downsampled using the computed sampling frequency. Let us define,

$$f_{lower} = \frac{2f_H}{n}$$

and

$$f_{upper} = \frac{2f_L}{n-1}$$

So that, the allowable range of sampling frequencies will be

$$f_{lower} \leq f_s \leq f_{upper} \tag{7}$$

The problem is that the computation of f_{lower} and f_{upper} requires f_L and f_H, which require f_c and B to be known. The bandwidth B for narrowband frequency hopping waveforms is usually known, but f_c is the unknown parameter to be identified. As a solution to this problem, by changing different carrier frequencies, bandpass theory was applied and sets of possible sampling frequencies were computed. Those frequency sets were then keenly observed and some common sampling frequencies were selected. The finally selected sampling frequencies are 6 MHz, 8 MHz and 10 MHz. These frequencies are then kept fixed for further research.

3.2. Downsampling

The received signal is then downsampled on the fixed selected frequencies. The downsampled signal corresponding to each selected frequency is analyzed in frequency domain. Multiple copies of the signal are created on $f_c \pm (n * f_s)$.

3.3. Finding f_c

To identify the current hop frequency f_c, the location of peak in the magnitude frequency response of the downsampled signal is found. Let this frequency be f_{peak}. Once f_{peak} is known, the hop frequency f_c' for the first sampling frequency can be found by reverse of 6.

$$f_c' = f_{peak} \pm (n * f_s) \tag{8}$$

This process of finding f_c' is repeated for all the three downsampled signals. Their results are finally compared with each other and the common frequency is considered as the detected carrier frequency.

3.4. Finding Hop Time

The detection time of the proposed algorithm is given as

$$T_{hop} = \frac{N_d}{f_{s,min}} \tag{9}$$

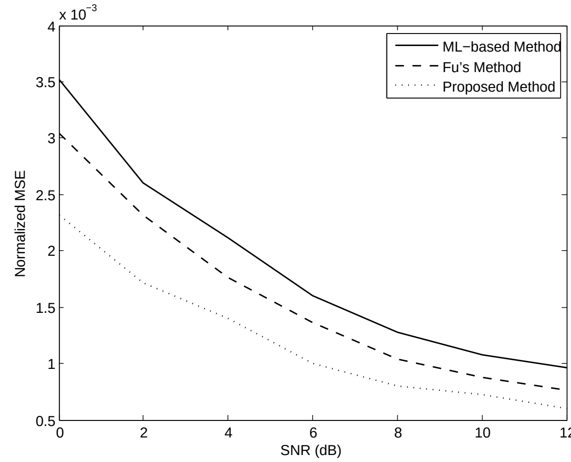

Figure 4. Performance comparison of the proposed algorithm with some existing techniques by using 3840 samples for detection

where N_d is the total number of samples used for detection and $f_{s,min}$ is the minimum sampling frequency used for downsampling.

4. Simulation results

In this section, we present the simulation results of the proposed algorithm. By keeping the total number of samples fixed at 3840, performance of proposed scheme is compared with Maximum Likelihood Based detection [6] and Fu's blind iterative detection [7]. The comparison is shown in figure 4, which shows that the the proposed algorithm is superior to other two algorithms in terms of mean square error (MSE) performance.

Figure 4 shows that in the same time duration of 0.64msec (for 3840 samples and $f_{s,min} = 6MHz$), the proposed algorithm detects the carrier frequency with minimum mean square error. As we know that on increasing the number of samples, performance gets better which can be seen in figure 5, where the number of samples are increased from 3840 samples to 6000 samples. So, carrier frequency is detected in 1ms and mean square error of ML-based technique moves from 3.5×10^{-3} to 2.75×10^{-3}, whereas mean square error of the proposed scheme reduces from 2.3×10^{-3} to 1.4×10^{-3}. Therefore, performance improvement is better in the proposed scheme.

With total number of samples equal to 1000, carrier frequency is detected in 0.16ms with mean square error of 2×10^{-3}. When numbers of samples are increased to 7000, carrier frequency is detected in 1.16ms with mean square error of 0.58×10^{-3}. As total number of samples is increased, Mean square error is decreased. This is shown in figure 6. For any count of samples, mean square error is decreased with the increasing Signal to noise ratio, which is shown in figure 7.

Whatever the carrier frequency may be, the response of proposed algorithm for its detection remains almost the same. Figure 8 shows the performance of the proposed algorithm for carrier frequencies of 20 MHz, 25 MHz and 30 MHz. Finally, the performance of the proposed algorithm is analyzed in Stanford University Interim (SUI) channel models. These are a set of six channels modeled for fixed wireless applications [13]. These six channels model different terrain types depending upon var-

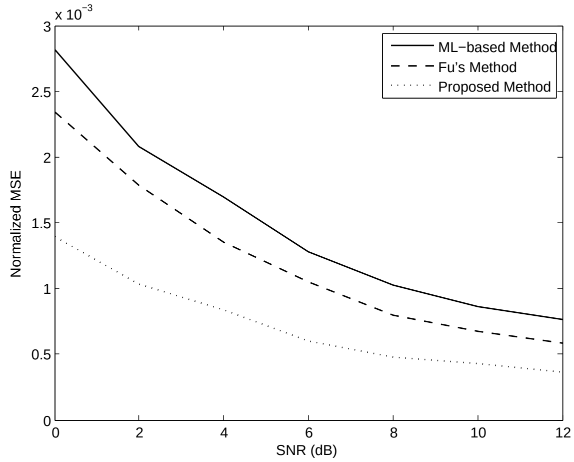

Figure 5. Performance comparison of the proposed algorithm with some existing techniques by using 6000 samples for detection

