DETECTION, LOCATION AND CHARACTERIZATION OF EVENTS FOR IMPROVED REFLECTOMETRY USING WAVELETS, WAVELET PACKETS AND GABOR FUNCTIONS

by

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1. Introduction

Besides studying all the FAX's received from X. Gu, and two extended summaries [1,2] which were recently accepted for the IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis, and a large amount of literature on multi-rate systems, filter banks and relationships to wavelets [3-6], I have studied much important available literature on three possible approaches [7-22] to denoising and event detection, location and characterization in fibre optic cables for the purpose of designing improved reflectometers. I have also had a very enlightening telephone conversation [20] with Professor Ronald Coifman of the Department of Mathematics at Yale University during which I was given information about the software package "Wavelet Packet Laboratory". This contains a paper on denoising by M.V. Wickerhauser and R.R. Coifman, and instructions on how to use the wavelet packet library to implement denoising.

2. Summary Description of the First Approach

The first of the three approaches is the result of research by S. Mallat and his doctoral students [7,8]. (I have not yet studied [9].) This approach describes how to detect and locate events by taking the wavelet transform of the curve of exponentially decreasing gain versus distance upon which localized events (due to faults, splices and end of fibre) and noise may be superimposed to detect and locate the events. The events may, furthermore, be characterized by Lipschitz exponents (α in [7]), smoothing components (σ in [7]), and a constant (K in [7]) measuring the amplitude of a sharp variation. In [8] a denoising procedure is given based on discriminating between Lipschitz constants for the signal and Lipschitz constants for noise, and an alternating orthogonal projections algorithm for reconstructing a signal from the modulus maxima of wavelet transforms at different scales [7,8].

3. Brief Evaluation of the First Approach

It is difficult to remove the wavelet transform modulus maxima due to noise analytically or numerically. Furthermore, the signal reconstructed using the alternating orthogonal projections algorithm is often visibly distorted compared to the original. Therefore, the first approach for denoising is not recommended. The characterization of events by Lipschitz events, smoothness components and amplitude constants should be useful in categorizing and characterizing events as faults, splices or end of cable in the denoised signal (i.e., in the denoised exponential gain versus distance curve with superimposed events).

4. Summary Description of the Second Approach

The second approach has been research by B. Friedlander and B. Porot [10-12], and was pointed out to me by C. Zarowski of the Department of Electrical Engineering at Queen's University [22].

This approach provides theory and algorithms based on the Gabor representation for the detection of transient signals with unknown arrival times. In [10] a one-sided exponential window function is used, but other window functions could be tried. The explicit expressions for the Gabor coefficients are given for the exponential window function. When the signal is random so are the coefficients. The second-order moments of the Gabor coefficients are computed for a white noise signal. These are then used to introduce a detection statistic based on the Gabor coefficients. The proposed detector is capable of separating transients having different arrival times, even in the case where their waveforms partially overlap.

The detector is clearly described on page 173 of [10]. The detector is localized and so is capable of detecting multiple signals separately, provided they do not overlap too much. The distributions of the test statistics are either central or noncentral chi-square, depending on whether there is noise only, or a signal plus noise.

The distribution of the test statistic when there is noise only enables the determination of the threshold for any desired probability of false alarm. The distribution of the test statistic when signal plus noise is present enables the computation of the detection probability as a function of the Gabor coefficients of the actual transient.

The theory and examples are extended, and unified in [11] and [12]. In [11] the STFT and two wavelet transforms are used in examples and detectors based on each of these are compared. The reader is referred to[11] for the results of these comparisons.

Further problems for research are described in the concluding sections of [10], [11] and [12].

5. Brief Evaluation of the Second Approach

This approach has the distinct advantage that the performance measures, probability of false alarm and probability of detection, can be computed for white Gaussian noise. For other noise distributions simulations can be used to determine these performance curves.

The method is also robust.

The use of a bank of Gabor detectors and other extensions and possibilities are noted in the concluding sections of [10], [11] and [12].

The writer also suggests that the use of wavelets appropriately matched to the events may also improve performance.

The computational load <u>may</u> create a problem. However, Professor Christopher Zarouski has identified matrix structures which would greatly improve speed of computation. The writer recommends that the long experience and recognized expertise of Professor C. Zarowski be sought if computational speed must be decreased for on-line operation.

This approach is quite appealing and should be implemented and tested, and possible problems with the computational intensity identified and solved if on-line operation is essential.

It should be noted that [10], [11] and [12] are particularly clearly written papers, with excellent analytical results.

6. Summary of the Third Approach

The author was fortunate to notice the (1 1/2-page summary [14] by Coifman, Majid and Saito, for he might not have discovered the very large amount of work that has been done at Yale University by Coifman and various colleagues and graduate students there on denoising using adaptive wavelet packet libraries. The method is summarized in [14] and the advantages of that method over the ones in [9] and [28] are set down. One advantage of the method appears to be that it produces superior results when the noise is not Gaussian. More details are provided in [21}, which the author received on 13 July 1994, and so has not had the chance to read and assess, but which appears to be quite comprehensive and solid.

