A SMART TIME-FREQUENCY EXCISER FOR SPREAD SPECTRUM COMMUNICATIONS[1]

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ABSTRACT

In this paper, a smart Adaptive Time-Frequency (ATF) excision algorithm is proposed to perform interference suppression in spread spectrum communications. The ATF exciser has the intelligence of deciding the domain of the excision. Additionally, adaptive subband transforms are utilized for frequency domain excision in order to track the spectral variations of the incoming signal. This adaptive transform approach brings significant performance improvements in spectral resolution. Bit error rate (BER) performance of the novel ATF exciser-based direct sequence spread spectrum (DSSS) system receiver is compared with other existing transform domain-based DSSS receivers. Time localized or frequency-localized interferer types and additive white Gaussian noise (AWGN) channels are considered in this study. In all cases, the smart ATF exciser-based DSSS receiver drastically outperforms the existing competitors. Its robust performance against the variations of the interferers is verified.

I. INTRODUCTION

Spread spectrum modulation techniques produce a transmitted frequency spectrum that is much wider than the information bandwidth. This increase in bandwidth yields a processing gain which provides the desired features like interference suppression, energy density reduction, good time resolution, and code-division multiple access in digital communications systems [1]. However, the interference rejection capability of spread spectrum systems is limited. It is defined by the processing gain of the spread spectrum system. Among different spreading techniques, direct sequence spread spectrum or pseudo-noise (PN) modulation is considered in this study.

The DSSS transmitter spreads the incoming data bit stream d_l ($d_l \in \{-1,1\}$, $\forall l$) and, therefore, its spectrum by multiplying it with the spreading sequence $\underline{c}$ ($c_i \in \{-1,1\}$, for $i = 1,..K$). During the transmission the channel adds a noise term $\underline{n}_l$ and other interferences $\underline{j}_l$. Therefore, the received signal $\underline{r}_l$ can be written as

$$\underline{r}_l = d_l\underline{c} + \underline{j}_l + \underline{n}_l. \quad (1)$$

The data bit stream d_l has a bit-to-bit duration of T_d seconds. The PN spreading code has a chipping rate of T_c seconds where $T_d \gg T_c$. Hence, the length of the PN code is obtained as $K = \frac{T_d}{T_c}$. Without any interfering signal $\underline{j}_l$, the transmitted DSSS signal has a flat spectrum. The receiver correlates the signal with a properly synchronized version of the spreading sequence $\underline{c}$. The length-K PN spreading code has the energy, $\underline{c}\,\underline{c}' = \sum_{i=1}^{K} c^2(i) = K$. The decision variable is therefore, obtained as

$$\begin{aligned} U_l &= \underline{r}_l\underline{c}' = d_l\underline{c}\,\underline{c}' + \underline{j}_l\underline{c}' + \underline{n}_l\underline{c}' \quad (2) \\ &= Kd_l + \underline{j}_l\underline{c}' + \underline{n}_l\underline{c}'. \end{aligned}$$

Eq. (2) indicates that the despreading operation recovers the desired signal while spreading the interference. In fact, if the interference power is greater than the system's jamming margin, the DSSS receiver fails to operate. The interference immunity of a DSSS receiver can be further improved by suppressing or excising $\underline{j}_l$ in Eq. (1) before despreading. Two classes of narrowband interference rejection schemes for DSSS communications have been extensively studied in the literature; least mean square estimation techniques, and transform domain processing structures [2][3].

In the first approach, when the statistics of the desired signal, interference and noise are known, the coefficients of the excision filter can be obtained optimally from Wiener-Hopf equations. However, in practice it is only possible to estimate the correlations. This leads to adaptive forms of these equations which are not necessarily optimal.

