Jamming Mitigation Techniques for Spread Spectrum Communication Systems

Anil Kandangath
anil.kumar@asu.edu

Abstract

Spread spectrum (SS) communication systems are now commonly used in civilian applications such as cellular systems and GPS and are fast becoming one of the most commonly used systems. Very low power SS systems such as Global Positioning Systems are extremely vulnerable to high power jammers. A vast array of techniques are available to resolve this problem and this paper attempts to review some of them. A jammer mitigation technique that uses bilinear signal distributions to construct the jammer signal is also implemented. Finally a summary of different techniques w.r.t complexity level, application and size will be presented.

I. INTRODUCTION

SPREAD spectrum communication systems have an inherent immunity to interference, but it is not difficult to jam such systems either, particularly if the spread spectrum system uses very low power levels for communication. This report presents a review of available techniques for removal of jamming interference in spread spectrum communication systems with a particular emphasis on the Global Positioning System (GPS). GPS systems are increasingly being used in critical civilian and military applications such as navigation. It is possible to jam such systems using very low power jammers as described in [1]. A variety of techniques are available for separation and removal of jamming interference signals using adaptive filtering [4], [3], time-frequency domain filtering [5] , subspace processing [7] and amplitude domain filtering [6].

This report is organized in the following fashion. A short overview of spread spectrum communication systems is provided along with a summary of GPS signals. The factors affecting the choice of anti-jamming technique is discussed and the features of the techniques discussed here are presented in tabular form. A wide variety of anti-jamming techniques that can be used in widely varying situations are discussed and summarized. Finally a technique that uses time-frequency distributions and bilinear signal synthesis to synthesize the jammer signal is implemented and the results are shown.

II. DIRECT SEQUENCE SPREAD SPECTRUM COMMUNICATION(DSSS)

In DSSS, the information sequence is multiplied with a pseudo-noise (PN) sequence to construct a longer sequence. Since the PN sequence resembles noise, it is inherently wideband and as a result it *spreads* the spectrum of the information sequence too to create a noise-like sequence. Since this sequence is spread over a large frequency band, it is less prone to interference while its noise-like characteristics make it difficult to detect. GPS employs BPSK-modulated DSSS signals that are spread by a coarse acquisition (C/A) code and a precision (P) code. The C/A code is a Gold sequence with a period of 1ms

Arizona State University, Tempe, AZ - 85281, USA.

TABLE I
SUMMARY OF GPS SIGNALS

Modulation Scheme	BPSK
f_{sym}	50 symbols/sec
Narrowband interference tolerance	$\sim$ 40dB JSR
C/A code chip rate	1.023 MHz
C/A code period	1023 chips
P code chip rate	10.23 MHz
P code period	1 week

while the P code is a pseudorandom code with a period of 1 week and they are multiplexed in quadrature phases.

The inherent tolerance to jamming that is present in GPS signals due to the DSSS scheme is offset by the fact that signals are extremely weak since they are typically 20 to 30 db [1] below the noise floor, and hence it is easy to obtain a high Jamming to Signal(J/S) ratio. The different methods presented below are suited for use in varied situations that affect receiver design such as cost and size constraints, location and environment.

III. CHOICE OF ANTI-JAMMING TECHNIQUE

There are various methods that can be used to combat jamming in GPS systems, but the choice of technique depends on various factors such as cost, space constraints, power consumption and the environment where it is used. Jammers can be either narrowband or broadband. Narrowband anti-jamming techniques include adaptive filtering, time-frequency methods, adaptive antennas and subspace processing. Some time-frequency domain techniques and spatial processing using antenna arrays are well suited for combating broadband jammers. Time-frequency methods such as short time fourier transform (STFT) based processing, filterbanks, wavelet transforms or subspace processing are well suited for low cost, low power and small form factor applications. Antenna arrays are expensive and are relatively large, so their applications are limited to fixed location GPS systems, or systems aboard ships or aircraft. Missile systems usually have space constraints which make antenna arrays unsuitable. Another constraint is that of environment. For systems aboard aircraft or missiles, it is imperative to adapt quickly to changing environment due to the speed of motion. STFT based techniques are highly suited for such applications. Adaptive antennas can also designed be used in rapidly changing environments. The features of different anti-jamming techniques that may influence a decision are summarized in Table 2.

