BROADBAND NONSTATIONARY INTERFERENCE EXCISION FOR SPREAD SPECTRUM COMMUNICATIONS USING TIME-FREQUENCY SYNTHESIS

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ABSTRACT

A new method is introduced for interference excision in spread spectrum communications. Time-frequency synthesis techniques are used to synthesize the nonstationary jammer from the time-frequency domain using least-squares methods. The synthesized jammer is then subtracted from the incoming data in the time domain, leading to increased signal to interference ratio at the input of the correlator. The paper focuses on jammers with constant modulus where the jamming signal is a polynomial phase. With this apriori knowledge, the jammer signal amplitude is restored by projecting each sample of the synthesized signal to a circle representing its constant modulus. With the phase matching provided by the least-squares synthesis method and amplitude matching underlying the projection operation, the paper shows a significant improvement in receiver performance/bit error rates over the case where no projection is performed.

I. INTRODUCTION

One of the primary motivations for direct sequence (DS) spread spectrum (SS) communications is that of interference mitigation. Several past contributions deal with the suppression of *narrowband* interference [7,8], and approaches for *broadband* interference excision based on time-frequency analysis have also been considered [1,2,6]. The recent development of bilinear (quadratic) time-frequency distributions (TFDs) for improved signal power localization in the time-frequency plane has motivated several new approaches for *nonstationary* interference excision in spread spectrum communications [1,3]. An implementation of an interference excision system using time-frequency distributions (TFDs) to determine the jammer IF has been thoroughly discussed [9]. However, this technique also creates a significant amount of self noise that forms an upper bound on the maximum attainable value of the correlator SNR, and in many cases the use of these filters makes the performance worse than when the preprocessing is disabled.

In this paper, the time-frequency (t-f) distribution is used to the fullest extent as a powerful tool for depicting a *locally narrowband* (FM, hopped, chirp, etc.) jammer over time and frequency. Since the interference is characterized by instantaneous frequency, its signature in the time-frequency domain is distinct from those of the noise and the spread spectrum signal, which have characteristically flat spectra by design. Therefore, time-varying filtering is achieved by masking the regions of high power concentration in the t-f domain, followed by a synthesis technique to recover the jamming signal. This constructed jammer is then subtracted from the incoming data to remove the interference component in the time domain.

Of particular interest in this paper are jammers with the constant modulus property. In this case, the jamming signal can be estimated more accurately through a two stage process. First, an estimate of the jammer is generated by masking out the signal and noise components of the received signal in the t-f domain and then performing a least-squares synthesis procedure. This estimate is then improved by projecting each sample of the synthesized signal on a circle representing the constant modulus of the actual jammer. By retaining the phase and performing this projection at each sample of the synthesized signal, we obtain an improved estimate of the jammer, which when subtracted from the received signal, a drastic enhancement in the DS/SS system performance is achieved.

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II. TIME-FREQUENCY SYNTHESIS

The Wigner-Ville Distribution (WVD) $W_x(n,\omega)$ of the discrete-time signal $x(n)$ is defined by [5] as

$$W_x(n,\omega) = 2\sum_{k=-\infty}^{\infty} x(n+k)x^*(n-k)e^{-jk\omega} \tag{1}$$

The synthesis problem is finding the sequence $x(n)$ whose WVD is closest in some sense to a desired real time-frequency distribution $Y(n,\omega)$ that may or may not represent a valid Wigner-Ville distribution.

If $Y(n,\omega)$ is indeed a valid Wigner-Ville distribution, a direct calculation of the corresponding time-domain sequence $x(n)$ can be accomplished according to [5]

$$x(n+k)x^*(n-k) = \frac{1}{2\pi}\int_{-\pi/2}^{\pi/2} W_x(n,\omega)e^{j2k\omega}d\omega \tag{2}$$

If, however, $Y(n,\omega)$ is not itself a valid WVD, we then wish to find a sequence $x(n)$ whose WVD best approximates $Y(n,\omega)$. This problem is formulated and solved in a least-squares sense by minimizing [4]

$$E(x) = \sum_n \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} \left|Y(n,\omega) - W_x(n,\omega)\right|^2 \tag{3}$$