Transform domain excision techniques often utilize a fixed block transform, such as a discrete Fourier transform (DFT), to map the signal into the frequency domain. Independently, eigen-analysis based excision techniques have also been proposed for narrowband interference scenarios in DSSS communications. This indeed is the optimal block transform, Karhunen Loeve Transform (KLT), based excision technique. However, their performance is limited by the transform size or resolution. More recently, better frequency localized subband transforms over the conventional block transforms have been employed for excision in DSSS communications [4]. It is naturally observed that fixed subband transforms have similar limitations as fixed block transforms, such as interband spectral leakage and fixed resolution. Particularly, for non-stationary interferers such as spikes, transform domain-based techniques fail [5].

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The proposed smart ATF exciser carries out an efficient examination of time and frequency domain properties of the received signal. It brings the novel concept of domain switchable signal processing. The smart ATF exciser first identifies the localization of interference and suppresses it in the proper domain. Additionally, it overcomes the fixed spectral resolution problem of existing transform domain-based excision methods by employing the adaptive subband tree structuring concept [6][7] which is also called as adaptive wavelet packets in the literature.

In Section 2, the adaptive subband tree-structuring algorithm is presented. In Section 3, the proposed smart ATF exciser algorithm is explained in detail. Finally, in Section 4, performance simulation results are given. The issue of robust performance is discussed and conclusions are made.

II. ADAPTIVE SUBBAND-TREE STRUCTURING

The octave-band or dyadic subband decompositions of signals have been extensively studied in image-video coding. The dyadic subband tree provides high spectral resolution for low frequencies and high time resolution for high frequencies. However, high spectral resolution might also be needed in some other frequency regions (Figure 1 (a)). This brings us to the concept of irregular subband trees. For a given input signal, the tree structuring algorithm (TSA) recommends the best subband tree consist of 2-band or 3-band prototype filter banks (Fig. 1(b)). The TSA considers both 2-band and 3-band PR-QMFs in order to overcome the problems at the filters' transition frequencies such as $\frac{\pi}{3}$, $\frac{\pi}{2}$, or $\frac{2\pi}{3}$. In particular, after justification, the input signal or any subband in the tree is decomposed into its orthogonal projections employing two or three-band orthogonal subspaces. Therefore, the best irregular subband tree for the given input spectrum is generated in order to localize narrowband interference.

The TSA algorithm analyzes the energy distribution at each node of the subband tree with the assumption of ideal filters used and decides whether to continue decomposition with additional branches or terminate the tree. A subband node is further decomposed if and only if the energy compaction value at this node exceeds a predefined threshold. The energy compaction measure quantifies the unevenness of the given signal spectrum. It is defined for an M-band linear transform as,

$$G = \frac{\sigma_x^2}{\left[\prod_{i=1}^{M} \sigma_i^2\right]^{1/M}}, \qquad (3)$$

where σ_x^2 is the input variance and $\{\sigma_i^2\}$ are the subband variances. The adaptive tree structuring algorithm can be outlined as follows:

I. Measure the power spectral density, $P_{xx}(\omega)$, of the received signal.

II -a. Calculate subband variances σ_{2l}^2 and σ_{2h}^2 for the 2-band split. Assume ideal filter banks employed, and find $G(2)$ (the energy compaction measure for the 2-band split).

-b. Calculate subband variances σ_{3l}^2, σ_{3b}^2 and σ_{3h}^2 for the 3-band split. Assume ideal filter banks employed, and find G(3) (the energy compaction measure for the 3-band split).

III. If $G(2) \leq T$ and $G(3) \leq T$, then the spectral evenness exists. Stop tree structuring, (where T is a predefined compaction threshold),
else proceed with the 2-band split
if $G(2) \geq G(3)$
or proceed with the 3-band split
which is the case if $G(2) < G(3)$.

IV. Check the subband variances and proceed splitting the interfered subband using 2-band or 3-band splits. Do not split the uncontaminated subbands.