The Heisenberg-Gabor uncertainty principle puts an additional constraint on anti-jamming techniques. Since it is not possible to achieve any desired precision in both time and frequency a tradeoff between time or frequency must usually be made in time-frequency methods. Subspace processing and wavelet transforms usually produce better time-frequency resolution than STFT based methods.
A short summary of each method is presented in subsequent sections.

IV. SUMMARY OF VARIOUS JAMMER MITIGATION TECHNIQUES

*A. **Adaptive Filtering Techniques***

Adaptive Filtering [3], [4] is effective for narrowband jammers and can be used in applications that require low power and small size. The disadvantage of these methods is that they cannot be used when the jammer does not have a predictable signal structure. When the jammer has a predictable structure, it is possible to subtract the predicted jammer signal from the received signal. Adaptive filtering techniques attempt to minimize the error involved in such a predictive filtering using techniques such as the Least Mean Squares algorithm [1].

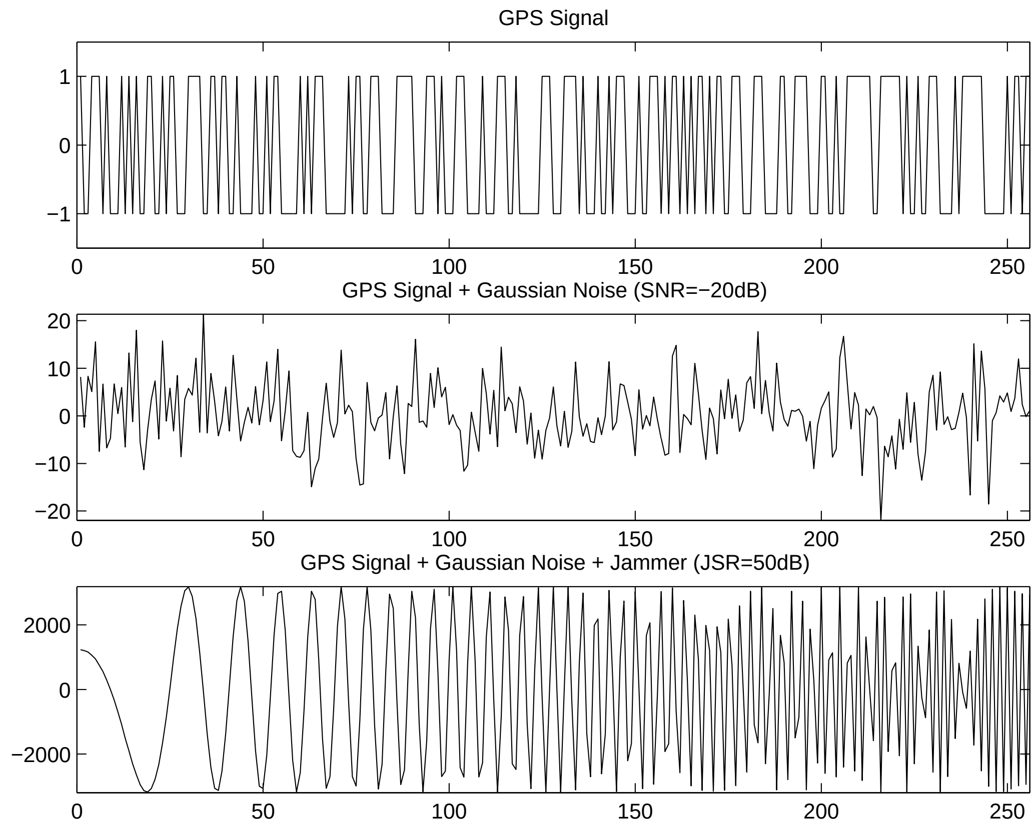

Fig. 1. The GPS signal is combined with additive white gaussian noise such that SNR=-20dB. Since GPS signals are not affected by jammers below 40dB, the jammer is combined with the noisy signal so that JSR=50dB. The jammer used is a chirp signal whose frequency increases linearly.

