DISTRIBUTED SPECTRUM DETECTION ALGORITHMS FOR COGNITIVE RADIO

T.J. Harrold, P.C. Faris and M.A. Beach

Centre for Communications Research, University of Bristol, United Kingdom. Email ccr-wireless@bris.ac.uk

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Abstract
Cognitive radio technology may offer the capability for suitably enabled terminals to sense spectrum activity and reuse free channels, thus allowing an increase in efficiency by permitting dynamic sharing of spectrum between users. Accurate spectrum sensing is a vital requirement. This work presents simulation of an algorithm that improves the accuracy of spectrum sensing by combining results from teams of co-operating sensing terminals, thus overcoming problems caused by localised shadowing. Results show that the detection algorithm performance is greatly improved by allowing neighbouring nodes to influence the channel sensing process at a particular cognitive radio location, and that a detection accuracy approaching 100% can be achieved in certain cases. Various other trade-offs exist in the weighting factors used to tune the algorithm performance.

1 Introduction and background
One of the benefits of the intelligent, flexible radio technology that has come to be known as cognitive radio, is that it may allow an improvement in efficiency by permitting the use of empty spectrum space as it becomes available, provided that no interference will occur to any other spectrum owner.

One of the key capabilities that a cognitive radio (CR) device must possess in order to implement this behaviour is the ability to assess spectrum occupancy at its own location with a high degree of certainty that the results of the measurement are correct. Further algorithms implemented within the radio can then decide whether the spectrum is suitable for use. Proposals to improve the accuracy of spectrum sensing [1] have suggested that a co-operative team approach to spectrum sensing, where a number of cognitive nodes collaborate to detect free portions of spectrum, brings benefits. In the team approach, the tasks of allocating spectrum portions to sense, and of making the final decisions on whether spectrum is actually free, are distributed among a collection of locally connected cognitive radio nodes.

The work described in this paper quantifies the benefits that are possible by combining the decision about which spectrum bands are free or not from a cluster of sensing nodes in different locations that will therefore have independent propagation characteristics. This is achieved by combining the results of individual free/not free decisions from different terminals.

2 Distributed detection

2.1 Spectrum detection
Spectrum detection is the means by which a portion of spectrum is measured, and a decision made on whether it is free from any existing transmission. Such transmissions may be either from transmitters belonging to any primary licence holder in the band of operation, or from other cognitive users also occupying vacant spectrum portions on an opportunistic basis. The ability to spectrum sense with accurate results is therefore a vital component of cognitive shared spectrum capability.

2.3 Challenges of spectrum sensing
The main implementation challenge of spectrum sensing is that it may be impossible for a single cognitive node to maintain an up to date continuous picture of the availability of spectrum channels.

An incorrect spectrum detection decision can mean falsely deciding that a portion of spectrum is free, when an existing transmission exists, or falsely deciding a transmission exists when the spectrum is in fact free. The latter case leads to an inefficient spectrum usage, the former may lead to catastrophic interference to other spectrum users. Inaccuracies in detection can be caused by propagation effects such as fading (either fast fading due to multipath effects, or slow fading due to propagation path blockage or shadowing). This effect is shown in Figure 1; as the building is blocking the line of sight (LOS) signal path from the primary transmitter to CR1, the CR will assume the channel is free. If the CR chooses to transmit, this may cause interference to the primary receiver located within its transmission range.

Another problem is that of the hidden terminal; this being defined as an undetectable terminal that will suffer as the result of any interference from the cognitive system. The hidden terminal may be undetectable because it inherently has
no transmission capability (such as a TV/Radio receiver), or because it is outside the range of its serving primary transmitter. The problem is also illustrated in Figure 1; CR2 is unable to detect the primary transmitter (as it is outside its transmission range) and, if it decided to transmit, will cause interference to the primary receiver. CR2 is therefore a hidden node.

Another possibility in distributed sensing is that of dividing up the frequency bands to be sensed between the terminals through a task allocation scheme – so that processing load is reduced in individual terminals and there is a higher probability of being able to scan the entire band of operation.

2.5 Practical considerations

The main disadvantage of distributed sensing lies in the fact that it requires some method of communication between neighbouring nodes. As this will require wireless resources, the overall efficiency of spectrum access will inherently be reduced, as the traffic on this control channel adds to the network overhead. This puts a restriction on the two main variable factors in a distributed sensing scheme; the number of neighbouring users to share information with, and the maximum spatial separation between co-operating terminals. It is logical to assume that a higher number of sharing neighbours would improve reliability, and hence is desirable. In the case of sparsely populated networks, it may be necessary to have a wide sharing range to obtain information from the desired number of sharing nodes. However it is possible that a wide range would give rise to inaccuracies as neighbouring nodes sensing data may not be locally relevant. Hence an upper limit would also be desirable.