V. Repeat procedures II, III and IV until an evenness or flatness level is reached in the subspectra.

For example, considering a 2-band lowpass/highpass PR-QMF and a 3-band lowpass/bandpass/highpass PR-QMF banks as

$$[A_l(z), A_h(z)] \quad , \quad [B_l(z), B_b(z), B_h(z)] \, ,$$

and for the given spectral decomposition in Fig. 1(a), the TSA algorithm recommends the following analysis filters and irregular subband tree, Fig. 1(b), as

$$\begin{aligned}
H_1(z) &= B_l(z) \\
H_2(z) &= B_b(z) \\
H_3(z) &= B_h(z) \\
H_4(z) &= B_b(z)A_l(z^3) = H_2(z)A_l(z^3) \\
H_5(z) &= B_b(z)A_h(z^3) = H_2(z)A_h(z^3) \\
H_6(z) &= B_b(z)A_l(z^3)B_l(z^6) = H_4(z)B_l(z^6) \\
H_7(z) &= B_b(z)A_l(z^3)B_b(z^6) = H_4(z)B_b(z^6) \\
H_8(z) &= B_b(z)A_l(z^3)B_h(z^6) = H_4(z)B_h(z^6)
\end{aligned} \qquad (4)$$

The corresponding synthesis filter functions $\{g_i(n)\}$ $[i = 1,..8]$ can be obtained as the time reversal of analysis filters $\{h_i(n)\}$ [8]. Clearly, while switching between 2-band or 3-band filter banks, paraunitary conditions are always preserved. The adaptive subband tree structure avoids unnecessary decompositions by pruning. As a result, signal dependent unequal bandwidth paraunitary basis functions are obtained. The advantages of tree structuring over fixed subband trees are highlighted as **a)** Superior frequency resolution, **b)** Reduced interband energy leakage, **c)** Reduced complexity of transform operations.

III. SMART ADAPTIVE TIME-FREQUENCY EXCISER

Unlike fixed transform techniques, the proposed ATF excision algorithm is capable of tracking and suppressing the time-varying interferences. The novelty of the smart ATF excision algorithm is two-fold. First, it evaluates the time features of the received signal in order to decide on the domain of the excision . A time window slides through the received signal and captures the samples which exceed an amplitude threshold. Then, the total number of the captured samples (N_c) is compared to a predetermined threshold (N_t). In fact, this threshold is a measure of energy distribution of the signal in the time domain. If N_c is less than or equal to N_t, then those interfered samples are nulled in the time domain. In particular, if the interference is time localized, a very simple time domain excision technique can outperform any transform domain technique. It is clear from the uncertainty principle that, for a time localized interference, no transform domain excision technique can be justified.

The second novelty of the proposed ATF excision algorithm comes in when a frequency domain excision is decided. In that case, adaptive subband transforms are utilized for transform domain excision. As explained in the previous section, the TSA examines the spectrum of the received signal and defines the most proper subband tree structure. The contaminated or jammed subbands are discarded in the synthesis stage. The subband tree changes whenever the input spectrum varies. The spectral decomposition is tracked to the variations of the input signal.

It is meaningful to perform the excision in the domain which properties of the interference is more localized. If the interference does not exist nor localize in any domain, the received signal is passed directly to the demodulator.

IV. PERFORMANCE RESULTS AND CONCLUSIONS

In order to evaluate the performance of a DSSS communications receiver employing the smart ATF exciser, a simulation package was developed. The performance of the proposed ATF exciser along with DFT, DCT and fixed filter bank based excisers, is evaluated. A 63-chip maximum length PN code is used to spread the input bit stream. This provides a white spectrum for the transmitted signal. The baseband signal bandwidth is normalized to unity and a BPSK modulation is assumed. The resulting DSSS signal is transmitted over an AWGN channel. Two types of interference sources are considered; a narrowband jammer (single tone), and a time-localized wideband Gaussian jammer. The BER results indicate significant performance improvements of the smart ATF exciser over the conventional techniques. Additionally, the superiority of the proposed technique for the narrowband Gaussian interference was also reported in [8].