It was shown in [4] that the even and odd indexed samples of the sequence $x(n)$ could be generated independently by solving the equations

$$C_e x_e = 4\|x_e\|^2 x_e \tag{4}$$

and

$$C_o x_o = 4\|x_o\|^2 x_o \tag{5}$$

where x_e and x_o are the eigenvectors corresponding to the largest eigenvalues of C_e and C_o in each equation. C_e and C_o are obtained from $Y(n,\omega)$ according to

$$C_e(p+1, m+1) = y(m+p, p-m) + y^*(m+p, m-p) \tag{6}$$

and

$$C_O(p,m) = y(m+p-1, p-m) + y^*(m+p-1, m-p) \tag{7}$$

where

$$y(n,m) = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} Y(n,\omega)e^{j\omega n}d\omega \tag{8}$$

The desired sequence *x(n)* can then be recovered from

$$x_e(n) = x(2n) \tag{9}$$

and

$$x_o(n) = x(2n+1) \tag{10}$$

Although this technique produces a sequence that minimizes the error in (3), the above solution is not unique. Since a multiplication of the even and odd components of *x(n)* by the phase constants a_e and a_o does not change the sequence's WVD, signal synthesis can only be achieved up to an arbitrary phase in both the even and odd components of the sequence. However, with the presence of a reference signal often chosen as the original data sequence, it is possible to find the parameters a_e and a_o that bring the synthesized signal as close as possible to the reference signal by phase matching. That is

$$a_e = \left[\frac{Imag\left[\sum_n s(2n)x_e^*(n)\right]}{Real\left[\sum_n s(2n)x_e^*(n)\right]}\right] \tag{11}$$

$$a_o = \left[\frac{Imag\left[\sum_n s(2n-1)x_o^*(n)\right]}{Real\left[\sum_n s(2n-1)x_o^*(n)\right]}\right] \tag{12}$$

where s(n) is the reference signal.

III. SELECTION OF THE SYNTHESIZED SIGNAL

Two possible approaches can be adapted in the application of t-f distribution synthesis techniques in interference mitigation in spread spectrum communications. The first approach is to synthesize the spread spectrum signal and correlate it with the PN sequence at the receiver, as shown in Fig (1-a). In the second approach, the jammer signal is synthesized from the t-f domain and then subtracted from the incoming data to remove, or at least reduce, the jammer contamination of the desired signal, as depicted in Fig (1-b).

The preference of using one approach over the other depends on the ability to obtain a synthesized signal which is a good copy of its correspondence in the input data. This requires the signal to be synthesized to have a clear t-f signature that distinguishes it from other components of the received data. Also, phase matching and restoration of the synthesized signal should be properly accomplished.

Figure 2 (a,b) shows an example of the Wigner-Ville distributions computed separately of a complex DS/SS signal and a linear FM interference. It is straightforward to conclude that synthesizing the spread spectrum signal from the t-f domain should generally be avoided due to the following reasons:

1) It is very difficult to distinguish between the noise and the spread spectrum signal signatures in the time-frequency domain. Therefore, time-varying filtering does not reduce the effect of noise or enhance the SNR.

2) Masking out the jammer by clipping or gating the high power values in the t-f domain may very well remove the main lobe, but it leaves behind the sidelobes which carry significant jammer power.

