Primary and Cognitive User Cooperative Spectrum Sensing in OFDMA Air Interface

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All about the research - an abstract

- How primary user (PU) can assist cognitive users (CUs) in PU’s activity sensing (detection)?
- How a PU should assist a CU,
  1. Minimizing the loss in it’s spectral efficiency?
  2. Maximizing the correct detection probability of it’s presence to a CU?
- PU can assist to improve 15% of the correct detection probability with a 5% reduction in spectral efficiency (in low-moderate SNR with two subcarrier (simplest) system)
- PU assistance only in initial phase/s of the transmission (overall reduction in spectral efficiency is minimized)
- Method is based on subcarrier based air interface and matches well with IEEE 802.22 standard
Spectrum Sensing and Open Issues

- Energy detection is promising. As,
  - Blind and does not exploit unauthorized details of PU communication
  - Simple in structure and less cost in implementation
- Fading, shadowing deteriorates the detection performance
- Receiver diversity combining improves, but not good enough
- CU Cooperation in sensing
  - Share the individual detection decisions among cognitive users
- We propose, PU and CU cooperation in sensing
  - A PU assist a CU to detect its presence
  - PU can assist to improve 15% of the correct detection probability with a 5% reduction in spectral efficiency in low-moderate SNR with two subcarrier (simplest) system
  - Band-manager facilitate the required information sharing
  - Can co-exist with CU cooperative sensing schemes
  - Underline detection by energy detector
  - Subcarrier based air interface (Suitable for IEEE 802.22 standard)
System Model - Detect PU

- OFDMA air interface - $N$ subcarriers indexed from 1 to $N$
- Interference included in noise (Energy detector cannot differentiate noise and interference)
- Parallel Gaussian channels (PU-CU & PU-BS)
- CU utilizes Energy Detectors
Problem Formulation

- PU has a total of $P_t$ power to allocate among $N$ subcarriers
- Conventional approach - allocate the $P_t$ power to maximize the PU’s spectral efficiency
- Proposed approach - allocate the power by PU to maximize the detection with a capacity constraint
  - Allow CU to detect PU easily - avoid transmissions on false detected spectrum holes
  - Allow CU to control transmitter power - interference constraint systems
  - Allow CU to share the individual decisions and improve detection (Co-existence with CU cooperative sensing schemes)
  - Capacity of PU is not severely reduced
    - PU has the flexibility on the operating point
    - Deployment only in initial connection establishment phases
- PU assist CU to detect its presence : Co-existence & cooperation is necessary among CU & PU in cognitive networks
Assist CU’s Detection under Capacity Constraint

- Optimization problem

maximize: \( P_d \left( \{ p_i \}_{1}^{N}, \lambda \right) \)

subject to: \( p_i \geq 0; \ i = \{1, \ldots, N\} \)

\[
\sum_{i=1}^{N} p_i \leq P_t
\]

\[
\sum_{i=1}^{N} \log \left( 1 + \frac{p_i}{n_i^b} \right) \geq C
\]

- \( p_i \) - the power allocated to the \( i^{th} \) indexed channel with noise levels \( n_i^b \) from the PU to the BS
- \( n_i^c \) - noise level of the \( i^{th} \) indexed channel from the PU to the CU
- \( P_d \left( \{ p_i \}_{1}^{N}, \lambda \right) \) - PU detection probability experienced by the CU
- \( \lambda \) - threshold of the energy detector (determined by the \( P_f \))
- \( C \) - Capacity constraint
Objective function - $P_d \left( \{p_i\}_1^N, \lambda \right)$

- **Fusion Rule**
  - CU detects individual subcarriers
  - Combines them through a predetermined fusion rule
  - Fusion based on 'OR' rule

- **Detection Probability by CU**

  $P_d \left( \{p_i\}_1^N, \lambda \right) = 1 - \text{Prob} \left( Y_1 < \lambda, \ldots, Y_N < \lambda \mid H_1 \right)$

  \[= 1 - \prod_{i=1}^{N} \text{Prob} \left( Y_i < \lambda \mid H_1 \right) \]

  \[= 1 - \prod_{i=1}^{N} \left[ \left. 1 - Q_u \left( \sqrt{\frac{2p_i}{n_i^c}}, \sqrt{\lambda} \right) \right] \right) \] (2)

- $Y_i$ : decision variable of subcarrier $i$ at CU
- Hypothesis $H_1$ : presence of PU transmission

- Problem is transformed to become a convex optimization problem
Power Allocation

- Lagrangian

\[
L(\mu, \{p_i\}_1^N) = -\log(P_d) + \mu_0 \left[ \sum_{i=1}^{N} p_i - P_t \right] - \sum_{i=1}^{N} \mu_i p_i + \mu_{N+1} \left[ C - \sum_{i=1}^{N} \log \left(1 + \frac{p_i}{n_i}\right) \right].
\]  

(3)