(i) Narrowband Interference: A continuous sinusoidal interference with a frequency of 1.92 rad/sec and uniformly distributed random phase on the interval $[0, 2\pi]$ is considered. The signal to interference power ratio is $-20dB$. Fig. 2 shows the BER performance of the ATF exciser-based DSSS system along with a few other fixed block transform exciser-based systems. The ideal curve represents the BPSK performance without any interference. The ATF exciser yields nearly optimal performance for this case. It has a fine spectral resolution around the interference frequency and minimum spectral leakage to uncontaminated bands because of the unequal bandwidth split. On the other hand, the fixed transforms (64-band filter bank, 64- and 128-point FFT, 64- and 128-point DCT) can not guarantee a good performance. Their performance depends on the frequency location of the interference signal. They perform relatively well if the frequency of the interfering tone exactly matches one of the transform bins.

(ii) Time-localized Wideband Gaussian Interference: Fig. 3 displays the performance of ATF and fixed transform-based excisers for the time-localized (pulsed) wideband Gaussian interference case. This interference is an on/off type which is randomly switched with 10% duty cycle. Signal-to-interference power ratio is $-20dB$. In this scenario, as expected, none of the fixed transform-based excisers is effective for interference suppression. However, the ATF exciser identifies the domain of the interference and successfully suppresses it in the time domain.

Robustness of Performance: One of the most important attributes of an interference suppression technique must be its robustness to time-varying interferences. In the case of single tone jammer with varying frequency, performance results of the ATF excision algorithm along with 64-band filter bank and 128-point FFT are displayed in Figs. 4, 5 and 6. It is observed from the figures that the ATF exciser is very robust to the variations of the input signal while the other two conventional techniques are not.

The smart ATF excision algorithm evaluates both the time and frequency domain properties of time-varying signals. The input signal is processed in the domain which the interference is more localized. For the frequency domain excision, the ATF exciser utilizes an unequal bandwidth adaptive subband tree. This method provides high spectral resolution in the spectral region of interest. The domain switchability and adaptation properties make the ATF exciser a smart, robust and meritful technique in spread spectrum communications.

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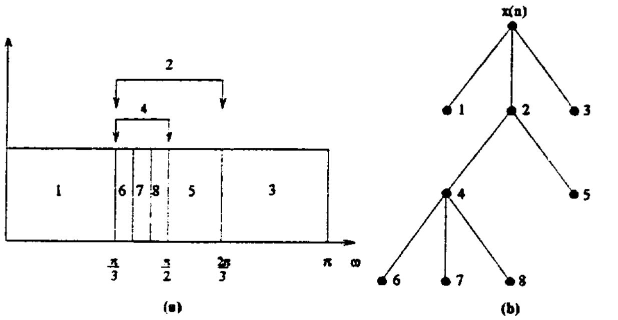

Figure 1: (a) Unequal bandwidth decomposition (b) Corresponding irregular subband tree.

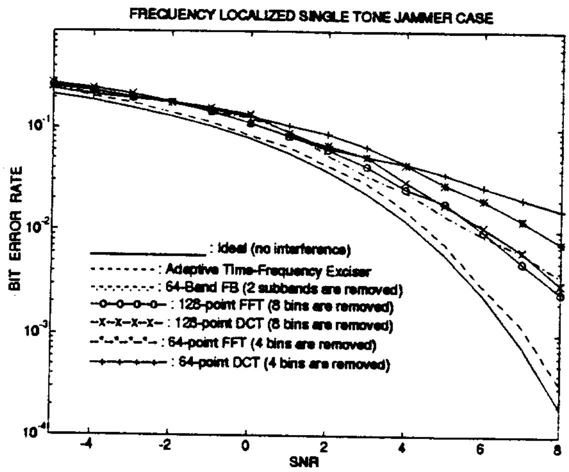

Figure 2: Bit Error Rate Curves for Single Tone Jammer Case (tone frequency = $1.92 rad/sec$, SIR = $-20dB$).

