Distributed Cooperative Sensing and Decision-Making in Cognitive Radio Networks

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OUTLINE

• Introduction
  – Bio-Inspired Collective Behaviors
  – Information Consensus

• A Comparison Between Centralized and Distributed Cooperative Spectrum Sensing

• The Algorithm: Weighted Consensus-Based Distributed Spectrum Sensing

• Preliminary Simulation Results

• Experimental Setup

• Proposed Future Work

• Summary and Publications
Bio-Inspired Collective Behaviors

• Observed in herds of animals and biological aggregations, collective behaviors are adaptive to environmental changes (self-learning capability)

• Cooperative control, the study of decision-making process towards collective behaviors, has progressed rapidly from modeling and simulation of specific examples towards a more fundamental explanation applicable to a wide range of systems
From Distributed Robots to Cooperative Sensing

A dynamic spectrum access/sensing network to cooperatively detect unauthorized users

A group of agents autonomously navigate through a tunnel by distributed control
Information Consensus

- Information consensus lays the groundwork to ensure system cooperation

Agent with single integrator kinematics:

\[ \dot{r}_i = u_i, \quad i = 1, \ldots, n, \]

Consensus algorithm:

\[ u_i = - \sum_{j=1}^{n} a_{ij} (r_i - r_j), \quad i = 1, \ldots, n, \]

- Communication topology: undirected or directed graphs
Centralized and Distributed Spectrum Sensing

- **Centralized Scheme:**
  - Fusion center (common receiver)
  - Reporting channels

- **Distributed Scheme:**
  - Local information exchange without the central station
## Comparison

<table>
<thead>
<tr>
<th></th>
<th>Centralized spec. sensing</th>
<th>Distributed spec. sensing</th>
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<tbody>
<tr>
<td>Fusion-center</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Scalability</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Reporting channel</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>dependency</td>
<td></td>
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<tr>
<td>Decision duration</td>
<td>Sensing + reporting + processing</td>
<td>Sensing + consensus durations</td>
</tr>
<tr>
<td>False alarm probability [Li et al.2010]</td>
<td>higher</td>
<td>lower</td>
</tr>
<tr>
<td>Missing detection probability [Li et al.2010]</td>
<td>higher</td>
<td>lower</td>
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Distributed Consensus-Based Cooperative Spectrum Sensing

• Two-stage process:
  – Sensing and measurement stage: each SU senses and makes measurement about PU;
  – Local information exchanging with neighboring agents and decision making on whether PUs are around

• The goal:
  Consensus is reached (on whether PUs are around) after a few iterations in the second stage.
The Model

• The spectrum sensing model:
The received signal $x(t)$ takes the form

$$x(t) = h s(t) + n(t),$$

- The channel gain $h$ can be decomposed into path loss, shadowing, and small-scale fading factors

$$G_r(x,t) = G_0 - 10\gamma \log_{10}(\|x - x_r\|) + s_r(x,t) + f_r(x,t)$$

- $s_r(x,t)$: Normal Distribution with zero mean and different variances (the degree of shadowing)
- $10^{0.1f_r(x,t)}$: Rayleigh Distribution, which can be averaged out
- Distances $\|x - x_r\|$ from SUs to PU are known (or known statistic distribution)
- The average SRN is known to SUs
The Consensus Algorithm

- Assuming we have the measurement $Y_i$ at time $k=0$, i.e., $x_i(0)=Y_i$, the iterative form of the consensus algorithm:
  
  $$x_i(k + 1) = x_i(k) + k \sum_{j \in N_i} w_{ij} (x_j(k) - x_i(k))$$

- We design the weighting, $w_{ij}$, of the consensus algorithm, so that confidence of SU is incorporated into the decision-making
Simulations
Comparison with Optimal Weighted Average

• Calculate the percentage of error with optimal weighted average
Comparison with Central Method

False Alarm: Threshold: 0.5  61100 times runs  No False Alarm Probability of False Alarm < 1.6E-5
Threshold: 0.45 10000 times runs  No False Alarm Probability of False Alarm < 1E-4
Threshold: 0.4 1000 times runs  No False Alarm Probability of False Alarm < 1E-3
Comparison with Existing Distributed Method


Potential Testbed Development

- About 10 - 20 USRPs are needed.
- Using Agilent signal generator to simulate different kinds of signal band, e.g., TV band, 3G, etc.
Potential Testbed Development

- **Monitoring and Management Server**
  - Acted by a desktop computer for monitoring the system state, and managing the functionality and resource of the system.

- **Secondary User (USRP)**
  - Detecting the unused spectrum, capturing available spectrum for communication, and applying specified applications in cognitive networks, such as security, resource management, etc.

- **User End**
  - Controlling or requesting from the system.
Potential Testbed Development
- Software Architecture

Diagram:
- Monitoring & Management System
- Mobility Control Component
- Spectrum Sensing Component
- Application-Specific Component
- GNU Radio Interface
- Mobile Driver
- Consensus Sensing Block
- Security Block
- Resource Management Block
- Internet
- User End
- Robots Interface
- Vehicles Interface
- USRP Interface
Potential Testbed Development
- Software Architecture

- Monitoring & Management System
  - **Mobility Control Component**: Controlling the mobility of the primary or secondary users in the system;
  - **Spectrum Sensing Component**: Sensing the spectrum usage for different kinds of wireless networks;
  - **Application-specific Component**: Applying different functionality in the system.
Nest Step

• Theoretical proof of the proposed distributed spectrum sensing algorithm
• Extensive simulations
• Experimental validation
Proposed Future Work

• Anomaly detection for dynamic spectrum access networks [Liu et.al. 2009]
  – Fusing local measurement of received signal strength,
  – New idea: Detecting unauthorized transmitters real time without a central monitoring station

• Localization with distributed spectrum sensing
  – By dynamic signal strength mapping [Liu, Chen, et. al 2009]
  – New idea: A distributed fusion solution based on consensus Kalman filter

In collaboration with Prof. Yingying Chen and Yu-Dong Yao’s group
Summary

• Inspired by herds of animals and biological aggregations, we aim to develop distributed spectrum sensing algorithms for cognitive radios to learn and adapt to dynamic and uncertain environments.

• We proposed a weighted distributed cooperative spectrum sensing algorithm.

• Preliminary simulations show promising results.

• Future work includes theoretical and experimental validations, and extension of the current framework to anomaly detection of dynamic spectrum access network and cooperative localization.
Publications

- Journal paper:

- Conference papers:
References


