A SUBSPACE-BASED METHOD FOR SPECTRUM SENSING

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ABSTRACT

A subspace-based method for gaining knowledge of the quality and usage of the spectrum is presented. The method separates so-called 'structured' and 'unstructured' components of a signal as determined by the eigenvalue decomposition. These components may be cast as carrier power and interference plus noise power (interference temperature), thus providing an estimate of the quality of a piece of spectrum even in the presence of incumbent services. Furthermore, the method may be extended to yield a unique signature for many different modulation types. Combination with a neural network leads naturally to a robust modulation recogniser which has been demonstrated on a spectrum analyser platform. Some applications for the technique are discussed.

Index Terms - Interference temperature, modulation recognition, subspace processing, eigenvalue decomposition, cognitive radio.

1. INTRODUCTION

A method for characterising the quality and usage of the spectrum has been developed under an Ofcom funded programme of work [1].

The objective of the study was to find ways of measuring the interference plus noise floor (I+N) in occupied bands. This quantity may also be thought of as the 'interference temperature' [2], [3].

The measurement technique must be viable in the presence of any signal type in order to assess spectrum quality across the entire frequency range. This objective has been met by use of a subspace-based algorithm that has also been developed into a working modulation recogniser by coupling it with a neural network.

The I+N measurement method has been verified through extensive testing, both in the laboratory and in field trials using the Autonomous Interference Monitoring System (AIMS).

The results of this work are presented here with examples of applications for the method.

2. SUBSPACE METHOD

Given a complex, zero-mean, sampled signal x_n, the covariance matrix, R can be estimated as:

$$R = E\left[xx^H\right] \tag{1}$$

where the H operator represents the Hermitian transpose. This can then be decomposed in the form:

$$R = U\Sigma U^H \tag{2}$$

where U contains the orthonormal eigenvectors of R and Σ contains the corresponding eigenvalues:

$$\Sigma = diag(\lambda_i) \tag{3}$$

The eigenvalues, λ_i, can be split into those corresponding to carriers plus interference plus noise and those that just correspond to interference plus noise. Given a successful decomposition, it is then possible to examine the eigenvalues and determine the power in the carriers and the power in the interference plus noise.

It is normal to assume that the noise component is approximated by a White Gaussian Noise (WGN) distribution and that a very large amount of data is available. Under these assumptions all the noise eigenvalues approximate the mean power of the WGN process. For real-time radio usage we cannot always make these assumptions. The noise may not be well modelled by a WGN process and it is desirable to reduce the number of samples needed to obtain the I+N measurement.

Any one of three different approaches can be adopted for separating the eigenvalues. These are:

- Information theoretic methods, as typified by the Minimum Description Length [4];
- Looking for the known shape of the part of the eigenspectrum corresponding to noise when the amount of data available is finite [5];

- Image processing to look for features relevant to the known signal types. This is easiest when the chip rate or symbol rate of the dominant source is known in advance, thereby facilitating good separation of signal and noise [6].

We have found that the first two approaches are more reliable when the receiver has no *a priori* knowledge of the environment and the measurement has to be generic. They lead to three partitions of the eigenspectrum, corresponding to structured signals, unstructured signals and WGN. This allows different ratios and powers to be calculated, depending on the needs of the end user.

If, on the other hand, a modulation-specific measurement is made, then the last approach can be used, either instead of, or as well as the first two. Thus the eigenspectrum estimator can be used for measuring I+N in different ways to handle different spectrum quality measurement tasks.

3. INTERFERENCE TEMPERATURE

For simple analogue modulations, the I+N power can be obtained by removing the largest eigenvalue, which represents the carrier power and averaging the other eigenvalues to estimate the interference plus noise power. For more complex modulations it is necessary to determine the rank of the matrix and then sum the largest eigenvalues.

A simpler approach is to estimate the I+N power by considering the smaller eigenvalues and then simply subtract this from the total power to obtain the carrier power estimate. This is a considerable simplification and very suitable when it is not necessary to demodulate the carrier.

