SPREAD SPECTRUM INTERFERENCE SUPPRESSION USING ADAPTIVE TIME-FREQUENCY TILINGS

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ABSTRACT

Interference suppression in spread spectrum communication systems is often essential for achieving maximum system performance. Existing interference suppression methods do not perform well for most types of nonstationary interference. We first consider interference suppression schemes based on adaptive orthogonal time-frequency decompositions, such as wavelet packet and arbitrary dyadic time-frequency tilings. These methods often reduce interference substantially, but their performance can vary dramatically with minor changes in interference characteristics such as the center frequency. To circumvent these drawbacks, we propose a multiple overdetermined tiling (MODT) with an accompanying blind interference excision scheme which appears very promising for mitigating time-frequency-concentrated interference. Simulations with narrowband, impulsive, and simultaneous impulsive and narrowband interference compare the performance of the various methods and illustrate the promise of approaches based on multiple overdetermined tilings.

1. INTRODUCTION

Direct Sequence Spread Spectrum (DS-SS) is a very important method of data communication. By superimposing a pseudo random (PN) sequence on each data bit, the data is spread over a larger bandwidth and is less susceptible to interferers while being more secure. At the receiver, the signal is simply despread back to its original bandwidth and the data is demodulated.

If an interferer is removed at the receiver before despreading, the performance of the DS-SS system can be greatly improved. A number of different methods exist which work well for certain types of interferers. These include techniques based on adaptive filtering and minimum mean-square-error (MMSE) criteria [1]. Overdetermined FFT-based methods have also been developed for narrowband interference suppression [2].

The FFT-based and adaptive MMSE techniques are very effective for stationary, narrowband interferers or when the interferer is slowly varying. If the interferers are highly nonstationary, these adaptive techniques do not react fast enough to remove them. Techniques based on linear and bilinear time-frequency representations (TFRs) have recently been developed to address this problem [3]. The basic motivation for time-frequency-based excision is that most interferers, including most communications signals, other man-made interferers such as radar or jammers, and even impulsive noise bursts, are in some way highly concentrated in time-frequency. A time-frequency decomposition will concentrate such interferers into a few large coefficients; any coefficient which exceeds a threshold is assumed to be dominated by interference and is set to zero, and an interference-reduced signal is then reconstructed from the remaining coefficients. The desired DS-SS signal appears noise-like and is spread relatively evenly over all coefficients and is thus mostly preserved by the interference excision.

Existing time-frequency methods can be effective for certain types of interferers, but they may struggle with other types of nonstationary interference or with multiple interferers. Wavelet packet transforms [4] can adapt an orthogonal subband decomposition to better match some interferers. "Adaptive time-frequency excision" has recently been developed in [5]. Effectively, this method adapts an orthogonal subband decomposition in either time or frequency to match the subbands to the frequency (or time) center of the interference. This decomposition is similar to wavelet packets except that it allows three-band as well as two-band splits, thereby often allowing better matching to the center frequency of the interference. More general orthogonal time-frequency tilings have been developed for better matching a broader class of signals [6]. Unlike the wavelet packet decompositions, the general method allows the tiling pattern to change over time.

In this paper, we apply wavelet packet and general orthogonal time-frequency tilings to DS-SS interference excision. We find that their performance is often disappointing, and argue that their weakness stems from the use of orthogonal tilings. We present a new method for interference excision based on overdetermined tilings. The signal representation is oversampled in both time and frequency, providing better alignment with interferers with arbitrary offsets, and overdetermined in tile shape, allowing reasonable matching with a wide variety of interference characteristics.

2. TIME-FREQUENCY TILINGS

A one-dimensional signal can be represented jointly in terms of both time and frequency by using time-frequency or wavelet bases. Each basis function of this expansion will have some region in the time-frequency plane where most of its energy is localized. If this region is defined to be rectangular for each basis function, then the set of regions is

commonly known as a time-frequency tiling.

2.1. Wavelet Packet Tilings

Wavelet packets represent a large class of time-frequency tilings that have arbitrary frequency localization. Within this class of tilings, there exists a wavelet packet basis which, in terms of some cost measure, is best at concentrating an interferer in as few coefficients as possible. This wavelet packet basis can be obtained using an efficient algorithm developed by Coifman and Wickerhauser [4] that requires $O(\log N)$ operations per sample for a length N input signal.

