Multiresolution Time-Frequency Techniques for Spread Spectrum Demodulation and Jamming

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Abstract

Frequency hopping is a simple and commonly used means for spreading the spectrum of a signal for transmission in a spread spectrum communication system. One central problem in demodulating or efficiently jamming a frequency hopping transmission is accurate estimation of the hopping function. This paper presents some preliminary work in which multiresolution time-frequency techniques are used to estimate the hopping function of an unknown (intercepted) slow frequency hopping signal in an uncluttered environment. Wavelet and short-time Fourier analysis are both used to measure the temporally evolving frequency characteristics of the hopping signal.

1 Introduction

Among the main reasons for the use of frequency hopping spread spectrum communication systems is their robustness with respect to detection and jamming [1]. Typical slow frequency hopping signals consist of an information signal of relatively small bandwidth modulating a carrier signal having piecewise-constant frequency that varies ("hops") within a band much larger than that of the information signal (Figure 1). The spreading function is known to intended receivers, but unknown to unintended receivers who may wish to demodulate or jam the transmission. This paper presents preliminary results of research into techniques for estimating the spreading function of an unknown frequency hopping transmission using only received (intercepted) data. Since such functions are characterized by the times and frequencies associated with the hops, techniques are sought to accurately estimate these parameters. Good estimates of the spreading function are directly useful in demodulation of such signals and may also be useful in jamming them.

2 Time-Frequency Techniques

The analysis tools used in this work were the short-time Fourier transform (STFT) and the wavelet transform (WT). Other approaches for analysis of signals with time-varying characteristics, such as the Wigner-Ville and related time-frequency distributions [2], may also be applicable to this problem. These were not used in the work presented here, however.

2.1 The STFT

As a signal analysis tool, the primary utility of the Fourier transform is decomposition of a finite-energy signal into individual frequency components. Its value in analysis of signals with time varying characteristics, such as frequency hopping signals, is limited because information about when the various frequency components are present in a signal is embedded in the phase of its Fourier transform in a way that is not easy to interpret. The magnitude of the Fourier transform of a frequency hopping signal, for example, contains no information about when the hops occur.

The STFT or time-windowed Fourier transform of a finite-energy signal \( f : \mathbb{R} \to \mathbb{R} \) is a function \( F : \mathbb{R}^2 \to \mathbb{R} \) defined by

\[
F(t, \omega) = \int_{\mathbb{R}} f(\tau)w(\tau - t)e^{-i\omega \tau} d\tau
\]
In this expression, \( w \) is a bounded function, generally even and with bounded support, called a window. In general, window selection is based on numerous criteria \([3]\). In the context of frequency hopping signal analysis, the primary tradeoff is in selecting the time duration of the window. Windows of short duration allow precise temporal localization of hops at the expense of frequency resolution. Analysis using long windows sacrifices temporal resolution but improves frequency resolution.

2.2 The WT

The wavelet transform of a continuous-time finite energy signal \( f \) with respect to an analyzing wavelet \( g \) has values

\[
W(a, b) = \frac{1}{\sqrt{a}} \int_{\mathbb{R}} f(t) g^*(\frac{t-b}{a}) \, dt
\]

In this expression, \( g^* \) denotes the complex conjugate of \( g \), \( a > 0 \) is called the dilation or scale parameter, and \( b \in \mathbb{R} \) is the time shift parameter. The class of admissible analyzing wavelets \( g \) is broad, but they must have finite energy and satisfy certain technical conditions \([4]\).

The wavelet transform has been shown to be of particular value in detecting and temporally localizing discontinuities and other sudden changes in signals \([4, 5]\). The ability of the WT using any given wavelet to resolve narrowband signals that are closely spaced in frequency is better at low frequencies than higher frequencies. This characteristic is ideally suited for certain applications in which frequency resolution requirements diminish in proportion to the center frequency of the band being analyzed (e.g., “constant-Q” settings). It is not desirable for analysis of frequency hopping signals, however, because the need for frequency resolution is uniform across a wide bandwidth.

3 Estimation Algorithm

The characteristics just discussed suggest a hybrid scheme for spreading function estimation in which WT analysis is used to estimate the hopping times and STFT analysis is used to estimate the frequencies of the signal segments. Such an algorithm is depicted in figure 2.