The carrier power and I+N power that arise from this process can therefore be thought of as 'structured' and 'unstructured' components respectively. Figure 1 shows a typical result of this decomposition in the FM radio band from 90MHz to 98MHz. The median carrier power is shown as the higher trace and the I+N power is the lower trace.

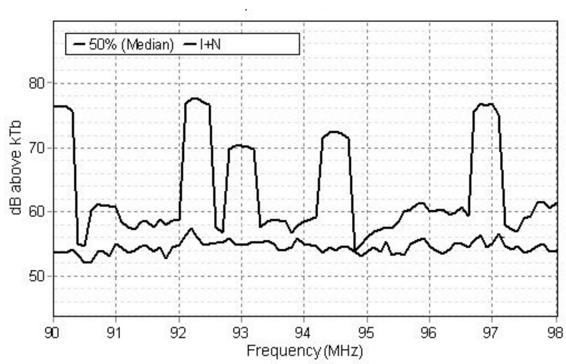

Figure 1. I+N power in the FM band

The FM radio transmissions stand out clearly in the carrier power trace. However the I+N floor may be seen to remain at a relatively constant level regardless of the carrier power. Thus the 'interference temperature' has been extracted correctly whether or not a channel is occupied.

A number of sources of emission will combine to form the aggregate I+N power including:

- Out of band (OOB) emissions including adjacent channel interference (ACI);
- Co-channel interference (CCI);
- Wideband (impulsive) noise;
- Thermal noise;
- Electromagnetic interference (EMI);
- Ultra-wideband (UWB) signals;
- Environmental noise.

For some purposes it is desirable to exclude the effects of ACI and CCI. This mode of operation is discussed in section 5 of this paper.

The measurement of I+N has now been conducted at a wide variety of sites across the UK using the Autonomous Interference Monitoring System (AIMS), which covers the frequency range 100 MHz to 11 GHz. For all signal types encountered the algorithm correctly separates the carrier and I+N. The accuracy of the I+N measurement is better than ±2 dB for all modulation types.

4. MODULATION RECOGNITION

By extending this subspace-based processing over multiple window lengths it is possible to generate unique signatures for different modulation types. In turn, these signatures may be fed into a neural network which outputs a match to a known signature. Figure 2 shows an example of a signature for an IEEE802.11b signal.

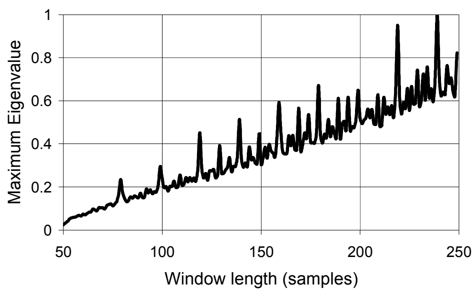

Figure 2. Subspace-based signature of IEEE802.11b signal

The peaks in this signature trace represent resonant features of the signal structure, for example the chip rate in the case of IEEE802.11b. In this way it is possible to build a library of known signal types, each with identifiable features such as chip rate, symbol rate, cyclic prefix interval, cyclic prefix length, training sequence etc.

Having generated a unique signature for the captured signal, a pre-trained neural network is used to convert the signature to a modulation type (Figure 3). Initial results show that this method is capable of distinguishing the major modulation types (FM, AMSSBv, GSM, DAB etc.)

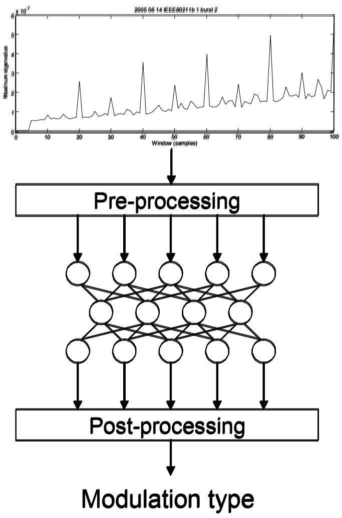

Figure 3. Neural network recogniser

5. APPLICATIONS

A subspace-based processing engine can be used to gain knowledge about the quality and usage of the spectrum environment. Some of the ways in which such a method may be used are described below.