*B. **Time-Frequency Domain Filtering***

Time-frequency domain filtering attempts to represent the transform the received signal in such a way that it is possible to easily distinguish the jammer from the data signal. Since GPS signals are low power wideband signals, the high power jammer signals can usually be distinguished very easily in the frequency domain. Different Time-Frequency Distributions (TFDs) such as the Spectrogram and Wigner-Ville distribution can be used to represent the signal in the frequency domain. It only remains to choose an appropriate threshold to excise the jammer from the received signal to obtain the transmitted data signal by transforming it back to the time domain. The disadvantage of these methods lies in the fact that the jammer can be effectively separated only if it is sufficiently stronger than the GPS signal.

1) Short-Time Fourier Transform(STFT): STFT based techniques [5] are used for narrowband jamming excision and can be implemented in situations that require low power and small form factor devices. The STFT essentially moves a window through the signal and takes the FFT of the windowed region. This approach can adapt rapidly to changing environments. The signal is filtered in the frequency domain to remove the jammer components before being transformed back to the time domain.

2) Filter Banks: Filter banks [10] are used to reduce spectral leakage in the frequency-domain and to obtain perfect reconstruction of the desired signal in the time-domain. These have all the advantages of STFTs with minimum signal distortion and can be implemented in situations that require low power consumption and small size.

3) Wavelet Transforms: The use of wavelet transforms makes it possible to control the tradeoff between time and frequency better than STFTs. The Wavelet Transform (WT) is computed by repeatedly decomposing the signal into bands and passing it through low and high pass filters. The STFT gives a fixed frequency resolution for a particular transform length and is therefore not flexible. The WT however provides a flexible resolution in both time and frequency and is therefore a better TFD tool than the STFT.

4) Subspace Processing: There are many subspace processing techniques that can perform jammer excision. One approach [9] involves estimation of the instantaneous frequency (IF) of the jammer to construct a signal space where the jammer signal can be projected onto a single subspace to enable removal of the jammer. The instantaneous frequency of the jammer can be estimated from the time-frequency domain and the signal space can be constructed such that the jammer subspace is orthogonal to the data subspace.

Another method uses the IF of the jammer to construct a time-varying notch filter that removes the jammer. However this method also causes undesirable distortions in the signal. Bilinear signal distributions [7] can be used to obtain better jammer excision with reduced GPS signal distortion. This method uses the extended discrete-time Wigner distribution(EDTWD) to obtain a time-frequency distribution of the received signal. For a received signal represented as

$$\mathbf{x} = \mathbf{p} + \sum_{v=1}^{J} \mathbf{j}_v + \mathbf{w}, \tag{1}$$

it can be shown that for a single jammer, the EDTWD is given by

$$\begin{aligned} W_{xx}(t,f) &= W_{pp}(t,f) + W_{jj}(t,f) + W_{ww}(t,f) \\ &\quad + 2Re(W_{pj}(t,f) + W_{pw}(t,f) + W_{jw}(t,f)) \end{aligned} \tag{2}$$

Since the spread data signal and the additive noise are both wideband, all the terms in Eqn. 2 are spread over the entire t-f domain except for $W_{jj}(t,f)$ which is localized. This method selects a threshold value for the EDTWD to create a mask to extract the jammer signal such that the extracted signal contains almost all of the jammer and none of the signal. This method can also be used when multiple jammer signals are present.

*C. **Adaptive Antennas***

Adaptive Antennas use spatial filtering techniques to eliminate the jammer signal. Like adaptive filtering, these techniques attempt to optimize a cost function. These techniques can be adapted for both narrowband and wideband jammers, but have the disadvantage of not being able to handle a large number of jammers in multiple locations. In antenna arrays, at least two antennas are required to eliminate the effect of jammers from one location, hence such arrays cannot eliminate jammers originating from more locations than the number of antennas present. The two basic approaches to spatial filtering are Null Steering and Beam Forming.