2.2. Arbitrary Tree-Structured Time-Frequency Tilings

One disadvantage of the wavelet packet transform is that its frequency localization is constant over time. If the signal block is not stationary, it may be desirable to change the tree "on the fly" in order to better match the time-varying signal statistics. This motivates the use of *time-varying* wavelet packets. The hierarchical double tree-structured double tree algorithm [7] jointly finds the best binary time segmentation and the best WP frequency decomposition for each segment. The recently proposed (balanced) *time-frequency tree* (TFT) algorithm [6] extends the double tree by being more balanced in its time-frequency choices, by additionally considering "time" segmentations of frequency decompositions. Such a basis can be obtained using an efficient algorithm in [6] and requires $O(N^2)$ operations for a length N input signal.

2.3. Shift-Invariant Tiles and Non-Dyadic Segmentations

A drawback of the above-mentioned tiling algorithms is that they are very sensitive to translations and are not shift-invariant: i.e. the best tile associated with a shifted version of the signal is not a shifted version of the best tile associated with the original signal. Two promising extensions involve shift-invariant critical representations [8] and non-dyadic arbitrary segmentations [9], as well as a hybrid combination of these [10]. While our studies in this paper are confined to the TFT tilings, extensions within the critical (non-oversampled) representation framework appear promising and will be investigated in future work.

3. BEST BASIS SELECTION

A number of factors influence the best basis selection of a wavelet packet or arbitrary tiling. Among these are the cost function, the wavelet filters, and the method of handling boundaries of finite length signals. Careful consideration of these issues is necessary to maximize the performance in spread spectrum interference mitigation.

3.1. Cost Function

In order to choose the best wavelet packet or arbitrary tiling basis, there must be some measure or cost function which reveals how good a particular basis is for an input signal. Additionally, in the interests of computational complexity, it is desirable for the cost function to lend itself to a fast divide-and-conquer based search for the best basis. This can be satisfied using an additive cost function [4]. In addition, the cost function should be matched appropriately to the given application. In the case of interference suppression, given the basic assumption that the time-frequency characterization of the (spread-spectrum) signal is uniform while that of the interference is highly concentrated, the goal is to locate a basis that maximally captures the energy in the fewest number of coefficients. An efficient cost function should capture the energy-compaction capability of the candidate bases. The vector entropy $\mathcal{H}$ [4]

$$\mathcal{H} \equiv -\sum_i \left|\frac{x_i}{||x||^2}\right|^2 log_2 \left|\frac{x_i}{||x||^2}\right|^2 \quad (1)$$

is considered to be an excellent energy packing cost function for this purpose, as we have verified.

3.2. Wavelet Filters

The choice of wavelet filters has a significant effect on the best basis selection and the quality of the time-frequency representation. They should be chosen according to the time-frequency properties of the typical signal block to be processed. Longer filters generally lead to enhanced frequency resolution while sacrificing some time localization, and the opposite is true for short filters. In the spread spectrum environment, if interferers are usually narrowband with long time durations, longer filters would be optimal.

Another important facet of determining the best basis is handling the boundaries when transforming a finite length signal block. Special care must be taken when filtering at the edges in order to preserve certain wavelet decomposition properties such as orthogonality and perfect reconstruction [11]. A number of methods have been developed to handle this problem, including special boundary filters, periodic extension, and symmetric extension [12]. We confine ourselves here to periodic extension, while recognizing that other methods can lead to superior performance.

4. OVERDETERMINED TIME-FREQUENCY TILINGS

Orthogonal tilings have several drawbacks for interference excision. If the interference does not precisely match one of the basis elements, both in shape and in time or frequency offset, the interference might affect a large number of tiles. Multiple non-orthogonal interferers are particularly likely to introduce such energy smearing. The requirement of perfectly orthogonal basis elements may also force the use of filters with relatively high sidelobes. Even adaptive orthogonal tilings suffer from these difficulties, suggesting that overdetermined representations may offer benefits over orthogonal decompositions for interference excision. The intuitive motivation for overdetermined decompositions is simply that the larger the collection of projections, now classified as a frame, the better chance of a subset of these frame elements geometrically matching the interference.