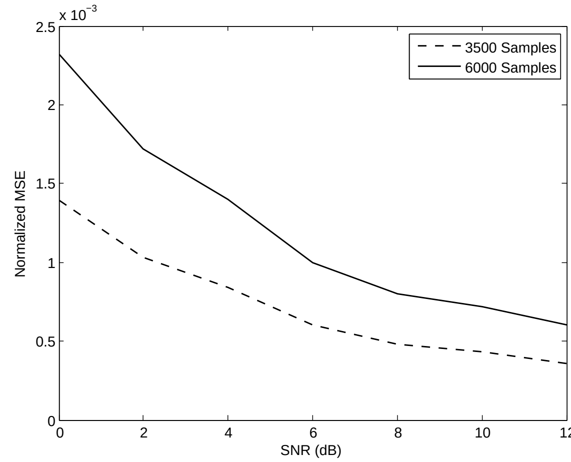

Figure 7. Performance of the proposed algorithm at different SNRs and number of samples

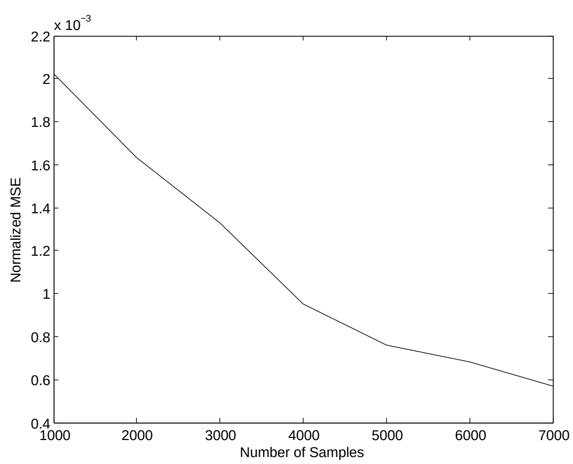

Figure 6. Performance of the proposed algorithm by varying number of samples

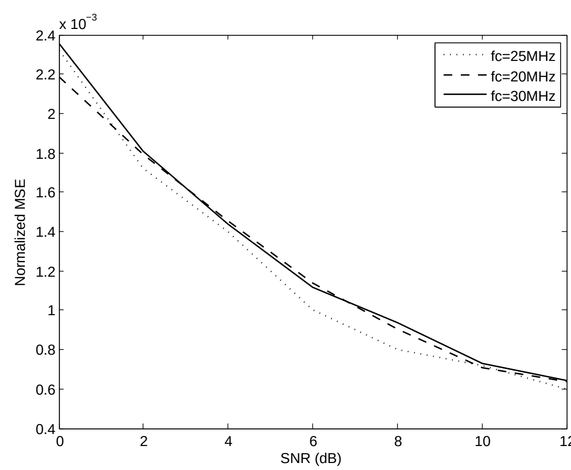

Figure 8. Detection of three different frequencies at varying SNR

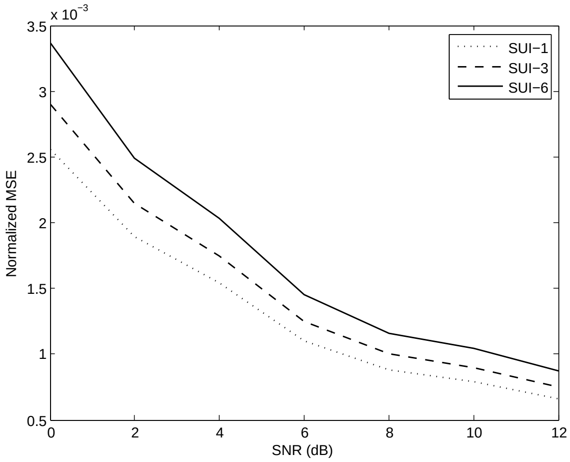

Figure 9. Performance of the proposed algorithm in SUI channel models

ious factors such as line of sight, delay spread, doppler spread, tree density etc. Terrain A (SUI-5 and 6) represent worst conditions, terrain B (SUI-3 and 4) represent medium conditions and terrain C (SUI-1 and 2) represent better channel conditions. Figure 9 shows the mean square error plots for SUI-1, 3, and 6. For terrain type A (SUI-6), mean square error is the maximum as it has zero line of sight and large values of delay spread and Doppler spread. For terrain type C (SUI-1), mean square error is the minimum because of good channel conditions.

5. Conclusion

A novel algorithm for frequency identification in a narrowband frequency hopping system by using bandpass sampling technique is proposed. Bandpass sampling downsamples the signal below the Nyquist frequency as a result of which, copies of signal are received at frequencies around carrier frequency which are integral multiple of the sampling frequency. The hop frequency is detected by exploiting this feature of bandpass sampling technique. The performance of the proposed algorithm is analyzed in Stanford University Interim (SUI) channel models. The proposed technique provides fast frequency detection with low probability of error and low computational complexity.

6. References

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