TABLE II

SUMMARY OF VARIOUS GPS ANTI-JAMMING TECHNIQUES REVIEWED

	Cost	Size	Power	Flexibility	Complexity
Adaptive Filtering	low	small	low		
Time-Freq Domain					
STFT	low	small	low	env	low
Filter Banks	low	small	low	env [1]	low
Wavelet Transform	low	small	low	env, res [2]	low
Subspace Processing	low	small	low		
Adaptive Antennae					
Null Steering	high	large	high		high
Beam Forming	high	large	high		high

1) Null Steering: Null steering uses the simple concept that GPS signals are much below the thermal noise level and hence any signal that has a power above the thermal noise has to be an interfering signal. The antennae in the array are weighted so that any particular signal can be nulled. Null steering constantly computes the weights in order to minimize the received energy level. In effect, this technique attempts to steer the antenna away from the jammer. This method has the disadvantage of potentially reducing the signal level too. This technique is a precorrelation technique and does not require any knowledge of the desired signal.

2) Beam Forming: Beam Forming tries to adjust the antenna in order to maximize the SNR. In effect, the antenna beam is steered in the direction of the desired signal. If the direction to the desired satellite is known, beam forming can effectively maximize the SNR. It is however, possible to end up in situations where the jammer is in the same direction as the signal source. This is a postcorrelation technique since the desired signal has to be correlated in order to obtain the SNR. Also, prior knowledge of the signal direction and the host location is required.

V. JAMMER MITIGATION USING BILINEAR SIGNAL REPRESENTATIONS

A. Bilinear Signal Representations

Time-frequency distributions (TFDs) are an effective way of identifying a narrowband jammer in a spread signal. The TFD of the jammer can be extracted using a mask which is designed to extract as much of the jammer energy as possible while leaving out most of the spread signal using a carefully constructed threshold. The jammer TFD can be used to synthesize the jammer signal using bilinear signal synthesis techniques.

B. Masking and Threshold Selection

Since the received signal has the desired low-energy spread spectrum signals, additive noise and the high-energy jammer, the time-frequency mask has to be designed such that it removes as little desired signal power as possible. The EDTWD for a single jammer case is described in Eqn. 2 where the autoterms are defined as

