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

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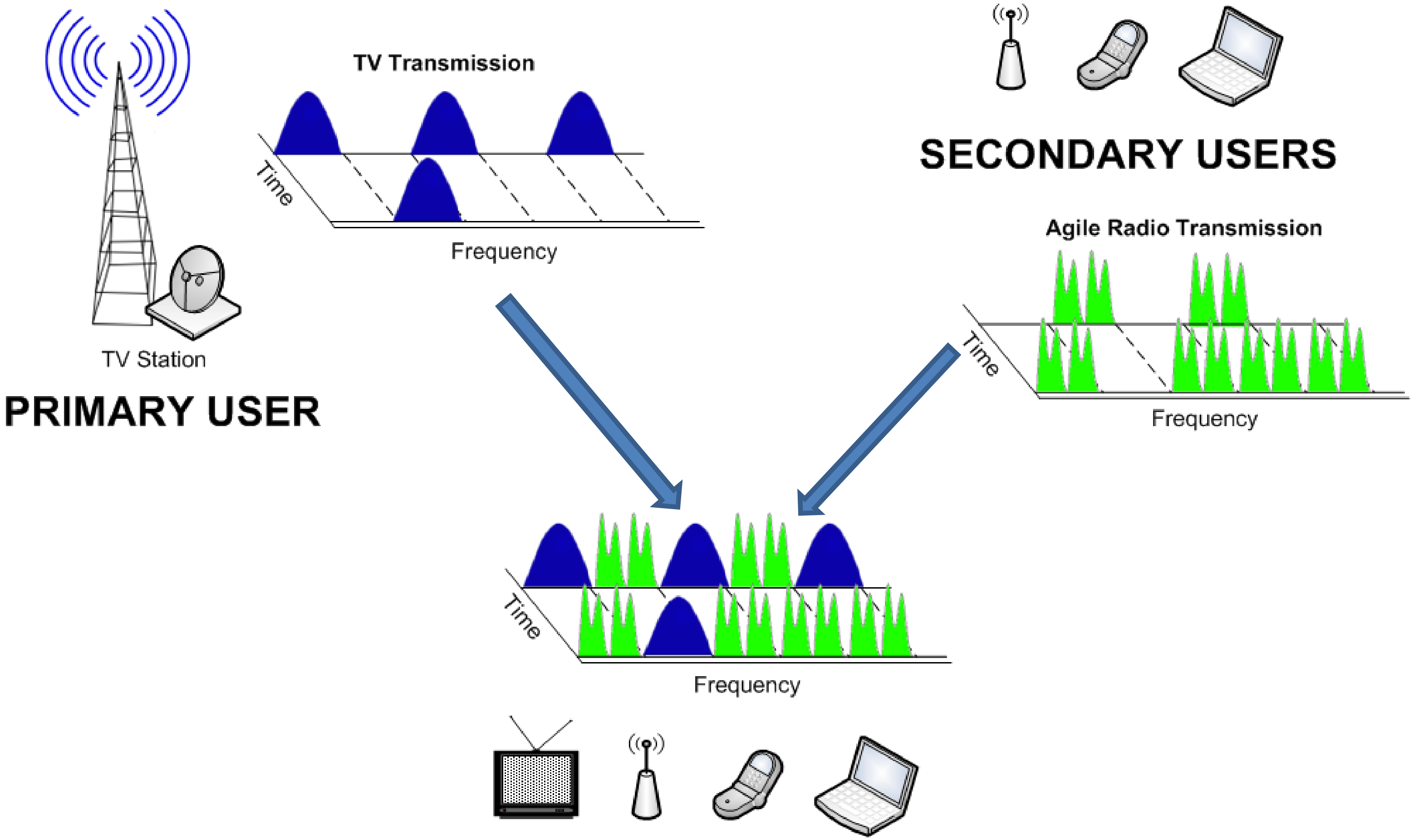
Outline

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

1. Cognitive Radio Systems



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?
- SUs cooperatively detect PUs using only binary information (thresholding energy detection)
- Can be effectively solved by Binary Independent Component Analysis (bICA)