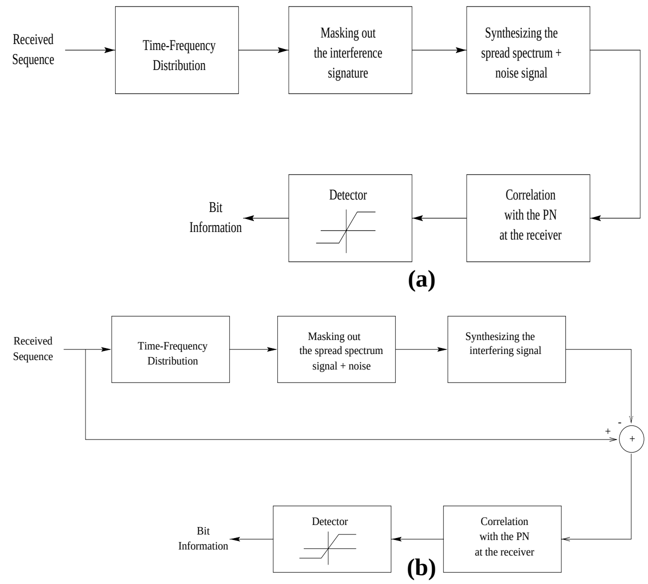

Fig. 1 Two approaches for interference mitigation in DS/SS communication systems (a) synthesizing the desired signal (b) synthesizing the interference

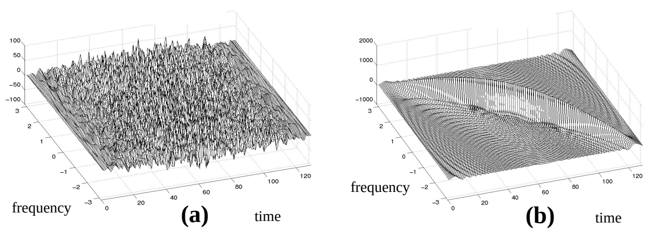

Fig. 2 (a) WVD of the DS/SS signal, L=128 (b) WVD of the chirp interference

3) The crossterms between the jammer and both the DS/SS signal and noise as well as the jammer self crossterms are often spread over the entire t-f domain, contaminating the spread spectrum signal within large regions of time and frequency.

4) Phase matching is often performed using the input data as a reference signal. Therefore, even with the assumption that the DS/SS signal is perfectly synthesized up to a phase ambiguity, the low desired signal power will make it very difficult to arrive at the correct phase by a simple matching to a data sequence in which the jammer is the dominant component.

Proper phase matching can therefore be obtained using the input data as a reference signal only through the second approach, provided that the JSR is relatively high, which is usually the case. It is expected, however, that the effectiveness of phase matching reduces with reduced jammer power.

IV. CONSTANT MODULUS PROJECTION

Let P_A define the constant modulus projection operator which when applied to the complex sequence *x(n)*, the resulting signal, $x_A(n)$, retains the phase of each sample of *x(n)*, but changes its amplitude to a constant value *A*. This is equivalent to projecting each sample of *x(n)* on the complex plane onto the closest point of a circle of radius *A* that is centered at the origin, as depicted in Fig. 3. Significant reduction of noise may be achieved through this operation when it is a applied to a signal that is known to be of modulus *A*, and whose phase is not significantly distorted.

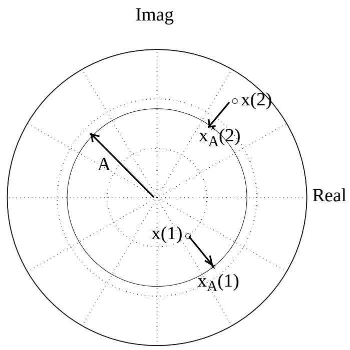

Fig. 3 Constant modulus projection operator (P_A) on the data sequence x(n)

In the excision of interference in DS/SS systems, it desirable to subtract an accurate estimate of this interference from the received signal prior to correlation with the PN sequence in order to enhance system performance. As stated in the previous section, a good estimate for this interference may come from synthesizing a masked t-f representation of the received signal. Fig. (4-a) depicts the original time-domain chirp jammer signal, and Fig. (4-b) is the synthesized interference estimate obtained from masking out the signal and noise components in the t-f domain where the JSR = 5 dB. Note that the phase of the even and odd samples are not matched either absolutely to the original jammer or relatively to themselves. After the phase matching operation defined by (16) and (17) is performed on the synthesized jammer estimate, the signal in Fig. (4-c) is produced. Projecting the phase matched synthesized jammer on the constant modulus circle produces the final jammer estimate, as shown in Fig (4-d). It is clear that through the phase matching and constant modulus projection, both the phase and modulus of the jammer estimate are significantly improved.