[1] changing environment

[2] resolution

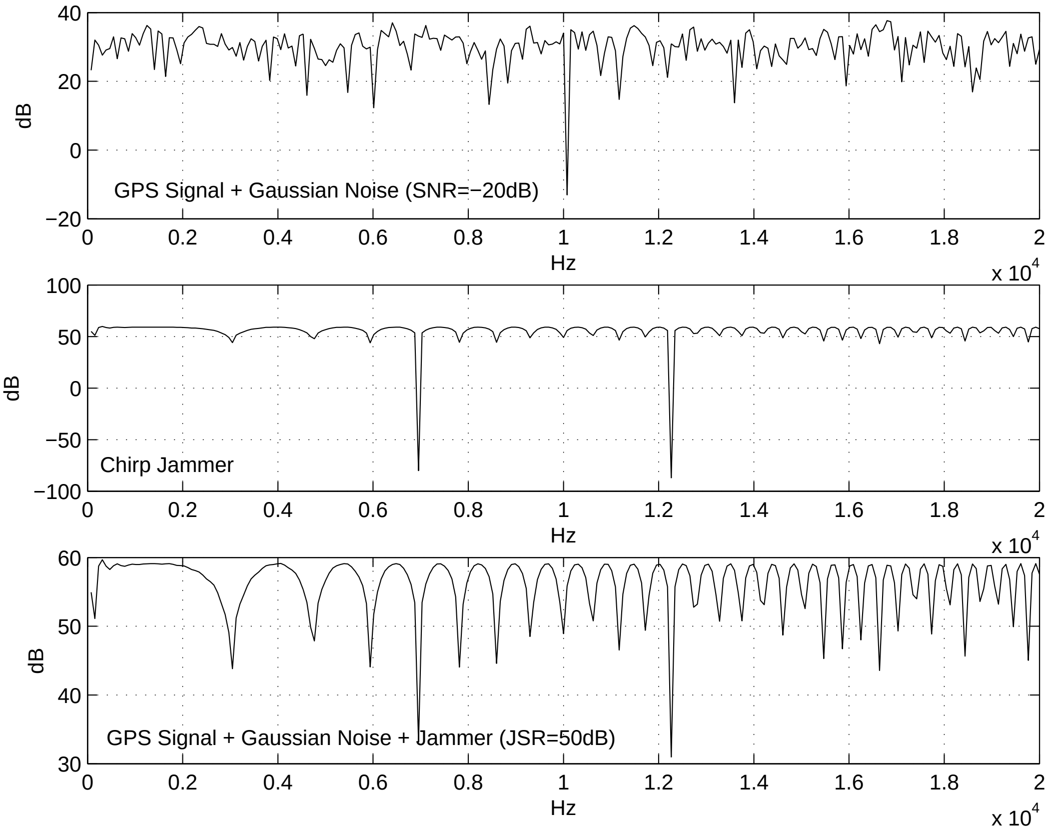

Fig. 2. The frequency domain representations of the signals is shown. The noisy GPS signal is wideband and is spread over the entire frequency spectrum. The chirp jammer has a frequency that increases linearly from 0 to 20kHz. The resulting contaminated signal has a power spectrum as shown.

$$W_{xx}(t,f) = \sum_{k:t+\frac{k}{2}\in Z} x(t+\frac{k}{2})x^*(t-\frac{k}{2})e^{-j2\pi kf}, \quad t = 0, \pm\frac{1}{2}, \pm 1, ..., \tag{3}$$

and the crossterm EDTWD between x(t) and y(t) are defined as

$$W_{xy}(t,f) = \sum_{k:t+\frac{k}{2}\in Z} x(t+\frac{k}{2})y^*(t-\frac{k}{2})e^{-j2\pi kf} = W^*_{xy}(t,f) \tag{4}$$

As noted before, all the terms in Eqn. 2 are spread over the entire t-f domain except for the jammer autoterm $W_{jj}(t,f)$. This makes it easy for us to eliminate the jammer as it only remains to design an appropriate threshold for jammer excision. The threshold is set [8] as

$$C = \alpha\sqrt{\sigma P_x} \tag{5}$$

where P_x is the total energy of the received GPS signal and σ is the standard deviation of white noise which is generally known. α is a constant which is chosen to be between 3 to 5. The choice of α affects the Signal to Interference Noise Ratio (SINR) as demonstrated in [8].