5.1 Spectrum Valuation

A regulator or service operator may wish to determine the quality and hence value of a region of spectrum. In the case of a regulator, it may be necessary to value a piece of spectrum prior to its sale. Service operators may wish to purchase and, in the future, sell off spectrum and therefore valuation will be of importance. This monetary value will be related to the amount of interference and noise in the band because of capacity and range considerations. However, if the piece of spectrum of interest is in use, then it may not be easy to ascertain the I+N floor in the presence of the carrier signals. The subspace-based method may be used to 'look beneath' the carrier and extract the I+N of the underlying spectrum. Two different implementations of the algorithm may be used to include or exclude the effects of ACI and CCI. These two modes are (see Figure 4):

- Channel mode, where a single channel is measured and the I+N in that channel extracted from the carrier. This I+N estimate includes ACI and CCI powers and therefore relates to the interference as seen by a single receiver;
- Band mode, where an entire band is measured and the I+N in that band extracted from the carrier. This estimate excludes ACI and CCI powers and therefore relates to the interference that would be present if the entire incumbent network were switched off.

In some instances, the channel mode will be of interest to network operators who are interested in the self-interference effects of their own networks. On the other hand regulators may be more interested in the band mode estimate because it eliminates the effect of the entire network.

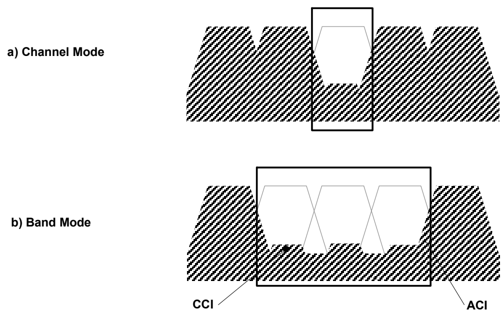

Figure 4. Two I+N measurement modes

A further benefit of this two-mode approach is that a piece of spectrum may be valued both at the edge of a band, where out of band (OOB) emissions may be present and also in the centre of a band, where they may have less of an effect.

5.2 Spectrum Protection

The move away from 'command and control' style of regulation to a more liberalised regime leads to the need for service operators to be able to monitor the impact of other licensees on their valuable spectrum holdings. The OOB emissions impacting on a user's spectrum may be tracked using the I+N metric as follows (Figure 5):

- The system is tuned to within the user's band;
- The measurement bandwidth is chosen to minimise OOB interference from the user's own network;
- The subspace algorithm splits the received signal into carrier and I+N components;
- Because only the skirts of the OOB interference are received at the user's frequency they appear as 'unstructured' and therefore contribute to the I+N power.

In this way, the I+N contribution from the OOB interferer may be isolated from the underlying I+N floor. In general, judicious use of tuning frequency and measurement bandwidth may be combined with the subspace algorithm to isolate different interference effects and gain more understanding of the interference environment.

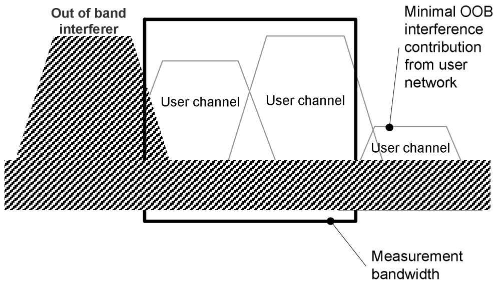

Figure 5. Measurement of out of band interference

5.3 Interference Resolution

Many interference effects may be the result of non-linear interactions of high power signals with radiative structures. The spurious products of these interactions may appear in-band and can be difficult to resolve because of their wide separation in frequency from the originating signal source. If the source of the spurious is a simple AM or FM modulated signal then merely demodulating the signal may reveal the source of the problem. However, digital signals are harder to demodulate.

The subspace-based modulation recognition technique may be used to assist the resolution of such interference problems. The system compares the received signal with the library of known modulation types and outputs the most likely match. The system is capable of recognising most common modulation types.