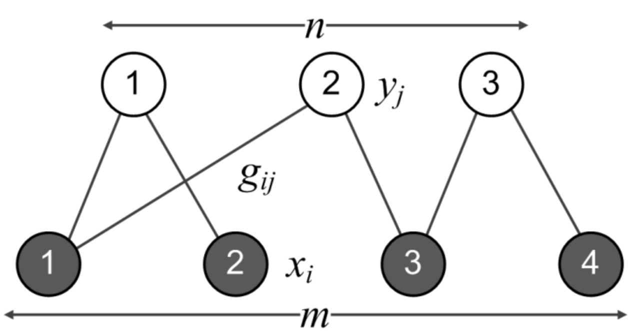
2. Problem Formulation

- *n* independent PUs: $\mathbf{y} = [y_1, y_2, \dots, y_n]$
- *m* binary monitor nodes (SUs): $\mathbf{x} = [x_1, x_2, \dots, x_m]$
- Binary mixing matrix:

$$\boldsymbol{G} = g_{ij} \in \{0, 1\}, i = [1, \dots, m], j = [1, \dots, n]$$

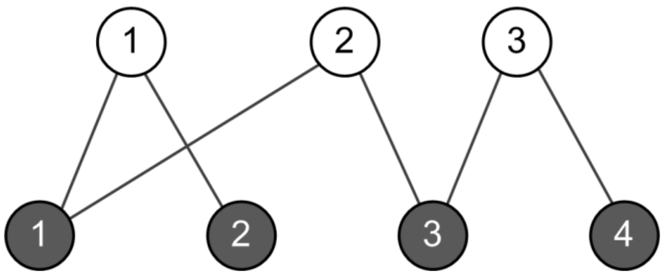
- Relationship between PUs and SUs

$$x_i = \bigvee_{j=1}^{n} (g_{ij} \wedge y_j), \ \ i = 1, \dots, m,$$



$$\boldsymbol{G} = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix}$$

2. A Toy Example



$$\mathbf{x} = \boldsymbol{G} \otimes \mathbf{y}$$

$$\begin{bmatrix} 1 & 0 & 1 & 1 & 0 & \ldots \\ 1 & 0 & 0 & 0 & 0 & \ldots \\ 1 & 0 & 1 & 1 & 1 & \ldots \\ 0 & 0 & 0 & 1 & 1 & \ldots \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \otimes \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & \ldots \\ 1 & 0 & 1 & 1 & 0 & \ldots \\ 0 & 0 & 0 & 1 & 1 & \ldots \end{bmatrix}$$

$\mathbf{x}$ $\boldsymbol{G}$ (unknown) $\mathbf{y}$ (unknown)

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3. Binary Independent Component Analysis

- Goal: Infer the mixing matrix $\boldsymbol{G}$ and active probability vector $\boldsymbol{p}$ from observation matrix X
- Use ICA/PCA then apply a quantization method to convert to binary simply won't work
- Initialize: $\boldsymbol{G} = m \times 2^m - 1$ matrix

  $\boldsymbol{p} = 1 \times 2^m - 1$ 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***

```
FindBICA ()
if m = 1 then
    p_0 = F(x_1 = 0)
    p_1 = F(x_1 = 1)
else
    p^0_{1:2^{m-1}-1} = FindBICA (X^0_{(m-1)×T})
    p^*_{1:2^{m-1}-1} = FindBICA (X_{(m-1)×T})
    for l = 1, ... 2^{m-1} - 1 do
        p_{l+2^{m-1}} = 1 - (1-p^*_l)/(1-p^0_l)
```

$$\begin{array}{l}
\texttt{FindBICA}\ () \\
\textbf{if } m = 1 \textbf{ then} \\
\quad p_0 = \mathcal{F}(x_1 = 0) \\
\quad p_1 = \mathcal{F}(x_1 = 1) \\
\textbf{else} \\
\quad p^0_{1:2^{m-1}-1} = \texttt{FindBICA}\ (X^0_{(m-1)\times T}) \\
\quad p^*_{1:2^{m-1}-1} = \texttt{FindBICA}\ (X_{(m-1)\times T}) \\
\quad \textbf{for } l = 1, \ldots 2^{m-1} - 1 \textbf{ do} \\
\quad\quad p_{l+2^{m-1}} = 1 - \frac{1-p^*_l}{1-p^0_l}
\end{array}$$