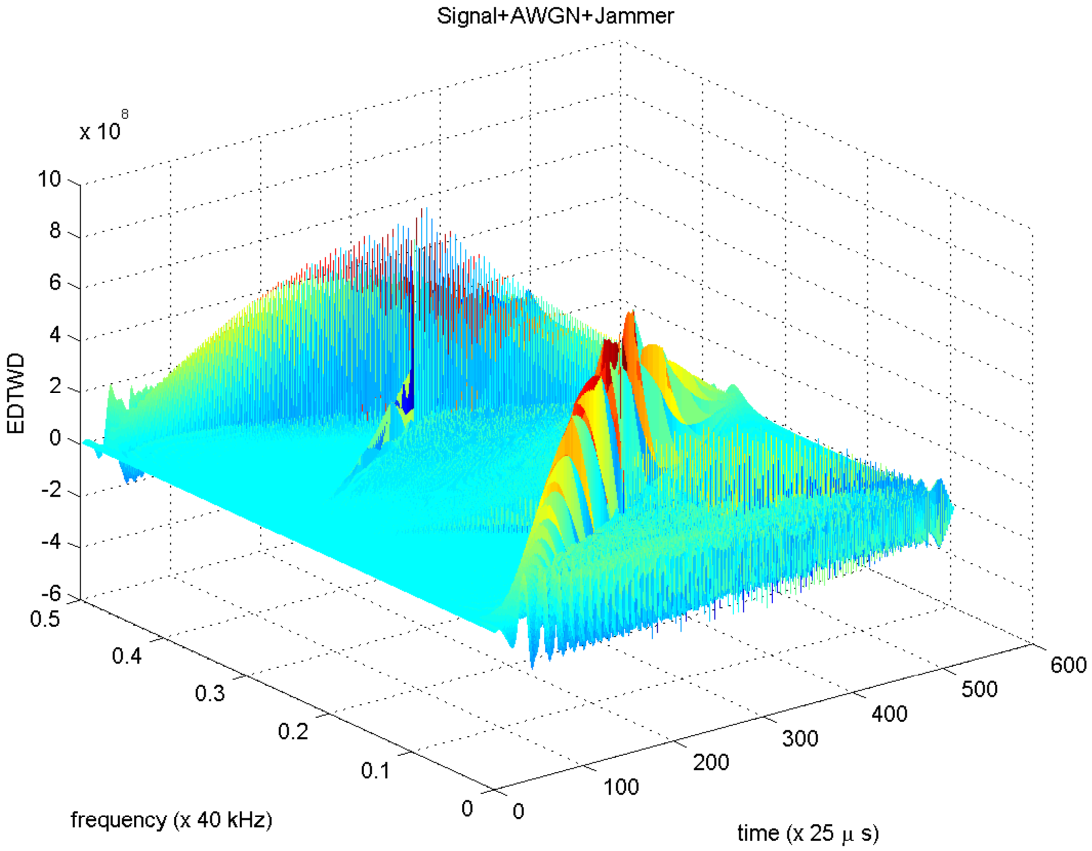

Fig. 3. Time-Frequency representation for the received contaminated signal. The GPS signals have low power and are spread all over the region, while the narrowband jammer signals are localized and have strong peaks which makes it easy to extract the jammer.

C. *Bilinear Signal Synthesis*

Once the jammer TFD is extracted from the TFD of the received signal, it is necessary to have the means of reconstructing the jammer signal from the TFD. This problem has been addressed by Hlawatsch and Krattenthaler [8] who have developed approaches to synthesize a signal $x(t)$ from the approximate Bilinear Signal Representation (BSR) $T(\sigma, \epsilon)$. In our case, the BSR corresponds to the TFD $W_{jj}(t, f)$. The detailed procedure is given in the appendix.

VI. Results

The TFD clearly showed the narrowband jammer due to the low power and wideband nature of the GPS signal. After choosing a threshold for jammer extraction, it was possible to successfully extract the jammer time-domain sequence using bilinear signal synthesis. The synthesized jammer showed the same frequency characteristics as the original jammer (chirp), but the envelope was slightly distorted. However, the method demonstrated the ability of bilinear signal synthesis to synthesize time-domain signals from their time-frequency representations, as also the principle of jammer extraction using TFDs. There exist other subspace processing methods too, such as projection techniques discussed earlier.

VII. Conclusion

Spread spectrum signals such as GPS signals can tolerate jammers to a large extent but they are still susceptible to jammers due to their low signal strength. We can see that while there are many techniques

