Non-linear Filtering Techniques for Narrow-Band Interference Rejection in Direct Sequence Spread-Spectrum Systems

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Abstract

The problem of narrow-band interference rejection in Direct Sequence Spread-Spectrum (DS-SS) systems has been studied extensively, and several suppression techniques have been proposed. Technological advancements have made possible real-time forward and inverse Fourier transforms, and thus allowed transform domain signal processing. In this paper, we propose the use of a conditional non-linear median filter operating in the transform domain, for the detection and suppression of narrow-band signals of sufficient power, without regard to their center frequency, bandwidth, or peak power. As it will be shown, this approach offers several significant advantages over similar techniques that have been used so far.

1 Introduction

It is well known that direct sequence spread spectrum signaling reduces the effect of interference due to intentional jamming. When the interference is narrow-band, the cross-correlation of the received signal with the the replica of the PN (pseudo-noise) code reduces the level of interference by spreading it across the frequency band occupied by the PN signal. Thus, the interference is rendered equivalent to a lower-level noise with a relatively flat spectrum.

The interference immunity of a direct sequence spread spectrum (DS-SS) communications system can be further improved by processing the signal prior to cross correlation, where the objective is to reduce the level of the interference at the expense of introducing some distortion to the desired signal. This processing can be accomplished by exploiting the wideband spectral characteristics of the desired DS signal and the narrowband characteristic of the interference.

Advancements in VLSI and surface acoustic wave (SAW) technology have made possible signal processing techniques that could not have been seriously considered in the past, such as Fourier transform domain processing. In this type of processing, the signal to be processed is Fourier transformed in real-time using either SAW or VLSI devices; the resulting Fourier domain signal is then processed followed by an inverse Fourier transform to recover the desired time domain signal. This type of processing offers several advantages. Filters that otherwise would be tedious to design in the time domain, such as tunable band-pass and notch filters, become straightforward in the frequency domain. Also, more sophisticated non-linear processing that would have been almost impossible in the time domain, becomes relatively easy in the transform domain.

Several techniques have been proposed for the detection and filtering of narrowband noise in DS-SS systems, varying from simple band-pass and notch linear filters ([1],[2]), to a variety of more sophisticated adaptive and non-linear filters ([3],[4],[5]). Simple band-pass and notch filters remove a range of frequency components where interference is expected to be ([1],[2]). Since significant frequency components of the desired signal are also lost, considerable distortion and artifacts result in the time domain. Other approaches ([3]) scan the spectrum of the input signal searching for large impulses that are subsequently suppressed, or they utilize saturation properties of amplifiers for soft-limiting of large signal components to minimize the effect of jammers. These techniques however, not only they require extensive hardware, but they may have limited success when multiple jamming sources are present. They may also introduce considerable signal distortion when jammers are not present.

In this paper, we concentrate on the problem of interference rejection for the cases of single and multiple-tone jammers. Interference rejection of single-tone or multiple-tone jammers is complicated by the following facts: The center frequency, power and phase of each interferer, as well as how many are present at any time, are generally unknown. Furthermore, their parameters (e.g. center frequency) may vary from time to time. Suppression however, is eased by the fact that usually all the energy of each interferer is concentrated either on a single frequency, or within a narrow band, and therefore their spectrum has large impulses. Suppression filters must tolerate all these complications, while introducing a minimal distortion to the desired signal.

We propose the use of a non-linear conditional median filter for frequency domain interference suppression. This approach in addition to being simple and efficient, it offers several other advantages compared to so far used techniques.

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2 Model

The block diagram of the receiver of our DS-SS system is shown in Figure 1. The received signal $r(t)$ is equal to:

$$r(t) = s(t) + j(t) + n(t) \qquad (1)$$

The system uses a BPSK modulation scheme with a PN sequence used for the signal spreading function. The PN code is chosen such that a data bit is modulated by a full sequence of the PN code. The PN code is assumed to be a sequence of N independent binary random variables, each one of which assumes the values of $+1, -1$ with equal probability. The signal can be expressed as:

$$s(t) = \pm\sqrt{2P_s}\sum_{i=0}^{N-1}\alpha_i$$
$$[\mathrm{U}(t - iT_c) - \mathrm{U}(t-(i+1)T_c)]cos(\omega_0 t) \qquad (2)$$

