Binary is Good: A Binary Inference Framework for Primary User Separation in Cognitive Radio Network

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Outline

1. Introduction
2. Problem Statement
3. Binary Inference Algorithm
4. Simulation and Experiments
5. Conclusion and Future Work
1. Cognitive Radio Systems

- TV Station
- TV Transmission
- Primary User
- Secondary Users
- Agile Radio Transmission

Diagram showing time-frequency representation of TV and secondary users.
1. Spectrum Sensing

• Key challenge in CR systems
• Determine presence and characteristics of PUs
• Can be done at SUs individually / cooperatively
• Motivation scenarios:
  – Some PUs are visible to only a subset of SUs in a SU cooperative environment
  – Redundancy in dedicated monitors’ observations

→ PU Separation Problem
1. PU Separation Problem

• Address the following questions:
  — What is the identity of PUs activate within a SU’s vicinity?
  — What is the distribution of PUs in the field?
  — What is the characteristic of each identified PU?

• SUUs cooperatively detect PUs using only binary information (thresholding energy detection)

• Can be effectively solved by Binary Independent Component Analysis (bICA)
2. Problem Formulation

• $n$ independent PUs: $\mathbf{y} = [y_1, y_2, \ldots, y_n]$

• $m$ binary monitor nodes (SUs): $\mathbf{x} = [x_1, x_2, \ldots, x_m]$

• Binary mixing matrix:
  \[ \mathbf{G} = g_{ij} \in \{0, 1\}, \, i = [1, \ldots, m], \, j = [1, \ldots, n] \]

• Relationship between PUs and SUs
  \[ x_i = \bigvee_{j=1}^{n} (g_{ij} \land y_j), \quad i = 1, \ldots, m, \]

\[ \begin{align*}
\begin{array}{c}
1 \quad 2 \quad 3 \quad 4 \\
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2. A Toy Example

\[ x = G \otimes y \]

\[
\begin{bmatrix}
1 & 0 & 1 & 1 & 0 & \ldots \\
1 & 0 & 0 & 0 & 0 & \ldots \\
1 & 0 & 1 & 1 & 1 & \ldots \\
0 & 0 & 0 & 1 & 1 & \ldots \\
\end{bmatrix}
\begin{bmatrix}
1 & 1 & 0 \\
1 & 0 & 0 \\
0 & 1 & 1 \\
0 & 0 & 1 \\
\end{bmatrix}
\otimes
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & \ldots \\
1 & 0 & 1 & 1 & 0 & \ldots \\
0 & 0 & 0 & 1 & 1 & \ldots \\
\end{bmatrix}
\]

\[ x \quad (\text{unknown}) \quad y \quad (\text{unknown}) \]
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3. Binary Independent Component Analysis

- Goal: Infer the mixing matrix $G$ and active probability vector $p$ from observation matrix $X$
- Use ICA/PCA then apply a quantization method to convert to binary simply won’t work
- Initialize: $G = m \times 2^m - 1$ matrix
  $p = 1 \times 2^m - 1$ vector
- $2^m - 1$: all possible PU connections (no PU have a same set of connections to SUs)
3. The Inference Algorithm

- **Input:** Observation matrix $X$
- **Output:** Mixing matrix $G$, active prob. $p$

```latex
\begin{align*}
\text{FindBICA()} \\
\text{if } m = 1 \text{ then} \\
& p_0 = \mathcal{F}(x_1 = 0) \\
& p_1 = \mathcal{F}(x_1 = 1) \\
\text{else} \\
& p_{1:2^{m-1}-1}^0 = \text{FindBICA}(X^0_{(m-1) \times T}) \\
& p_{1:2^{m-1}-1}^* = \text{FindBICA}(X_{(m-1) \times T}) \\
& \text{for } l = 1, \ldots, 2^{m-1} - 1 \text{ do} \\
& \quad p_{l+2^{m-1}} = 1 - \frac{1 - p_l^*}{1 - p_l^0}
\end{align*}
```

* more details in the paper
4. Simulation Setup

- 10 monitors (SUs) are deployed on an 1000x1000 square meter area
- 5 to 20 PUs are placed randomly on the area (random topology) – no PU observes a same set of monitors
- PUs’ activities are modeled as 2-stage MC with transition probability in [0, 1]
- Number of monitor observations \( T = 5000 \)
- Simulation platform: Matlab 2009b, Windows 7 running on Intel Core 2 Duo T5750@2.00GHz and 2GB RAM
4. Simulation Setup

- Noise: randomly flip an entry of $X$ with probability $p_e$

- **Structure Matching Problem:**
  - **Motivation:** how to evaluate accuracy of bICA when:
    - Inferred result $G$ may contain up to $2^m - 1$ components, and they could be in any order
    - Some inferred components may be slightly different compared to the ground truth (1-2 bits different)
  - **Solution:**
    - Select the top $n$ components (with highest active prob.) in $G$
    - Permute these $n$ columns in $G$ to find a best match with the ground truth (using Hungarian algorithm)
4. bICA Framework

Observation matrix $X$

bICA → Structure Matching → Evaluation process

PU
Monitor
Monitor range

Original $G$

Reconstruction of $G$

Difference Matrix

DIFF
4. Performance Metrics

Measure accuracy and speed of the proposed method

1. Normalized Hamming Distance

\[ \bar{H}(G, \tilde{G}) \triangleq \frac{1}{mn} \sum_{i=1}^{n} d^H(g_{:,i}, \tilde{g}_{:,i}) \]

2. Root Mean Square Error Ratio

\[ \bar{P} \triangleq \sqrt{\frac{\sum_{i=1}^{n} (\bar{p}'_i - p_i)^2}{\sum_{i=1}^{n} p_i}} / \sum_{i=1}^{n} p_i \]

3. Computation Time
4. Evaluation Results
5. Conclusion and Future Work

• Derive and address PU separation problem in CR systems with binary data
• **Propose bICA** — a binary inference framework
• Simulation results show that bICA can effectively solve PU separation problem

• Future Work
  — Real environment experiments
  — The inverse problem
  — Reducing noise effect