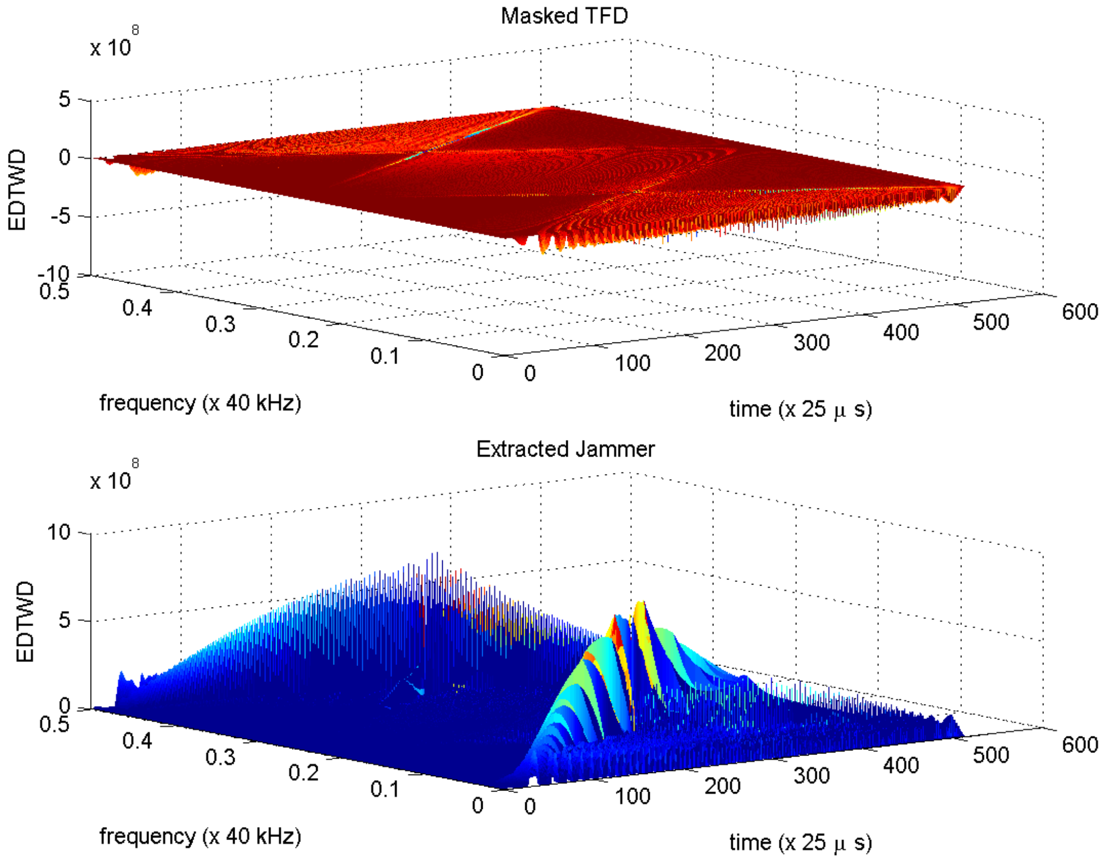

Fig. 4. Time-Frequency representation for the masked signal and the extracted jammer. The jammer can be extracted at different threshold levels which depend on the value of α. In this example α = 3.0.

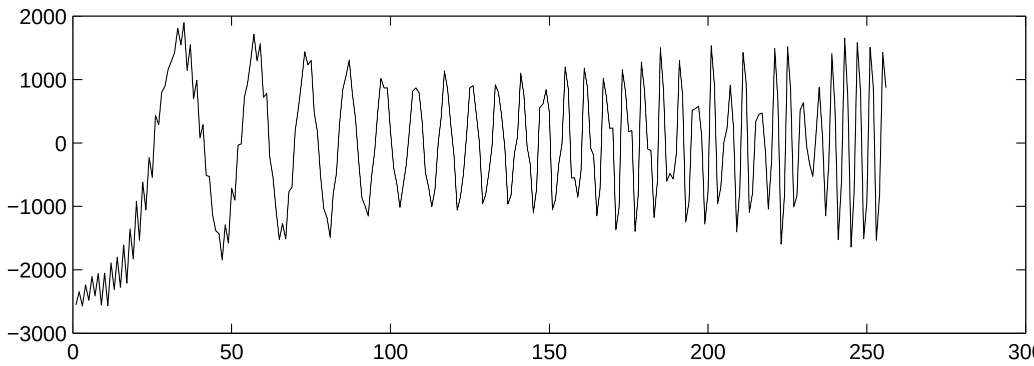

Fig. 5. The chirp jammer as synthesized by the bilinear signal synthesis method after extraction from the received signal TFR.

available for jammer mitigation and excision from spread spectrum communication systems, no single method can provide jammer immunity in every situation. Most computational techniques are useful only for narrowband jammers, while antenna based techniques prove useful against wideband jammers. The choice of antijamming technique also depends on the environment, cost and size and a combination of techniques might be necessary to combat jamming.

