WIDEBAND COOPERATIVE SPECTRUM SENSING AND SIGNAL DETECTION (BRIEFING SLIDES)

JULY 2013

INTERIM TECHNICAL REPORT

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14. ABSTRACT
These presentation slides are provided as an interim report of the in-house project titled “Wideband Cooperative Spectrum Sensing”. The objective of this effort is to develop wideband cooperative spectrum sensing and signal detection techniques. Two sensing steps are used to detect and exploit the signals of interest: Coarse sensing to determine the presence or absence of signals within scanned frequency bands; and fine sensing by exploiting the features of signals.

15. SUBJECT TERMS
Cooperative Spectral Sensing, Energy Detection, Frequency Allocation

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<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
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1 Abstract

This presentation slides are provided as an interim report of the in-house project titled “Wideband Cooperative Spectrum Sensing”. The objective of this effort is to develop wideband cooperative spectrum sensing and signal detection techniques. (Slide 3) Two steps sensing are used to detect and exploit the signals of interest: Coarse sensing to determine the presence or absence of signals within scanned frequency bands; and fine sensing by exploiting the features of signals. (Slide 5)
2 Presentation Slides

The presentation slides provided in the next pages summarize the work performed in this in-house project during the FY-12.
DoD use spectrum to provide capabilities

- Communication
- Telemetry
- Surveillance
- Radio location
- Radio navigation
- RDT&E
Program Objective

• To achieve effective spectral awareness
  – Sensing method capable of making cooperative decisions over multiple frequency bands is essential
  – Many conventional spectrum sensing methods
    • Either single-channel or non-cooperative signal detection
    • Vulnerable to noise uncertainty, fading, and shadowing
• Objective: develop wideband cooperative spectrum sensing and signal detection techniques
  – Spatial diversity: multi-sensors joint decision
  – Spectral diversity: multi-channel detection
  – Effective spectral awareness
Approach

- Cooperative sensing: single sensor to multiple sensors
- Wideband sensing: single-channel to multi-channel
- Two steps sensing to detect and exploit the signals of interest (SOI)
  - Coarse sensing (signal detection): determine the presence or absence of signals within scanned frequency bands
  - Fine sensing (feature recognition): exploiting the features of signals
Coarse Sensing/Signal Detection

- Objective: quickly & reliably determine the existence of signals in multiple frequency bands by joint detection

- Challenge:
  - No prior information about the signals, blind/semi-blind detection approaches
  - Speed: low computational complexity to achieve quick sensing (low complexity leads to less accurate sensing result)
  - Accuracy: multi-sensors/antennas cooperative sensing to improve the performance

- Two main tasks:
  - Develop a wideband blind/semi-blind sensing method that has the right balance between speed and accuracy
  - Find optimal cooperation strategy to combine sensing results from multiple sensors
Objective: exploit & estimate the features (i.e. bandwidth, center frequency, modulation type, etc.) of a signal

- Fine sensing initiate only when signals been detected in the coarse sensing

- Some information regarding the noise distribution or signal distribution may already been obtained

- Known pieces of information can be passed on to fine sensing to assist with features recognition

- Methods require signal and/or noise information can be used
Sensing Methods

• Spectrum sensing & signal detection is not new

• Cognitive Radio further stimulates its development

• Each method has different requirements for implementation

• Complexity and accuracy of sensing methods is increasing as the information required for detection increasing
Cooperative Detection

• Constraint of many conventional detection methods
  – Non-cooperative signal detection in single frequency band
  – Sensing reliability degraded due to noise and fading

• Information from multiple sensors can be combined to obtain more accurate decision

<table>
<thead>
<tr>
<th>Cooperative Sensing</th>
<th>Distributed</th>
<th>Centralized</th>
</tr>
</thead>
<tbody>
<tr>
<td>share information among each other but make own decisions</td>
<td>Data feed: each node send raw data, central unit make decision</td>
<td>Decision feed: process data, send only the decision to central unit</td>
</tr>
</tbody>
</table>
Each cooperation strategy has its own decision rule for signal detection:

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Decision Rule for Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voting</td>
<td># of votes for detection &gt; # of votes for no detection</td>
</tr>
<tr>
<td>OR</td>
<td>Out of N individual decision, any one detected signal</td>
</tr>
<tr>
<td>AND</td>
<td>All sensing nodes have to detect signal</td>
</tr>
<tr>
<td>Linear combination</td>
<td>Normalized weight assign to local decision according to their SNR, global decision reach by combine weighted local decision</td>
</tr>
</tbody>
</table>
The problem of detection of the signal can be modeled as a binary hypothesis testing problem:

\( \mathcal{H}_0 : y_i(n) = w_i(n) \)

\( \mathcal{H}_1 : y_i(n) = s_i(n) + w_i(n) \)

The performance of the detection algorithm can be summarized with 2 probabilities: probability of detection and probability of false alarm:

\( p_f = \Pr(T > \gamma | \mathcal{H}_0) \)