5.4 Cognitive Radio

Some of the spectrum sensing requirements of cognitive radio (CR) may be met through a subspace-based approach. A CR will require spectral awareness for a number of reasons:

- Optimising the link budget so that only the minimum power is utilised to achieve the desired quality of service;
- Performing signal detection and recognition of other devices on a link channel to identify the appearance of a primary user;
- Performing signal detection across a wider band to identify unused channels.

Optimising the link budget is necessary for the purposes of maximising spectral efficiency and battery life of the CR. An estimate of the I+N floor experienced by a device is a key parameter for a link budget and could be transmitted to the other end of the link to speed up the optimisation process. This method is preferable to model based or iterative techniques because of the greater accuracy and speed in setting up the link. Figure 6 shows the time-varying I+N estimate on a channel in use by an XG cognitive radio at the IEEE DySpan 2007 conference. It shows the XG radio coming and going on the channel while the I+N estimate remains relatively constant. The radio system is switched off overnight and resumes operation the following morning.

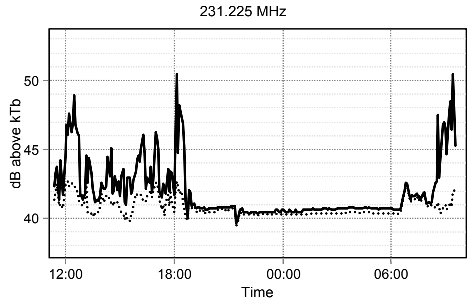

Figure 6. I+N estimation in presence of XG radio

A CR must detect the appearance of a primary user on a link in order to know when to jump channels. The overhead associated with jumping channels is considerable and so the sensing algorithm to handle this function must be robust to interference and noise. Constant false alarm rate (CFAR) processing is often used to achieve this robustness. However, CFAR methods may not be able to distinguish between a genuine carrier and interference. This could result in the CR erroneously jumping out of the way of interference.

A more accurate method of achieving this robustness is to use the I+N estimate from the subspace method. A constant estimate of the I+N floor may be maintained and if the signal power between CR packets rises significantly above this I+N floor then there is a high probability that a primary user has appeared on the channel. However, if the I+N floor rises then it is more likely that the interference rather than the carrier power has increased and the only consequence is a reduction in the available channel capacity. Thus a more informed decision about whether to jump channels may be made.

Modulation recognition is an important feature of a cognitive radio. Knowledge of the types of service operating on a channel can again assist the decision to jump channels in a way which minimises overhead to the CR and its impact on the primary users of the spectrum. For example, it will be important for a CR to be able to recognise other CRs on the link channel to prevent them sensing each other as primary users and jumping out of each other's way. Moreover, a simple CFAR system might interpret a constant amplitude signal (such as FM) as the noise floor and allow illegal CR operation on a channel which is in primary use. Again, the extra spectral awareness provided by modulation recognition contributes to a safer environment for the primary users and higher CR performance. Current cyclostationary based techniques for achieving this suffer from synchronisation problems [7]. Various methods for ameliorating these issues (including averaging) introduce their own trade-offs in terms of processing time. The subspace-based method can offer benefits in terms of robustness and efficiency.

A cognitive radio needs to maintain an up-to-date list of available channels within a band. This is to optimise the process of rendezvous in an available channel if a primary user suddenly appears on the link channel. Maintaining awareness of the wider spectrum environment outside the link channel is important for this reason.

6. SUMMARY

A subspace-based method for spectrum sensing has been described. The method can extract the interference plus noise (I+N) or 'interference temperature' from measurement of an occupied channel using standard measurement hardware and in the presence of all major modulation types.

The method may be extended and combined with a neural network to perform modulation recognition of all major modulation types. Tests in the laboratory and in the field have confirmed that the accuracy of I+N measured is better than ±2 dB for all modulations encountered.

Applications to spectrum valuation, spectrum quality assessment, spectrum protection, interference resolution and cognitive radio have been explored.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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