APPENDIX A
BILINEAR SIGNAL SYNTHESIS ALGORITHM

The algorithm [7], [8] for synthesizing a signal from the time-frequency representation is as follows.

1. Compute the time-frequency distribution (say EDTWD). Let the TFD be described by $W_{xx}(t, f)$.
2. Generate the inverse fourier transform of $W_{xx}(t, f)$.

$$p(t, \tau) = \int W_{xx}(t, f) e^{j2\pi\tau f} df \tag{6}$$

3. Construct the matrix $Q = [q_{i,j}]$ with

$$q_{i,j} = p(\frac{i+j}{2}, i-j) \tag{7}$$

4. Form the Hermetian component matrix Q_H.

$$Q_H = \frac{1}{2}[Q + Q^H] \tag{8}$$

5. Use eigen-decomposition to obtain the maximum eigen value λ_{max} and the corresponding eigen-vector u. The synthesized signal is given by

$$x = e^{j\phi}\sqrt{\lambda_{max}}u \tag{9}$$

   where ϕ is an unknown representing the phase ambiguity.

REFERENCES

[1] Bradley P. Badke, ”Global Positioning System Anti-Jamming Techniques”, *Ph.D Dissertation*, Arizona State University, 2002.

[2] Raja Iqbal, and J.S Bedi, ”Performance Analysis of Interference Rejection Techniques in Spread Spectrum Communication”, *TENCON ’91, IEEE Region 10 International Conference on EC3-Energy, Computer, Communication and Control Systems*, Vol. 3 , Aug. 28-30, 1991

[3] Laurence B. Milstein, ”Interference Rejection Techniques in Spread Spectrum Communications”, *Proceedings of the IEEE*, Vol. 76, No. 6, June 1998

[4] A. Haimovich, and A. Vadhri, ”Rejection of Narrow-Band Interferences in PN Spread Spectrum Systems Using an Eigenanalysis Approach”,IEEE Seventh SP Workshop on Statistical Signal and Array Processing, pp.383-386, 1994.

[5] Robert C. DiPietro, ”An FFT Based Technique for Suppressing Narrow-Band Interference in PN Spread Spectrum Communications Systems, ”ICASSP-89”, Vol. 2, pp.1360 -1363, May 1989.

[6] R. Abimoussa, R.J. Landry, ”Anti-jamming solution to narrowband CDMA interference problem,” *Canadian Conference on Electrical and Computer Engineering,* Vol.2, pp. 1057-1062, 2000.

[7] Yimin Zhang, Moeness G. Amin, and Alan R. Lindsey, ”Anti-jamming GPS Receivers Based on Bilinear Signal Distributions”, *IEEE Military Communications Conference, Communications for Network-Centric Operations: Creating the Information Force*, Vol. 2, pp. 1070-1074, 2001.

[8] Werner Krattenthaler and Franz Hlawatsch, ”Time-Frequency Design and Processing of Signals Via Smoothed Wigner Distributions”, *IEEE Transactions on Signal Processsing*, Jan 1993.

[9] Liang Zhao, Moeness G. Amin, and Alan R. Lindsey, ”Subspace Projection Techniques for Anti-FM Jamming GPS Receivers”, *Proceedings of the Tenth IEEE Workshop on Statistical Signal and Array Processing*, 2000.

[10] W.W. Jones, K.R. Jones, ”Narrowband Interference Suppression Using Filter-Bank Analysis/Synthesis Techniques,” *IEEE MILCOM Conference,* San Diego, California, Paper 38.1.1, 1992.