where $NT_c = T_b$, P_s is the signal power, $\mathrm{U}(t)$ is the step function, and T_c, T_b are the chip and bit periods, respectively. The general expression of a multiple-tone interferer is as follows:

$$j(t) = \sum_{k=1}^{K}\sqrt{2P_{j_k}}cos((\omega_0 + \delta\omega_{0k})t + \theta_k) \qquad (3)$$

where P_{j_k} is the jamming power, $\delta\omega_{0k}$ the offset from the carrier frequency ω_0 and θ_k is the phase of the k-th interferer. The phases of the interferers are assumed to be independent random variables, each one of which is uniformly distributed in the interval $[-\pi, \pi]$.

The noise $n(t)$ is AWGN (additive white gaussian noise) of zero mean and two-sided power spectral density $N_0/2$. It is worth mentioning that the receiver depicted in Figure 1, without the block entitled "Frequency Domain Processor", is optimum in the presence of AWGN. A more detailed block diagram of the frequency domain processor, which is used for interference suppression, is exhibited in Figure 2.

3 Conditional Median Filters

The median filter (MF$_L$) [6] is a local rank operator that slides a window of size L along an input sequence, and at each position the output is taken to be the median of the window elements, i.e.:

$$y_i = \mathrm{median}(x_j | j = i-k, ...i+k) \qquad (4)$$

where x_i, y_i are the input and output sequences respectively, and $L = 2k+1$ is the window size. Two fundamental properties of this non-linear filter are that it preserves well signals with smooth transitions, while any impulses in the input that are narrower than $k = (L-1)/2$, will be removed from the output sequence without reference to their polarity, amplitude, or position within the sequence. This means that if a smooth signal is contaminated with random impulses, the MF will be the ideal filter choice to remove these impulses. If however the impulse-free signal is oscillatory, then while the MF removes the stray impulses, it will also introduce significant signal alterations. The spectrum, of a DS-SS signal has oscillatory components riding on a $\sin(x)/x$ envelope and this type of signal will not be preserved by a MF. The presence of narrowband jammers, however, will be evident by narrow impulsive frequency components, that are usually significantly larger than other signal components. These large impulses can be removed without effect to lower-level signal frequency components, by filtering with a modified version of the MF which is named the conditional median filter (CMF). The CMF will selectively remove impulses depending on both their relative width as compared to the window size, and their relative amplitude compared to adjacent signal values. The CMF operates as follows: Assume that the filter window is centered on input sample x_i, and y_i is the output sample computed according to (4). Then:

$$y_i = \begin{cases} x_i, & \text{if } |y_i - x_i| < C; \\ y_i, & \text{otherwise.} \end{cases} \qquad (5)$$

where C is a threshold parameter. The CMF will not affect any signal that does not meet the threshold condition in (5), but any impulse that meets both the maximum width (imposed by the window size) and minimum amplitude (set by the C parameter) conditions, will be suppressed. Note that when $C = 0$, then the CMF reduces to an (unconditional) MF.

The performance of the CMF is illustrated in Figure 3. Figure 3(a) displays the main lobe of the magnitude Fourier spectrum of a DS signal (randomly generated sequence of chips), and Figure 3(b) is the spectrum of the same sequence corrupted by four single-tone interferers of unknown frequencies. Figure 3(c) displays the result of a CMF$_5$ with the threshold manually set at $C = 400$. Notice that the large impulses have been removed, without any effect to lower-level values. It is worth mentioning that the same result as in Figure 3(c) would have been produced if a CMF with larger window were used.

4 New Interference Suppression Approach

In Figure 1, the block diagram of a BPSK DS-SS receiver with interference suppression capabilities (frequency domain processor) is shown. We propose to use a frequency domain processor, as in Figure 2, with the CMF as the interference suppressor. The important advantages of this approach are:

- The center frequency, bandwidth, phase, and peak power of each interferer, need not to be known a-priori, or to be determined by initial search cycles (as in other approaches) that first locate and then suppress each jammer.