\( p_d = \Pr(T > \gamma | \mathcal{H}_1) \)

- Small \( P_f \) results in higher spectrum efficiency
- Large \( P_d \) value lead to better chance of detecting signal
Linear Cooperative Sensing

- **Individual sensor**
  - Calculates a summary statistic over an interval of $N$ samples
  - Then statistic is sent to fusion center

- **Fusion center**
  - Assigns a weight to each sensor based on the summary statistic received, then combine them linearly
  - The weight for a particular sensor represents its contribution to the global decision
  - Large weight assigns to those sensors have high-SNR; small weight for sensors with low-SNR
MATLAB Simulation

Parameters: Primary user’s signal s(k) = 1; # of samples: N=20;
fixed channel noise variance of 0.5; # of cooperative sensors: M=1, 3, and 6

<table>
<thead>
<tr>
<th></th>
<th>M=1</th>
<th>M=3</th>
<th>M=6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR (dB)</td>
<td>8.3</td>
<td>{10.4, 9.3, 2.6}</td>
<td>{7.2, 5.1, 10.8, -1.2, 3.6, 9.7}</td>
</tr>
<tr>
<td>Sensing noise Variance</td>
<td>1.9</td>
<td>{0.7, 1.0, 0.9}</td>
<td>{0.9, 1.3, 1.0, 2.0, 1.8, 1.2}</td>
</tr>
</tbody>
</table>

Result of optimal weights and P_d values for a given P_f value

<table>
<thead>
<tr>
<th></th>
<th>M=1</th>
<th>M=3</th>
<th>M=6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Vector</td>
<td>1</td>
<td>{0.8348, 0.5165, 0.1909}</td>
<td>{0.4713, 0.2328, 0.1285, 0.4986}</td>
</tr>
<tr>
<td>P_d (given P_f=0.1)</td>
<td>0.4342</td>
<td>0.7408</td>
<td>0.8265</td>
</tr>
<tr>
<td>P_d (given P_f=0.6)</td>
<td>0.8463</td>
<td>0.9599</td>
<td>0.9803</td>
</tr>
</tbody>
</table>
Simulation Plot

Probability of detection vs. Probability of false alarm

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Wavelet-based Sensing

Goal:
- Investigate the potential of wavelet transform for wideband cooperative signal detection

Motivation:
- Extensive research on wavelet analysis for images and time series
- Only limited research has applied wavelet approach to spectral detection
  - Non-cooperative detection
## Time-Frequency Analysis

### Fourier Transform vs. Wavelet Transform

<table>
<thead>
<tr>
<th>Processing Signal Type</th>
<th>Fourier Transform</th>
<th>Wavelet Transform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationary</td>
<td>Non-stationary</td>
<td></td>
</tr>
<tr>
<td>Provided Information</td>
<td>Frequency</td>
<td>Both time and frequency</td>
</tr>
</tbody>
</table>

![Short Time Fourier Transform (STFT) vs. Wavelet Transform (WT)]
Wavelet Transform

- Continuous Wavelet Transform (CWT)
  - The mother wavelet function $\psi(t)$
  - The scale factor $a$

- Discrete Wavelet Transform (DWT)
  - Decomposition by Filter Bank

<table>
<thead>
<tr>
<th>Level</th>
<th>Frequencies</th>
<th># of Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0 to $f_n/8$</td>
<td>$n/8$</td>
</tr>
<tr>
<td></td>
<td>$f_n/8$ to $f_n/4$</td>
<td>$n/8$</td>
</tr>
<tr>
<td>2</td>
<td>$f_n/4$ to $f_n/2$</td>
<td>$n/4$</td>
</tr>
<tr>
<td>1</td>
<td>$f_n/2$ to $f_n$</td>
<td>$n/2$</td>
</tr>
</tbody>
</table>

$$X_w(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-b}{a}\right) dt$$

A3 Level Filter Bank

DWT Frequency domain representation
Next Step

• Linear Cooperative Sensing
  – Extend to wideband detection

• Wavelet-based Sensing
  – Continue working on the simulation code to investigate the effectiveness for wideband sensing
  – Feasibility for cooperative sensing

• Investigating other blind detection methods
  – Eigenvalue-based
  – Sub-space analysis
# Program Schedule

<table>
<thead>
<tr>
<th>Project Phases</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Algorithm for coarse sensing</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Algorithm for fine sensing</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Software Development</td>
<td></td>
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<tr>
<td>Software Test</td>
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<td>Final Technical Report</td>
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3 References


### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>SOI</td>
<td>Signals of Interest</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>Pd</td>
<td>Probability of Detection</td>
</tr>
<tr>
<td>Pf</td>
<td>Probability of False Alarm</td>
</tr>
<tr>
<td>CWT</td>
<td>Continuous Wavelet Transform</td>
</tr>
<tr>
<td>DWT</td>
<td>Discrete Wavelet Transform</td>
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