TRIAL Heritage - Lessons learned on Mobile and Cooperative Sensing in ENCOR preojects

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Motivation
Motivation

http://cabspotting.org
Spectrum Sensing for Cognitive Radios

- Spectrum sensing provides the **awareness** regarding the radio environment needed for cognitive processing:
  - **Exploring Spectrum Opportunities**
  - Signal Classification
  - Radio Environment Maps
  - Traffic analysis

PU: primary user (licensed or legacy user)

SU: secondary user (cognitive radio)
ENCOR2- project overview

- Algorithm development and research
- Harware nonideality compensation with DSP
- Field tests/applications
- Algorithm implementations
Clarifying The Big Picture

- Algorithm development and research
- Field tests/applications
- Algorithm implementations
- Hardware nonideality compensation with DSP

Aalto University
School of Electrical Engineering

Tampere University of Technology
Detector development
Detector development

FPGA implementation properties

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Power diss. [mW]</th>
<th>Logic elements</th>
<th>Registers</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy detector</td>
<td>1.47</td>
<td>612</td>
<td>290</td>
<td>0</td>
</tr>
<tr>
<td>FFT-based cyclostationary feature detector</td>
<td>55.21</td>
<td>16591</td>
<td>8802</td>
<td>405674</td>
</tr>
<tr>
<td>Time domain cyclostationary detector</td>
<td>42.15</td>
<td>8593</td>
<td>1291</td>
<td>327680</td>
</tr>
<tr>
<td>Spatial sign Cyclic Correlator</td>
<td>12.77</td>
<td>5044</td>
<td>811</td>
<td>327680</td>
</tr>
<tr>
<td>Spatial sign Cyclic Correlator with angular domain computation</td>
<td>4.70</td>
<td>945</td>
<td>198</td>
<td>131072</td>
</tr>
</tbody>
</table>

Evaluated with FPGA implementation
Detection Performance

• Detection sensitivity stays at -115 dBm when using AGC (maximum gain)

• At high signal levels AGC sets lower gains which degrades noise figure but improves linearity and prevents clipping
  • Reduces false alarms
Detection Performance

- Performance of a mobile spectrum sensor has uncertainties
- Removing the uncertainties is impossible
- Cost of reducing the uncertainties grows exponentially (1st order estimate).
- Have to find a way to live with the uncertainties,
- Have to determine the spatial and temporal resolution of the whole system, which defines the available capacity for the secondary communication.
Field tests and Cooperative sensing
Cooperative Sensing: Distributed Detection

Listening Channels

PU Tx

Reporting Channels

SU 1

PU Rx

SU k

SU N

Reporting Channels

Fusion Rule:

\[ f(L_1, L_2, \ldots, L_N) \rightarrow H_0 \text{ or } H_1 \]

Advantages:
1. Mitigates effect of multipath fading and shadowing such as hidden node problem
2. Improves detection performance
3. Facilitates simpler detectors

\[ L_n = f(x_n) \text{ (for example log-likelihood ratios)} \]
Cooperative sensing

- **CS schemes**
  - K-out-of-N (if K CUs decide H1 => Declare H1)
    - AND (K=N)
    - OR (K=1)
    - MAJORITY (K=ceil(N/2+0.5))
  - SUM of cyclostationary based GLLRT statistics

- Neyman Pearson detection strategy: Pf=0.1

- Comparison with cyclostationary based single-user detector or local sensing (LS)
Cooperation Model

- Distributed detection with a fusion center, but non-dedicated
- Each sensor sends data to neighbors and each sensor fuses the incoming decision statistics to make a decision locally.
- Suitable for ad-hoc networks
Evaluation of CS performance in practice

• Motivation
  – Most of the results are theoretical.
  – Very few measurement campaigns with bulky spectrum analyzers and energy detection.
  – In simulator and laboratory environment, the uncertainties are controlled and reduced -> model of the reality is inaccurate.
  – Put the theory in practice to see if it really works.
Evaluation of CS performance in practice