- Apply Karush-Kuhn-Tucker (KKT) conditions

\[
\mu_0^* = \mu_i^* + \frac{\mu_{N+1}^*}{1 + p_i^*/n_i} + \frac{\partial \log(P_d)}{\partial p_i} \bigg|_{p_i=p_i^*}
\]

(4)

- Complementary slackness

\[
\mu_0^* \left[ \sum_{i=1}^{N} p_i^* - P_t \right] = 0.
\]

(5)

- \(\mu_0^* > 0, \sum_{i=1}^{N} p_i^* - P_t = 0 \Rightarrow P_t \) will be allocated for optimality
Numerical Results

- Solved in MATLAB
- Capacity constraint - set by reducing a certain percentage from the capacity ($C_{com}$)
- Two subcarrier system with $P_t = 10\, W$
- Instantaneous noise levels

<table>
<thead>
<tr>
<th>Scenario</th>
<th>PU-BS (W)</th>
<th>PU-CU (W)</th>
<th>Figure</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$n_1^b$</td>
<td>$n_2^b$</td>
<td>$n_1^c$</td>
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<tr>
<td>(1)</td>
<td>1</td>
<td>2</td>
<td>1</td>
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<td>(2)</td>
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</tr>
<tr>
<td>(3)</td>
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<td>2</td>
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</tbody>
</table>

- Three different scenarios - noise levels
  1. PU to BS & PU to CU are the same - Scenario (1)
  2. PU to CU better than PU to BS - Scenario (2)
  3. PU to BS better than PU to CU - Scenario (3)
Scenario 1 - PU, BS same

Figure: Capacity and $P_d$ over $C_{com}$ - Scenario (1)

- 5% of $C_{com}$ gains 0.15 in detection
- Rate of improvement in detection decreases as $C_{com}$ increases
- Most efficient trade off at lower values of $C_{com}$
Scenario 2 - PU, CU better

Figure: Capacity and $P_d$ over $C_{com}$ - Scenario (2)

- Reaches saturation at $C_{com} = 22\%$
- Detection cannot be improved arbitrarily by lowering the capacity
- Consequence of total power constraint
Scenario 3 - PU, BS better

Figure: Capacity and $P_d$ over $C_{com}$ - Scenario (3)

- $C_{com} = 5\%$ gains 0.05
- $C_{com} = 22\%$ gains 0.15 while in Scenario 1,2 over 0.25
- If CU experiences noisy channels, PU cannot facilitate CU with detection (Pick a CU with better channel conditions)
Proposed Implementation

- PU picks a CU with lowest channel noise levels
- Advantages
  - Single CU cooperation scheme - simplicity in resource allocation problem
  - Faster and efficient in implementation
  - PU capacity will not be severely affected
  - Multiple CUs exist around a PU ⇒ share the targeted CU’s decisions among CUs
  - Cognitive network select the best CU and provide the subcarrier noise levels to PU
  - Reduces the burden over the feedback channel
- PU can assist to improve 15% of the correct detection probability with a 5% reduction in spectral efficiency in low-moderate SNR with two subcarrier (simplest) system
- Higher the number of subcarriers, better the performance (see the paper for more results)
Band Detection

- Assume set of $N$ subcarriers are physically adjacent in frequency
- CU detects the whole band without the knowledge of subcarrier boundaries
- CU knows the two edges of whole band
- Avoids the requirement of bank of energy detectors at CU
- Objective function - $P_d \left( \{p_i\}_1^N, \lambda \right)$

\[
P_d = Q_u \left( \sqrt{\frac{2 \sum_{i=1}^{N} p_i}{\sum_{i=1}^{N} n_i^c}}, \sqrt{\lambda} \right).
\]  

- Formulation is transformed to be a convex optimization problem
- Total power $P_t$ will be allocated for optimality
Band Detection cont...

- Optimal detection $P_d^*$

\[
P_d^* = Q_u \left( \sqrt{\frac{2P_t}{\sum_{i=1}^{N} n_i^c}}, \sqrt{\lambda} \right).
\]  

\[ (7) \]

- CU cannot gain in terms of primary detection
- The optimum power allocation for maximizing capacity is the optimal solution for band detection
Conclusion

- Notions of cooperation among primary and cognitive users for detection
- Primary user assisted cooperative spectrum sensing scheme
- System model: OFDMA based air interface and suits for IEEE 802.22
- Resource allocation - as an optimization problem
- 15% detection improvement by a 5% reduction in capacity (The most basic case with two subcarriers)
- Avoids CU transmission over false detected spectrum holes
  - Avoid severe interfere to primary transmission
  - Improve the overall spectrum utilization
- Coexists with cognitive user collaborative schemes
- Combination of two types of cooperation
  1. Among CUs &
  2. CUs and PUs - detection in lower SNR regions is possible
Future Work

- Multiple user networks
- Channel fading conditions
  - Rayleigh, Rician, Nakagami-$m$
- Different detection mechanisms - simpler & less complex in implementation
- User mobility
- Imperfect estimates
Some References