We propose the following multiple overdetermined tiling (MODT) and blind interference excision scheme. The multiple ODT is the collection of several short-time Fourier transforms (STFTs), each STFT being computed with a different window length corresponding to a differently shaped

tile. This multiple overdetermined representation can be interpreted as a three-dimensional time-frequency-scale representation with lapped transforms. After thresholding of all coefficients, the interference-reduced signal is reconstructed via efficient least-squares synthesis [13] then despread and demodulated.

One drawback of this method is that the interference will overlap many of the basis elements; if some of these projections fall below the threshold, some portion of the interference energy will be retained. We argue heuristically, however, that by setting the threshold to about the level of the larger true signal projections, in the worst case the retained interference should remain at about the energy level of the original transmitted signal; as long as a substantial fraction of the projections are retained, the resultant SNR should be little less than zero dB, from which the inherent processing gain of DS-SS demodulation can easily recover the data.

By using a multi-layered STFT, both the MODT and the least-squares reconstruction can be computed with equal efficiency using the fast algorithm in [13], at a computational cost of order $O(L_f L_t N \log^2(N))$ per length-N data block, where L_t and L_f are the oversampling factors in time and frequency, respectively. (We use $L_t = L_f = 4$ in the simulations presented here, and $L_t = L_f = 2$ works almost as well.) The MODT is thus only $O\log(N)$ more expensive than wavelet packets and is considerably less expensive than the adaptive arbitrary dyadic tilings and does not require a search for the best representation.

5. SIMULATIONS AND RESULTS

We will now demonstrate the strengths and weaknesses of the time-frequency tilings described in the previous sections by considering three different interferers: narrowband with slowly varying frequency, time-localized impulses, and a combination of the two. Thus, we will consider cases requiring time, frequency, and joint time-frequency excision.

For each interference case, 100 symbols were projected onto a length-32 spreading sequence and added to noise with variance equal to the chip power. Interference was added to test signal-to-interference ratios (SIR) of -100 dB to -10 dB in increments of 10 dB. The receiver processed length-32 non-overlapping blocks to remove interference, followed by despreading. A fixed threshold for excision was chosen for each method to maximize results at all SIR levels.

The output of the matched filter with no interference is also tested for comparison with the other four methods. Vector entropy was chosen as the cost function for the best wavelet packet and arbitrary tiling bases using Daubechies-8 filters , and the Blackman-Harris window was used for the MODT.

5.1. Narrowband Interference

For this case, the interference was a sinusoid with slowly varying frequency. The results in Figure (1) show that the DFT and MODT performed well, as expected, because their basis functions are better matched to narrowband signals. On the other hand, the basis functions for the wavelet decompositions are not a good fit, and the results confirm this.

Based upon the DFT and MODT results, it is clear that time-frequency representation is not needed in this case, and the extra computational complexity provides no performance enhancement.

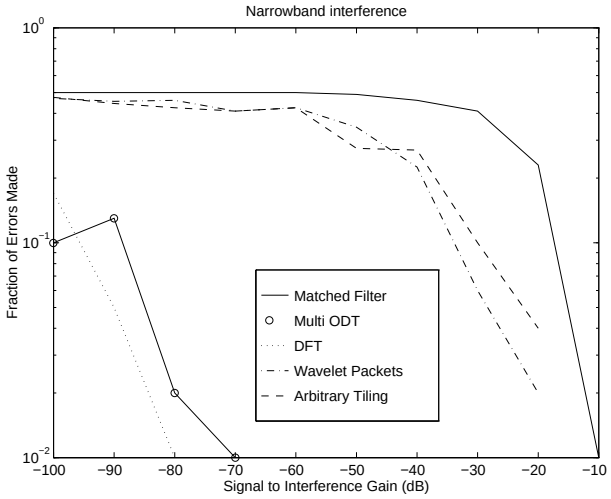

Figure 1. Narrowband interference results.