- Objective: analyze and validate the theoretical CS gains
  - Two extensive field measurement campaigns
    - MC-I: Stationary, 93 locations, six sensors, Helsinki City Center, 9km\(^2\)
    - MC-II: Non-stationary, 2 sensors, Espoo and Helsinki, 100 km\(^2\)
  - DVB-T transmission as primary user; channels 42-57
  - Cyclostationary based detectors
  - Mobile sensors
  - CS schemes: OR, AND, MAJORITY and SUM
Measurement Set-Up

- Setup: Sensor, Laptop, GPS, Battery
- Sensor designed for Nokia N900 phone

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensing Time</td>
<td>57 msec</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>36 Ms/s</td>
</tr>
<tr>
<td>Decimation Rate</td>
<td>1024</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>-8 dBi @ 470 MHz</td>
</tr>
<tr>
<td></td>
<td>-4 dBi @ 750 MHz</td>
</tr>
</tbody>
</table>

- Antenna: Planar PWB 470-750 MHz DVB-H EU
Primary User Transmission

- Digital TV (DVB-T)
- Center frequencies in the range of 642 MHz – 742 MHz
- Channels 42-57
- Other Specifications

<table>
<thead>
<tr>
<th>Modulation</th>
<th>OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT Size</td>
<td>8192</td>
</tr>
<tr>
<td>Cyclic prefix</td>
<td>1024</td>
</tr>
<tr>
<td>Non-zero subcarriers</td>
<td>6817</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>8 MHz</td>
</tr>
</tbody>
</table>
Transmitter Specifications

- Parameters of the transmitters on the representative channels 42 (Free), 44 (Occupied), and 45 (Partly occupied).

<table>
<thead>
<tr>
<th>DVB-T Transmitters</th>
<th>Espoo</th>
<th>Tallinn</th>
<th>Nummi-Pusula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>60.1778</td>
<td>59.4713</td>
<td>60.45</td>
</tr>
<tr>
<td>Longitude</td>
<td>24.6403</td>
<td>24.8875</td>
<td>23.8833</td>
</tr>
<tr>
<td>Mast height</td>
<td>313 m</td>
<td>272 m</td>
<td>70 m</td>
</tr>
<tr>
<td>Transmission power</td>
<td>77 dBm</td>
<td>71.67 dBm</td>
<td>53 dBm</td>
</tr>
<tr>
<td>Channels transmitted</td>
<td>44, 46, 53</td>
<td>45</td>
<td>42, 47</td>
</tr>
<tr>
<td>Avg. dist. from MC</td>
<td>16.76 km</td>
<td>77.2 km</td>
<td>66.5 km</td>
</tr>
</tbody>
</table>
Measurements: Behavior of test statistics

Test Statistics

Mean and Variance

Channel 42:
Low values of test statistics and their mean and variances. Typical of null hypotheses. Free

Channel 44:
High values of test statistics and their mean and variances. Typical of Alternative hypotheses. Occupied

Channel 45:
Moderate values. Significant decay. Effects of shadowing and fading. Partly occupied
Measurement campaign I

Stationary measurements; 6 distinct sensors; 1 sensor at each location; 93 locations; 200 test statistics/loc/channel; 16 DVB-T channels (42-57); 9 km^2
Results: Probability of detection for CS with N=5

- **Channel 42**:  
  - Pd is on the order of Pf=0.1 irrespective of scheme.  
  - Free

- **Channel 44**:  
  - Pd one irrespective of sensing scheme.  
  - Occupied

- **Channel 45**:  
  - Pd between 0.1 and 1  
  - Partially occupied  
  - Cooperation improves performance
Avg. Pd for CS over all meas. locs.

- **Free**: 42, 49, 50, 57
- **Occupied**: 44, 46, 53
- **Partially occupied**: Rest of the channels (43 and 45 are mostly occupied)
Results: ROC for CS with N=5 at loc. Index 83, ch. 45

- Channel 45
- This location is heavily shadowed. Single-user sensing has worst performance.
- **Cooperation provides diversity gain** and SNR gains to improve the performance.
Cooperation gain for ch. 45, N=5, Pf=0.1

Region I: Cooperation gain due to diversity or SNR gain not significant. However, still possible to obtain other CS gains like reduction in sensing time, simplicity of detector and robustness to non-idealities

Region II: Diversity and SNR gains significantly improve performance over single-user sensing