At the first stage, the WT of a segment of the intercepted data is computed digitally. The discrete wavelet transform used at this stage is dyadic and provides one output value \( w_{0,1} \) at the coarsest scale \( a_0 \). It provides two output values \( w_{1,1} \) and \( w_{1,2} \) at the next finer scale \( a_1 = 2^{-1}a_0 \). At scale \( a_n = 2^{-n}a_0 \), it yields \( 2^n \) values \( w_{n,1}, \ldots, w_{n,2^n} \), resulting in a dyadic tree of output values ending at the finest scale \( a_N = 2^{-N}a_0 \). The occurrence of a hop within the segment is determined by comparing the sequences \( [w_{0,1}], [w_{1,1}], \ldots, [w_{N,1}] \) and \( [w_{0,1}], [w_{1,2}], \ldots, [w_{N,2^n}] \). These sequences may be interpreted as crude local spectral estimates of the signal near the leading and trailing edges of the segment, respectively. Thus, if a hop occurs within the segment, the change in frequency structure of the signal will be reflected in the sequences. If a hop is indicated, the outputs form the finer scales are used to estimate the precise time(s) of the hop(s).

The next stage of the algorithm processes a segment of data bounded in time by two hops, as detected in the first stage of the algorithm, using a STFT with a window whose length precisely matches that of the segment. This is implemented by a zero-padded FFT \([7]\). The spectral estimate obtained is used to estimate the frequency of the carrier between hops.

4 Simulation Results

A digitized frequency hopping signal with the following characteristics was produced:

- BPSK baseband modulation
- Bit rate of 9600 bps
- Hopping rate varying randomly between 50 and 250 ms
- Smallest frequency hop of 20 KHz

Figure 2: Flow diagram of a hybrid algorithm for estimating the spreading function of an intercepted frequency hopping signal.
Because the true spreading function of this signal was known, it was possible to reconstruct the baseband signal from the frequency hopping signal simulating the reconstruction possible under ideal conditions at an intended receiver. The signal-to-noise ratio (SNR) obtained in this reconstruction was approximately 25 dB.

The hybrid algorithm described above was used to estimate the spreading function of the simulated signal. The parameters of the algorithm were chosen based on the assumption that the shortest time between hops would be no less than 25ms and that the smallest frequency hop would be no less than 10 KHz. Otherwise, the algorithm used no specific a priori knowledge about the signal. The baseband signal was reconstructed using the estimated spreading function with a SNR of approximately 14 dB.

A similar spreading function estimation algorithm using STFT rather than WT to estimate the hopping times was implemented and run on the same data. It was found to be much more computationally efficient, but the estimated hopping times were not as accurate as those obtained using WT. This loss of accuracy reduced the reconstruction SNR to approximately 8 dB.

5 Demodulation versus Jamming

In principle, accurate estimation of the spreading function of a frequency hopping signal can be useful in jamming as well as in demodulation. For jamming applications, a hop must be detected and the frequency of the new segment estimated essentially immediately in order for the jamming transmitter to switch to the new frequency before the next hop. Thus, estimation algorithms must be causal and very fast for this application. On the other hand, the accuracy of the estimate may not be crucial. Just having a general idea where in the phase plane the signal is concentrated will allow much more efficient use of jammer energy than constant jamming of a broad frequency band.

For demodulation of an intercepted signal neither causality nor fast algorithm execution may be necessary. Latencies of seconds or even minutes may have little effect on the utility of the spreading function estimate in demodulation. However, accuracy of the estimate in this application is crucial.

6 Conclusions

This paper has described preliminary work on spreading function estimation for an intercepted slow frequency hopping signal. A hybrid algorithm using wavelet transform to accurately estimate the hopping times and time-windowed Fourier transform for subsequent frequency localization of the signal segments between hopping times has been introduced. In noise-free simulations, this algorithm provided much better spreading function estimates and reconstructed signal SNR's for a single frequency hopping signal than one based on single-resolution Fourier processing. It also yielded somewhat better spreading function estimates and reconstructed signal SNR's than an algorithm using dual-resolution Fourier analysis in this scenario.

Further work on this problem is expected to include scenarios involving noise, clutter, and multiple frequency hoppers. The utility of the Wigner and related time-frequency distributions in this problem should also be explored.

References