The author has completed reading [13-19] to understand wavelet packets, libraries of wavelet packets and best basis selection. I am prepared to provide any unavailable references, detailed explanations and step-by-step algorithms if requested. However, I believe that these can be extracted without too much difficulty from the cited references. I can help Antel Optronics understand any difficulties encountered.

Probably the most exciting and significant result of my explorations stems from a telephone conversation which I had with Professor Ronald Coifman on 13 July 1994 and a book chapter by Naoki Saito [21] (Tel: 203-431-5209) which I received by e-mail on the same day. R. Coifman's telephone number is (203) 432-4175.

Professor Coifman was thoroughly familiar with the papers I had read, soon stated that they were about five years old, and that in his group in the Department of Mathematics at Yale University there had been an enormous research effort expended on denoising signals using wavelet packet based methods. He believed that the currently best methods for this had been developed by them. The author is presently quite strongly convinced that this is highly probable, and that Antel Optronics would have a very high probability of the best success in designing very high performance reflectometers using the wavelet packet based approach.

Professor Coifman told me about a windows-based program, or toolkit under windows, called Wavelet Packet Laboratory, which enables one to experiment with all possible wavelet libraries. This toolkit includes 15 to 20 libraries. It includes an instruction booklet with a paper by M.V. Wickerhauser and R.R. Coifman on how to use the program for denoising. The program can be obtained from A.K. Peters Publishing, for which the telephone number is (617) 235-2210, and the Fax number is (617) 235-2404.

False alarm probabilities and probabilities of detection can be obtained by running simulation experiments to extract events.

Yale has filed for licensing but the cost would be less than 2%.

There is a need to make the method more robust. R. Coifman described an unpublished method which improves performance "enormously", as he put it. The procedure follows:

1. Shift the signal, say, 4 or 5 times by 1, 3, 5, 7, etc. units. (Do not use even shifts.)

2. Denoise the shifted versions one by one using the wavelet packet laboratory.

3. Shift back the denoised signals.

4. Average the denoised versions.

The computations are stable and possible artifacts are eliminated.

The denoising algorithm can be done in real time.

7. Brief Evaluation of the Third Method

The third method appears to offer a high probability of success in designing considerably improved reflectometers. With the reputation which R. Coifman and his colleagues achieved by winning a famous FBI competition in fingerprint file compression and identification using best bases from wavelet packet libraries, and with their great experience, it is almost certain that their Wavelet Packet Laboratory offers the best possible tool for denoising. After denoising there are three options for locating and characterizing events in the denoised signal.

1. Represent the signal using the best wavelet packet basis obtained from the Wavelet Packet Laboratory, and use experience with simulations to characterize faults, splices and end of cable events based on experimental results.

2. Use the Friedlander and Porot method, based on Gabor, STFT or wavelet representations to locate and characterize events, with given probabilities of false alarm and detection. This has the advantage of giving performance measures. The denoised signal should yield high performance.

3. Use Mallat and Zhong's approach to characterize the events by α, σ, and K. This does not provide performance measures.

I recommend trying the first two of these experimentally until experience favours one choice or the other.

8. Brief Comments on Other Ideas and Methods

I have studied the subband coding and filter bank theory extensively [3-6], but I have not synthesized this yet to obtain creative solutions or approaches.

The methods and theories in [1] and [2] will be thoroughly examined in the course of writing the final papers, and upgraded and updated as appropriate by about the middle of August 1994.

The choice of techniques will affect practical considerations, so these must be re-considered when these techniques are tried.

9. Conclusions and Recommendations

The Mallat and Hwang and Mallat and Zhong approaches, while providing excellent fundamental theory do not appear to offer the best available solution to the problems at hand. Performance measures are not clear.

The Friedlander and Porot approach provides an excellent method with performance measures for white Gaussian noise. It gives probabilities of false alarm and detection and is quite robust. Computational problems may be ameliorated with methods best obtained by consulting Professor Christopher J. Zarowski. Computational experience is necessary to determine whether online computation is feasible, although it appears likely, with Professor Zarowski's help. Performance in non-Gaussian noise has not been investigated. Various avenues for improvement are discussed in [10-12], and could be helpful. The three events can be characterized after transformation by the Gabor, STFT or wavelet representations.

The most exciting and promising approach would employ the Wavelet Packet Laboratory for both denoising and event location and characterization using a best wavelet packet basis. Performance measures can be obtained by simulation experiments. Performance can be greatly improved by a simple shifting, denoising, shifting back and averaging of the signal. Noise need not be Gaussian and white.

An alternative is to use the Friedlander and Porot approach for event location and characterization, with performance measures, after denoising with the Wavelet Packet Laboratory. This appears, intuitively, to have the potential for designing reflectometers with performance far beyond any that exist today.

Further help and literature can be obtained from the author.

Practical problems will have to be considered when the techniques are tried, for they will depend upon which of the techniques are chosen.

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