Cooperation gain expressed in terms of relative increase in probability of detection (RIPD) given by

\[
RIPD = \frac{P_{d,N} - P_{d,1}}{P_{d,1}} = \frac{P_{d,N} - P_{d,1}}{P_{d,1}} \times 100\%
\]
Cooperation improves performance over single-user sensing. CS schemes in descending order of performance: SUM, OR, MAJ, AND.
Measurement campaign II

- Mobile measurements; 2 sensors; 2290 locations
- Not synchronized; 1 test statistic per location; 100 km^2
Avg. Pd over all locations for N=5

- Cooperation provides diversity gain and SNR gains to improve the performance even in case of fast fading.
Avg. RIPD over all locations for N=5

- AND does not provide diversity gains and therefore suffers performance degradation due to fast fading during non-stationary measurements
Summary

- Spectrum sensing provides **awareness** regarding the **radio environment** that is essential for cognitive processing.
- Cooperative sensing **improves detection performance**.
- Two **extensive measurement campaigns** carried out for validating the CS in practice based using cyclostationary based mobile sensors.
- The results validate the theoretical gains of cooperative sensing in practical scenarios with mobile sensors.
  - Avg. RIPD for different schemes in MC-I for N=10: SUM (82.5 %), OR(82.5 %), MAJORITY (76.8 %) and AND (18 %).
  - Avg. RIPD for different schemes in MC-II for N=10: SUM (73%), OR (73%), MAJORITY (30%) and AND (-19 %).
Dissemination
Recent publications


Database

- Available at: http://nano.aalto.fi/research/grups/ecd/cognitive_radio_database
- Web application under development.

Database access description

- Database type: mysql
- Server name: galaxy.codi.hut.fi
- Database and table: aaltocrdb.static
- username: staticreader
- password: JWn67xf

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Date and time</td>
</tr>
<tr>
<td>MSEC</td>
<td>Milliseconds after TIME</td>
</tr>
<tr>
<td>Latitude</td>
<td>Latitude in wgs84-format</td>
</tr>
<tr>
<td>Longitude</td>
<td>Longitude in wgs84-format</td>
</tr>
<tr>
<td>Lowfreq</td>
<td>Lower bound of the frequency band [Hz]</td>
</tr>
<tr>
<td>Highfreq</td>
<td>Higher bound of the frequency band [Hz]</td>
</tr>
<tr>
<td>Teststat</td>
<td>Test statistic</td>
</tr>
<tr>
<td>Distir</td>
<td>Distribution of their test statistics</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received signal strength estimate [dBm]</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio estimate [dB]</td>
</tr>
<tr>
<td>System</td>
<td>System the detection is performed for</td>
</tr>
<tr>
<td>Detector</td>
<td>Detector identifier</td>
</tr>
</tbody>
</table>

For further information, contact helpdesk(at)ecdl.tkk.fi
The Future
Near Future

• Further processing of the data from the measurement campaigns
• Visualization of data and developing web interface (along with Markus Laatta (TUT))
  – Target is to make the data and results public.
• Measurement campaign during Summer 2014
• Future work: More measurement campaigns in Summer 2014 to further examine the spatial and temporal resolution issues and the role of the RSSI.
  – stable RSSI values
  – only 6 channels 42-47 (more data, on interesting channels)
  – Shorten sensing times
  – In collaboration with WISE (use of TSM-DVB receiver)
  – Comparison of CS using energy detection and cyclostationary detection
The Future

- Will There be the Internet of Things?

www.computerweekly.com
The Future

- Number of mobile devices will proliferate.
- There is a very strong ongoing effort to enable "Internet of Things"/"Physical Internet" with energy autonomous wireless sensor nodes combined with mobile devices and "The cloud".
- Lots of sensors monitoring everything, everywhere, all the time.
- Spectrum sensing is just one more sensor in the IoT -> Enormous amount of information available for further usage.
- The future world will increasingly rely on information gathered with IoT devices, and there is no reason to assume that spectrum sensors would be excluded.
- Hardware has been prototyped and the functionality has been demonstrated.
- The work has to be expended to cover more systems, to gather more data, and thus improve the resolution.
- Effects of emerging IoT on xG standardization? (optimization for cognitive communication)
Thank you