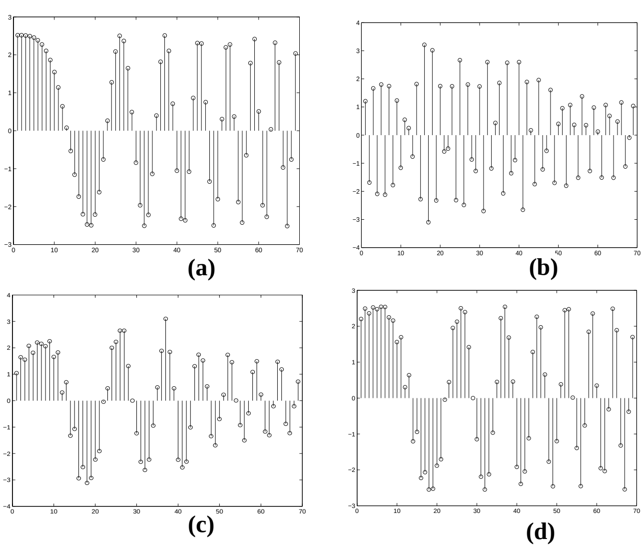

Fig. 4 Jammer estimates for a complex chirp (a) Original Jammer (b) Masked and synthesized jammer estimate (c) Phase matching introduced (d) Projection Introduced

There are several factors that may inhibit the effectiveness of projecting the jammer estimate onto a constant modulus circle in order to produce an improved estimation. If the value *A* of the modulus chosen is inaccurate, the projection operation may actually induce extra noise into the estimate of the interference. Also, even with the exact knowledge of *A*, if the phase of the estimate is inaccurate, projection may prove ineffective.

V. SIMULATION RESULTS

We now present computer simulations for the cases considered in the preceeding sections. The L=23 chips/bit are taken at a sampling frequency of 1 sample/bit for all simulations. In each case, the interference terms are either linear or sinusoidal FM. The linear FM interference is a chirp that sweeps the entire frequency band every bit period. The sinusoidal FM jammer is an FM signal whose instantaneous frequency (IF) is cos(.04 n). In this case, the jammer signal is offset to reach its highest IF in the middle of the bit duration. By so doing, we account for most of the self interference terms in the simulations. A zero-mean, white Gaussian noise is added in all cases at an SNR = 0 dB.

Figure 5 gives a benchmark for the rest of the simulations by plotting the bit error rates (BERs) against different JSRs for the case when the preprocessing implementing the t-f interference synthesis is disabled, allowing interference mitigation to be only performed using spreading/despreading operations. Also included in the same figure is the case where the jammer is masked and synthesized with phase-matching, then subtracted from the received signal without the benefit of projection. Note that enabling preprocessing without performing the projection actually increases the overall noise at the receiver, and performance is hindered from the unprocessed case.

Figure 6 shows the improvement in system performance when the masked-synthesized jammer estimate is projected onto a circle of constant modulus before it is subtracted from the received signal. Figure (6-a) illustrates the result of projecting the jammer estimate both before and after the phase matching is performed for the case of chirped interference. A sinusiodal FM jammer is considered in Fig. (6-b). In each case, a comparison with Fig. 5 makes it clear that as the interference increases in power, the estimate of the interference becomes more accurate, and lower bit error rates are produced. For these plots, the estimated modulus value used by the projection operator was taken from the received signal. At low JSRs, enabling preprocessing hinders the DS/SS system since the jammer estimate is highly contaminated by the signal and noise. Subtracting this poor jammer estimate actually serves to increase the noise in the signal. It is apparent that the interference mitigation using t-f synthesis techniques prior to correlation with the receiver PN sequence starts to produce improved results over the preprocessing disabled case around a JSR of 15 dB, depending on the t-f representation of the interference.

Also included in Figure 6 is the ideal case when the exact amplitude of the jammer is known and can be used to define the constant modulus circle used in the projection operation. This produces a further reduction in BER, as the projection always produces an improved estimation of the interference, and additional noise from the inaccuracy of estimating the amplitude of the projected signal is no longer produced.