- Multiple narrowband interferers are automatically handled without any modifications.
- The filter will selectively affect only those frequency components that meet the minimum power, and maximum bandwidth conditions, but not any other components. Therefore, minimum possible alteration to the overall signal is introduced.
- The filter remains inactive when no interference is detected.
- Two simple filter parameters, namely the window dimension and the threshold value, determine the maximum bandwidth and minimum power requirements for impulse removal, respectively. The threshold parameter can be set either manually depending on the type of signal to be processed, or adaptively based on previous signal values, or other signal parameters.
- Since both FFT and MF hardware is available, simple real-time implementations with precisely known processing delay time are possible.

Theoretical derivation of the performance of this approach is difficult due to the non-linear characteristics of the CMF. Instead, the performance judged by the bit-error rate, is calculated via computer simulation of the receiver.

5 Simulation Results

For comparison purposes two other receivers are also simulated. One uses a frequency domain notch anti-jam filter [1], and the other does not use any anti-jam filtering (see Figure 1). It is assumed that interference is powerful enough to activate the CMF. In these simulations, FFT was used, and only the magnitude spectrum was processed.

The simulation package that we have developed is divided into three blocks: The transmitter, the channel effect simulator, and the receiver. The transmitter generates a seven bit PN sequence which spreads the data spectrum by multiplying each transmitted data bit. The channel effect simulator adds jammers and AWGN to the signal. The jammer used in the simulations was a single-tone, located within the signal main lobe, with variable amplitude and phase randomly changing from bit to bit within the interval $[-\pi, \pi]$. In the receiver each transmitted bit is processed individually. The CMF window size used was $L = 5$ and the threshold parameter was manually set at $C = 70$. The notch-filter was 2-bin (discrete frequency components) wide, and it was centered on the jammer. The received signal was low-pass filtered (see Figure 1) to the main lobe only.

Simulation results are summarized in Figure 4, which displays the bit error probabilities versus signal to noise ratio (E_b/N_0) for the single jammer case and for three jamming levels (P_{j_1}/P_s). From Figure 4 the following can be observed:

- There is a significant improvement when anti-jam processing is used.
- In the presence of interference the performance of the CMF and notch filter techniques is about the same.
- In the absence of interference, the performance of the CMF technique is identical to that of the matched filtering with no-antijam technique. This is because the CMF remains inactive when no jamming is present. The notch filter on the other hand continues to notch out signal components.

Another important advantage of the CMF technique which is not obvious from Figure 4 is that the CMF uses no information about the interferer, except that it is sufficiently powerful and narrow. In contrast, the notch filter bandwidth and position were chosen by assuming knowledge about the frequency and bandwidth of interferer. This information, however, is generally not a-priori known. If for example the jammer increases its bandwidth or changes its center frequency the CMF will automatically account for that, where as the notch filter may totally fail to combat the jammer without re-adjustment.

6 Discussion and Conclusion

Due to very long computer run-time of the simulations, the results derived so far are not exhaustive. Additional results for the single-tone and multiple-tone jammers for a spread spectrum system with higher processing gain is an issue of an ongoing research effort. In our simulations we used a pessimistic processing gain of 7. This illustrates less effectively the performance difference between a conventional DS-SS system with no anti-jam technique and a system with anti-jam capabilities (e.g., notch filter, CMF filter).

The use of a CMF in the frequency domain for interference suppression offers several advantages. The results displayed in Figure 4 demonstrate the robustness of the proposed approach compared to that of the notch filter. Comparisons with other frequency domain techniques as those used in [3], were not performed since those techniques require extensive hardware development, that is not necessary for our approach.

In conclusion, we proposed a robust method for narrowband interference suppression. A primary application is anti-jamming protection of DS- SS systems. The performance of this approach was demonstrated via computer simulations.