3 Implementation

3.1 Simulation

In order to test the potential benefits of adopting a distributed approach to spectrum sensing, a series of simulations was carried out. The basic task allows each cognitive node to measure a channel and make a decision on whether there is an existing transmission present; “sensed” or not “not sensed”. Decisions can then be modified by incorporating additional results from surrounding nodes and previous measurement times.

To emulate this, a simulation has been created in MATLAB where a number of sensing nodes (e.g. CR terminals) can be placed in a grid, together with a collection of primary transmitters that must be detected. The propagation model, including slow fading due to shadowing, is given in Equation 1.

\[
PL_{(dB)} = 10n \log_{10} d + 20 \log_{10} \left( \frac{4\pi}{\lambda} \right) + X_{(dB)}
\]  

(1)

\(PL_{(dB)}\) is the Path loss in dB, \(n\) is the path loss exponent (PLE), \(d\) is the distance from transmitter (m), \(\lambda\) is the wavelength of transmitted signal (m) and \(X_{(dB)}\) is the shadowing factor, modelled as a log normal random variable [3] with variance \(\sigma\).
3.2 Algorithm

The single node “sensed” or “not sensed” decision is made by setting a decision threshold in dB relative to the receiver noise floor; the threshold can be varied in order to investigate different performance. A signal arriving above the threshold results in a “sensed” decision. The distributed detection algorithm implemented at each CR is then run and can modify the detection decision based on factors such as the detection results from surrounding CRs. This decision algorithm can be represented by Equation 2. The terms in Equation 2 have meanings given in Table 1.

\[ Q = [X_1 \ldots X_n] \begin{bmatrix} D_1 \\ \vdots \\ D_n \end{bmatrix} + [Y_1 \ldots Y_M] \begin{bmatrix} T_1 \\ \vdots \\ T_M \end{bmatrix} + S \times Z \]  

(2)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Number of previous results/time-steps included</td>
</tr>
<tr>
<td>N</td>
<td>Number of neighbouring nodes included</td>
</tr>
<tr>
<td>X_n</td>
<td>Sensing result from neighbouring node n [+1,-1]</td>
</tr>
<tr>
<td>D_n</td>
<td>Weighting factor according to distance applied to neighbouring node n</td>
</tr>
<tr>
<td>Y_m</td>
<td>Result from m time-steps previously</td>
</tr>
<tr>
<td>T_m</td>
<td>Weighting applied to previous result m</td>
</tr>
<tr>
<td>S</td>
<td>Weighting applied to the node’s own result</td>
</tr>
<tr>
<td>Z</td>
<td>Node’s own result [+1,-1]</td>
</tr>
<tr>
<td>Q</td>
<td>Final result [positive, negative]</td>
</tr>
</tbody>
</table>

Table 1 – Detection Algorithm Terms

The neighbour weighting factor, \(D_n\), is applied such that the detection decisions from more distant CRTs have less influence on the final result, selected so as to be proportional to the inverse of the distance between the neighbour and detecting node. A hard upper distance limit can be set to prevent distant nodes having any influence on the detection decision at all. The default value of \(D\) is 1000/d where d is the separation in metres; the value of D is capped at 1.

The incorporation of the detection decision from a previous time interval can smooth out the effects of slow fading on the result, the effect of these historic results can be modified with the time weighting factor \(T_m\). This is always set such that the historical sensing decisions always have much less influence than the neighbour detection decisions. The weight of the CR’s own detection can be set so as to carry more influence than the other detection factors by changing the value of \(S\). Additionally, a weighting factor can be set to increase the importance of positive results as it is highly unlikely that a false detection will arise in the individual sensing case, whereas a missed detection is probable in a shadowing region. The final “sensed” or “not sensed” output is determined from the value of \(Q\) being positive or negative respectively. It should be noted that the simulation does not specifically address the mechanism by which the detection decisions are shared. It also assumed that the distance measure, d, required by the neighbour weighting function is also known.

4 Results

Results of the simulation are presented that show the accuracy of primary signal detection. The key parameter is the probability of detection, which determines the likelihood that the detection algorithm at each CR correctly detects the primary transmission, if the CR is located with transmission range.

Three scenarios were defined, each with a different area size and simulation parameters (path loss exponent n and shadowing variance \(\sigma\)). These are given in Table 2.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Area Size</th>
<th>n (PLE)</th>
<th>(\sigma) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>100km²</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Urban</td>
<td>4 km²</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>Dense Urban</td>
<td>4 km²</td>
<td>4.5</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2: Summary of Simulation Scenarios

Various simulations were run to investigate the effects of varying the algorithm parameters given in Table 1.

4.1 Distributed Detection

A comparison of results for single node sensing and distributed sensing is shown in Figures 3 and 4. A distribution of 500 receivers was used in each case, with all other parameters fixed. Five different transmitter types with varying transmit powers for detection were defined. In this case the relevant values for the detection parameters are \(N=10, S=4\). The time weighting matrix \(T\) was [0.5 0.3 0.2] (\(M=3\)).