Simulations were also run to show the effect of synthesizing the jammer without applying any masking in the t-f domain. Phase matching before and after projection was considered for both the chirp and sinusoidal FM jammers. Note that performing a phase matching prior to projection is equivalent to projecting the received signal in the time-domain and ignoring the t-f domain altogether. This technique also produces better results with increased jammer power, and it outperforms the original DS/SS case for JSRs above 20 dB, depending on the nature of the interference. However, this technique is inferior to the one considered in the previous figure.

VI. CONCLUSIONS

In this paper, mitigation of narrowband nonstationary interference in DS/SS communication systems is achieved by subtracting an estimate of the interference from the received signal. This estimate is obtained by masking out the signal and noise components of the received signal's time-frequency distribution, and synthesizing the result. When the interference is known apriori to be a polynomial phase which is uniquely described by its instantaneous frequency characteristics, an improved estimate can be generated by projecting the synthesized jammer estimate onto a circle of its constant modulus. The direct synthesis of the received signal from the t-f domain is also shown to be undesirable primarily due to the inclusion of the jammer sidelobes and the loss of a meaningful phase reference.

Simulations were performed for two jammer types utilizing several processing techniques. It was shown that the lowest BERs were obtained when the jammer estimate was the result of both a phase matching and a projection operation. The order of these two operations that produce the best system performance, however, depend on the JSR and the time-frequency characteristics of the jammer signal.

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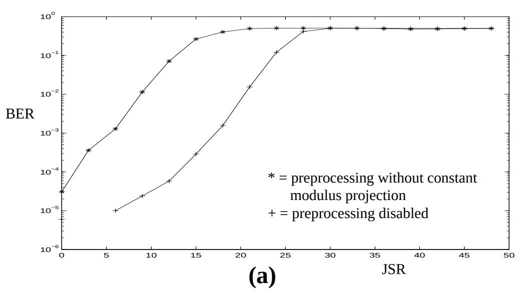
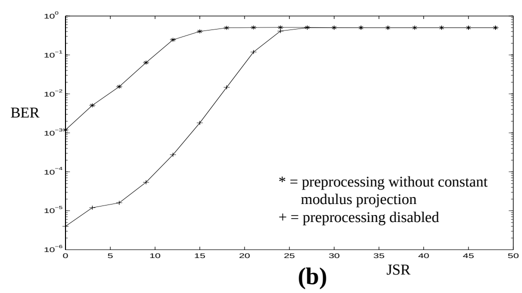
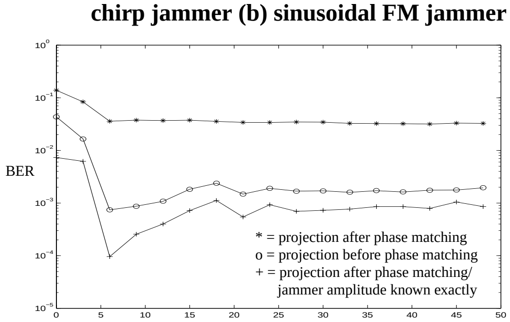


(a)

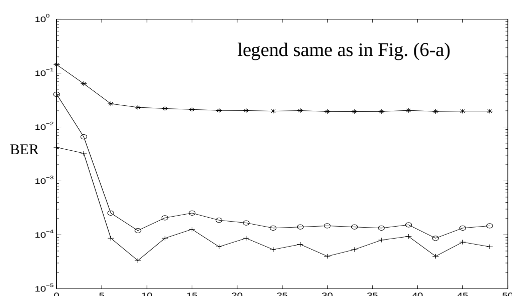


(b)

Fig. 5 BERs of the unprocessed and the preprocessed signal without constant modulus projection (a) chirp jammer (b) sinusoidal FM jammer



(a)



(b)

Fig. 6 BERs of the preprocessed signal with phase-matching and constant modulus projection for the cases of estimated and known amplitude of the interference (a) chirp jammer(b) sinusoidal FM