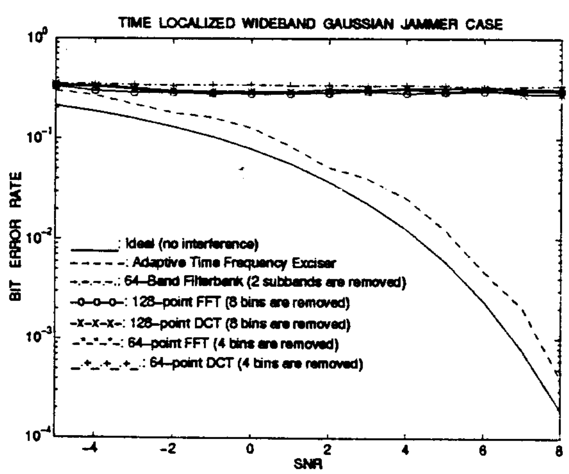

Figure 3: Bit Error Rate Curves for Time Localized Wide-Band Gaussian Jammer Case (10% duty cycle, SIR = $-20dB$)

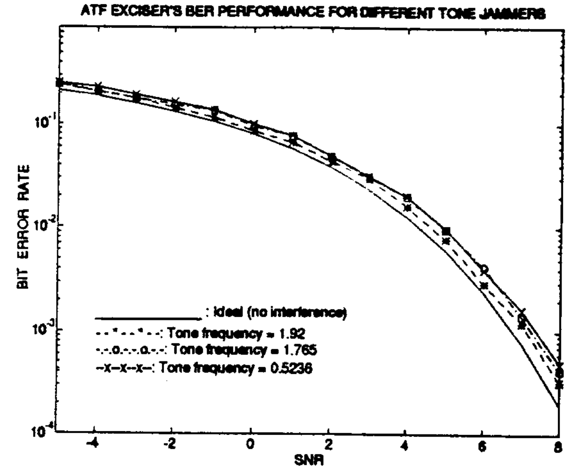

Figure 4: BER Performance of ATF Exciser for Various Frequency Tone Jammers.

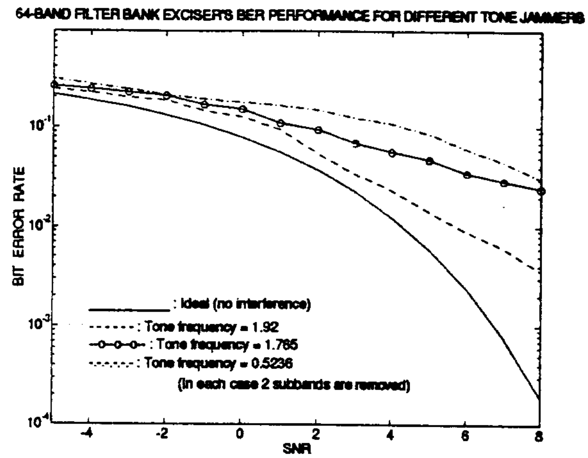

Figure 5: BER Performance of 64-band Filter Bank Exciser for Various Frequency Tone Jammers.

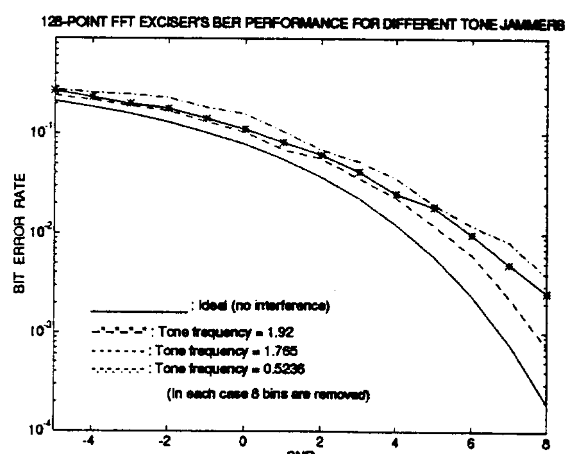

Figure 6: BER Performance of 128-point FFT Exciser for Various Frequency Tone Jammers.