5.2. Impulsive Interference

Impulsive interference was generated from a Poisson distribution with a mean arrival time of 16 samples using a length-5 windowed Gaussian pulse. The results shown in Figure (2) show that DFT excision performed rather poorly, whereas detection with MODT excision was error-free for all tested SIRs. This is expected since the DFT has no time-localization properties and smears the impulse energy across all projections.

Both wavelet decompositions performed much better than the DFT, but did not compete with MODT. The length of the wavelet filters played some part in this, but we also believe that the best basis selection was also a problem. Based upon some simple examples, the vector entropy cost function does not appear to be optimal for interference excision, since it determines the best basis independent of the threshold. This can explain why the wavelet packet did better than the arbitrary tiling at some SIRs.

5.3. Combined Narrowband and Impulsive Interference

Equal energy narrowband and impulsive interferers were added to form our final test case. The results shown in Figure (3) clearly indicate that the critically determined methods offered little improvement in performance over the matched filter relative to the redundant MODT-based technique. Intuitively, this is because a critically sampled technique is forced to make time/frequency localization tradeoffs that an overdetermined representation without basis adaptation does not.

6. CONCLUSIONS

While time-frequency decompositions seem promising for the excision of nonstationary interference in DS-SS systems, fixed orthogonal representations cannot adequately match

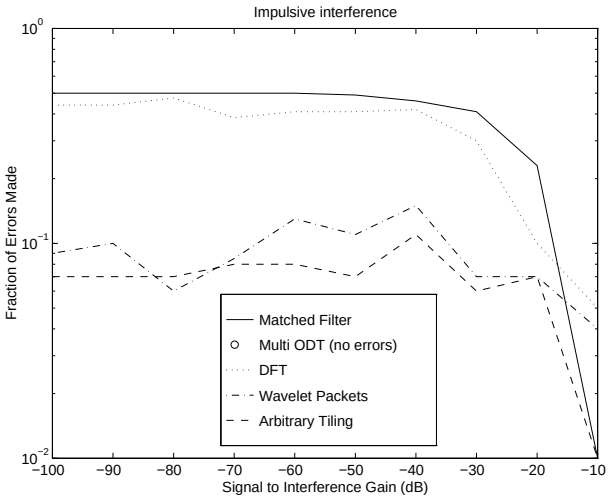

Figure 2. Impulsive interference results.

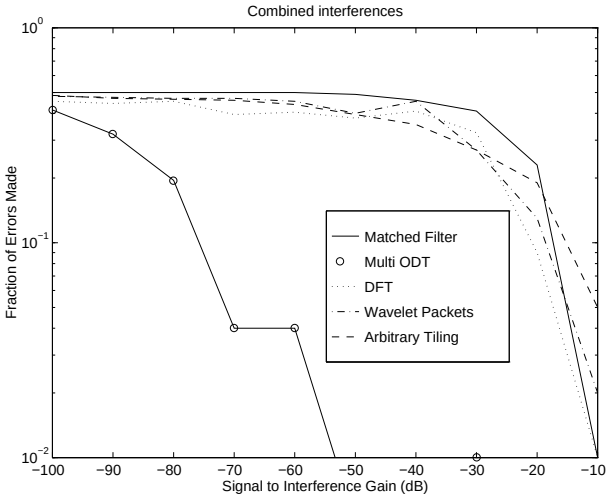

Figure 3. Combined interference results.

most interferers. Adaptive orthogonal time-frequency tilings offer one approach for better matching a large class of interferers. These methods perform well for certain signals but relatively poorly for others, and they are very sensitive to interferer characteristics such as frequency offset. Extensions such as shift-invariant tilings may improve this somewhat, but some of these problems appear inherent to critically sampled (orthogonal) tilings.

Overdetermined time-frequency decompositions may overcome some of these difficulties. A multiple overdetermined tiling introduced here works very well in simulations and is computationally quite efficient. Overdetermined time-frequency methods thus appear quite promising for blind nonstationary interference excision.

Adaptive time-frequency-based interference excision is a relatively new field of study, and many fundamental issues remain unresolved. Overdetermined decompositions are even less understood, and significant performance improvements seem likely as they are further developed and improved.

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