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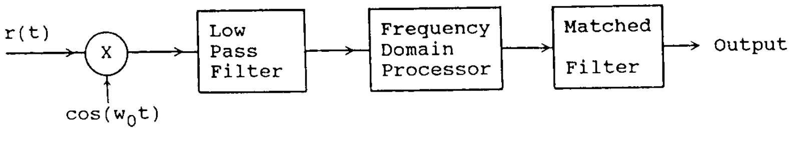

Figure 1: Block diagram of a BPSK DS spread spectrum receiver with frequency domain (interference suppression) processor

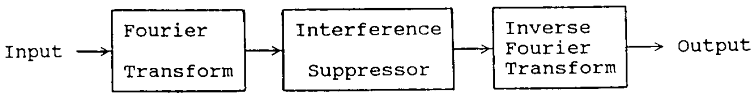

Figure 2: Block diagram of a frequency domain processor

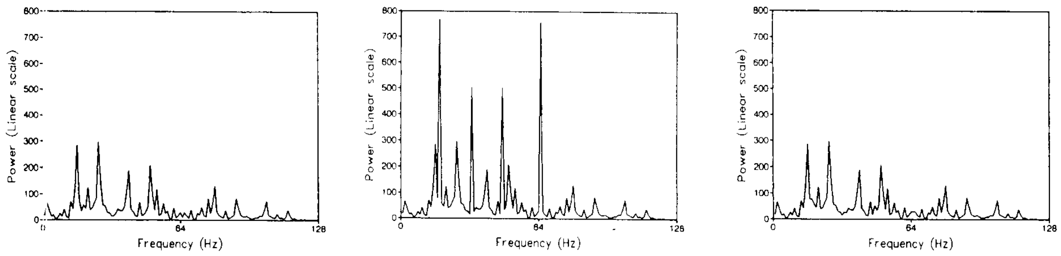

Figure 3: Interference suppression using a CMF (a) Spectrum (main lobe) of a DS signal. (b) Spectrum of a DS signal corrupted by four single-tone interferers. (c) Figure 3(b) processed with an CMF$_5$ ($C = 400$).

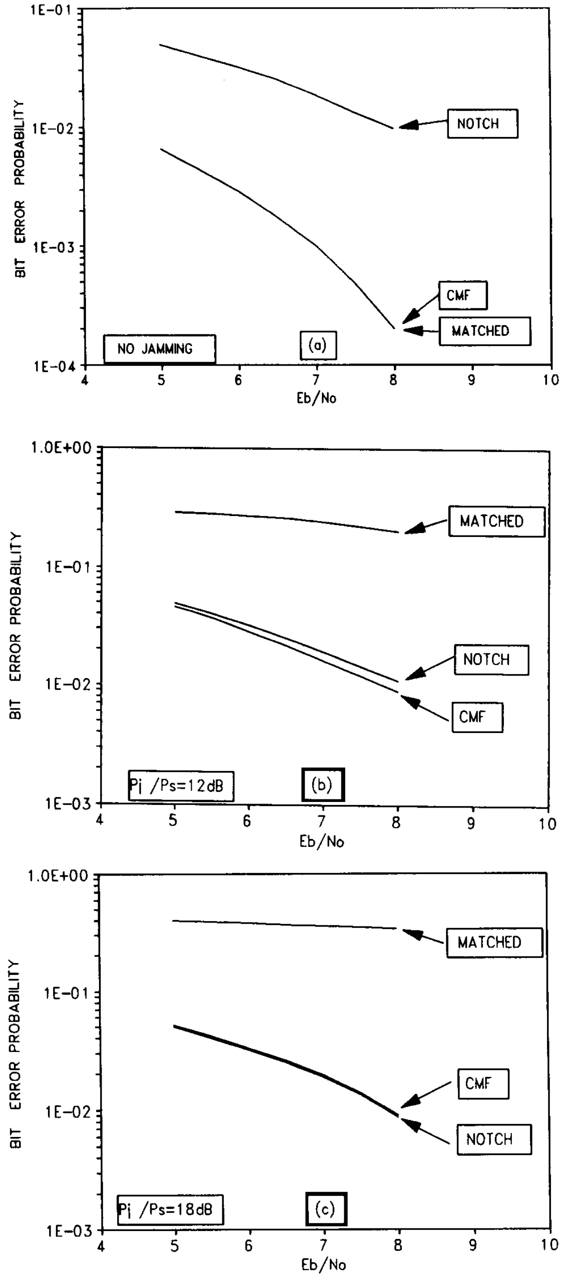

Figure 4: Bit error probabilities for three simulated receivers using no anti-jam (labeled as matched), notch and CMF filters, for the single jammer case and three different jamming (P_j/P_s) levels.