As can be seen in Figure 3, single node sensing can perform detection of high power TV broadcasts with 100% accuracy for the “Rural” and “Urban” environments, yet accuracy is not guaranteed for either UMTS systems or lower power TV broadcasts. The probability of detection if distributed sensing is employed, is given in Figure 4. Improvements in performance can be seen for all systems and across all environments, with the exception of the UMTS microcell transmission in the “Dense Urban” scenario. As accuracy levels in all other cases are improved to above 99%, it can be concluded that the proposed distributed sensing method is a reliable technique for detection of most types of primary transmitter.

4.2 User Density

In order to improve the reliability of detection of low power primary users the density of users within the cell’s transmission range needs to be considered, as well as the
number of neighbouring nodes information is shared with. Figure 5 shows the effect of increasing the density of receivers, with the overall area reduced to 1km$^2$ (for the “Dense Urban” scenario). Clear improvements in the performance of the detection algorithm can be seen, but the slope flattens out at ~98% with densities above 500 users per square kilometre. Hence it can be concluded that increasing the density cannot guarantee absolute reliability in this case, but is beneficial nonetheless.

### 4.3 Number of Neighbours

It seems logical to assume that increasing the number of neighbouring nodes that a terminal shares information with would offer improvements in probability of detection (i.e. changing the value of $N$ in Equation 2). This is demonstrated in Figure 6.

Increasing the number of sharing nodes offers increased performance in all cases – with 100% reliability with 10 sharing nodes for 4 out of the 5 cases. Improvements can be seen in the UMTS microcell, but the increase in performance of detection falls off with a greater number of sharing nodes. This is because the influence of neighbouring nodes decreases with distance.

### 4.4 Positive Weighting and Self-Weighting

The results for far have only considered the accuracy of results from nodes within the primary transmitter’s coverage region have been considered – as minimising interference to the primary user is of paramount importance. However, the probability of generation of false positive results, also needs to be considered, as this will affect the overall efficiency of the cognitive system. As an example, the positive results weighting factor is considered, as shown in Figure 7. Results are shown for the DVB-T channel for the “Urban” scenario, with a total area of 400km$^2$. These parameters were used so that an approximately equal number of receivers would be located inside and outside the coverage region. A clear trade-off can be seen between the improvement in accuracy and the increase in probability of false detections. This is similarly found to be the case if the self weighting factor is varied as in Figure 8.

In both cases the point of intersection and hence theoretical optimum performance lies at ~60%. Clearly a probability of detection of primary user of 60% is unacceptable, and hence performance outside the coverage region must be sacrificed in order to minimise the probability of interference. It should be noted that the resulting inefficiency in spectrum access will only occur close to the coverage region boundary, and in this
case is partly due to the inability to correctly define the coverage region.

![Graph showing effects of increasing positive weighting factor](image1)

Figure 7: Effects of increasing positive weighting factor

![Graph showing effects of increasing self weighting factor](image2)

Figure 8: Effects of increasing self weighting factor

### 5. Conclusions

In this paper a distributed method for spectrum sensing for cognitive radio has been proposed. In particular the challenging effects of shadow fading have been considered, and the case has been made that distributed sensing should resolve these inaccuracies, through local sharing of information. The distributed sensing algorithm is implemented as a majority polling system between the results of all neighbouring nodes. A decision is formed based on the result of a weighted summation of these neighbouring results. The proposed method includes several variable weighting factors – such as weighting according to distance to neighbouring nodes, increased influence of positive results and increased influence of a node’s own result. In addition the inclusion of historic results to the decision making process is possible.

It has been found through simulation across various environments and with various transmitted powers that the proposed method is highly effective in detecting high power primary systems such as TV broadcasts and UMTS macrocell transmissions, as 99 – 100% accuracy may be obtained through distributed sensing. In the worst case “Dense Urban” scenario, for a DVB-T 27dBW transmission an improvement from 51.4% to 99.2% accuracy is seen. However the method is not suitable for detection of similar systems with lower transmit power when located in densely populated urban environments, as reliability greater than 99% cannot be guaranteed. A UMTS 17dBW transmission was found to achieve 54% accuracy under the same simulation parameters as the above systems, which is clearly unacceptable performance when considering the possibility of causing interference to primary users. It is found that accuracy depends heavily on the density of users within the region. Increasing the density of users can improve the accuracy, but it should be noted that in reality this will vary widely with time and availability of sensing nodes cannot be guaranteed.

In order to reduce the probability of generation of false positive results outside the coverage region, and hence improve the efficiency of spectrum access, the self and positive weighting factors may be adjusted. However this is at the expense of accuracy of detection within the coverage region, with the crossover point at ~60% in both cases. As it is imperative to minimise the probability of interference to primary users, it is concluded that the accuracy within the coverage region should take precedence within this trade-off. The resulting detrimental effect to efficiency of spectrum outside the coverage region can be considered to be acceptable, as accuracy will be improved as users move further away from the coverage region boundary. In any case it may not be safe to access the spectrum while close to the boundary - as this could still result in interference.

### Acknowledgements

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### References