* *more details in the paper*

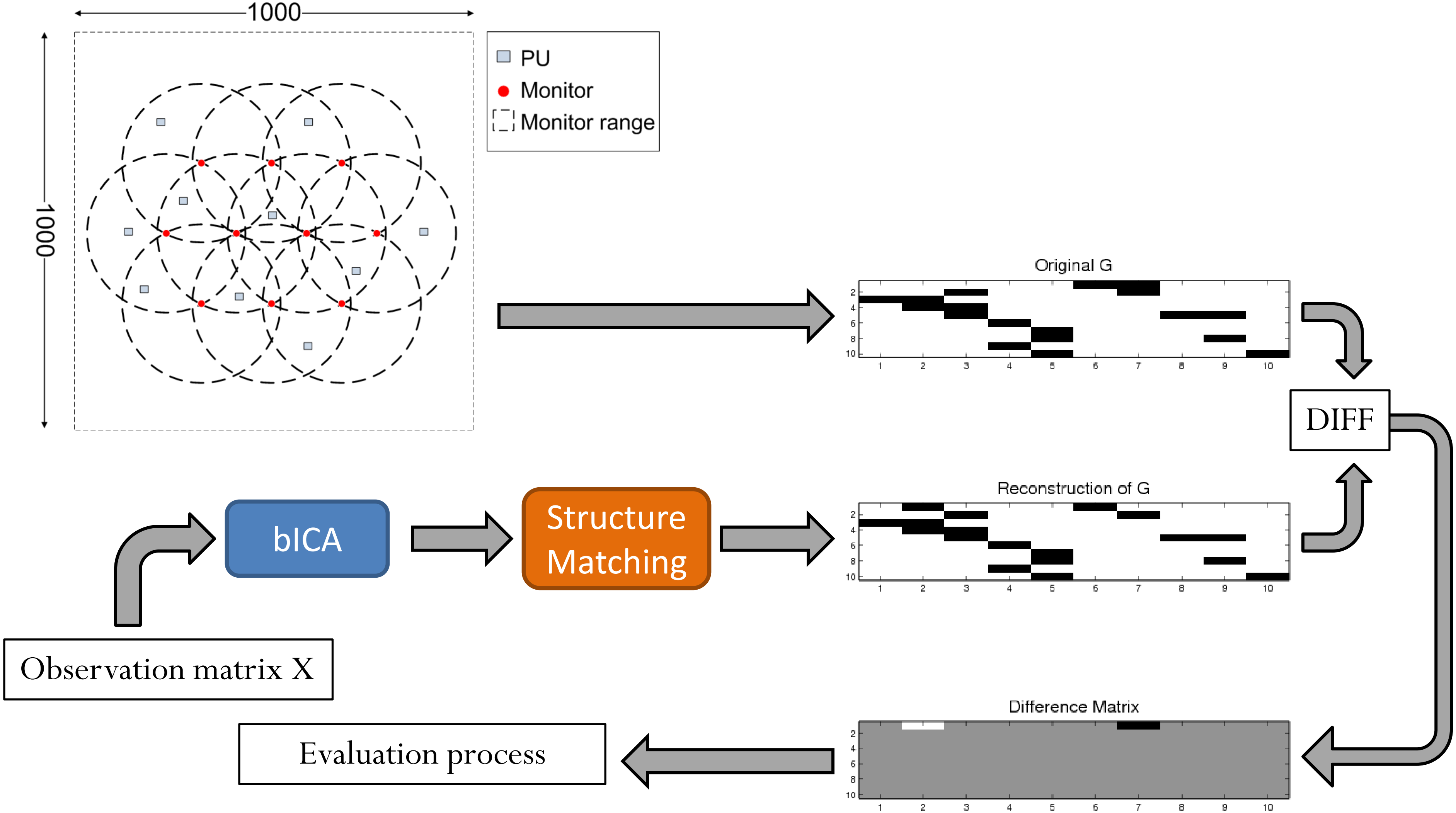
4. Simulation Setup

- 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



4. Performance Metrics

Measure accuracy and speed of the proposed method

1. Normalized Hamming Distance

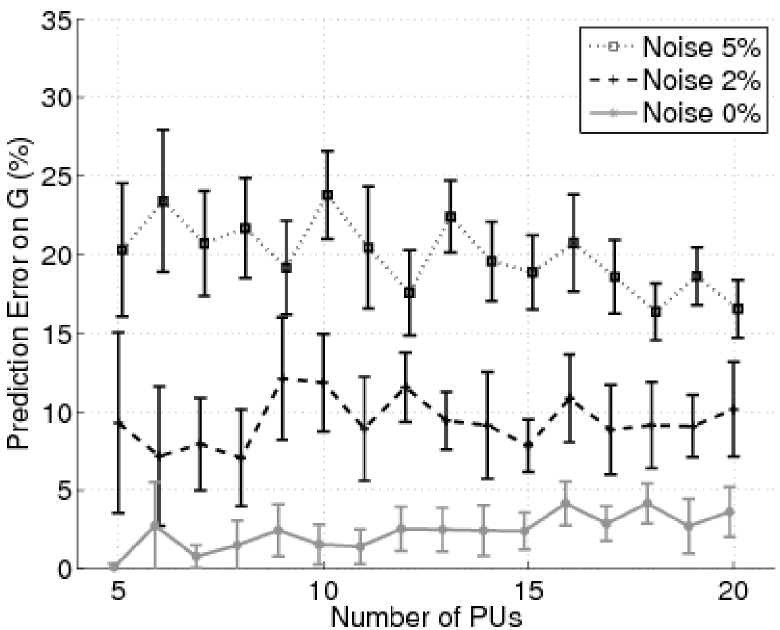
$$\bar{H}(\boldsymbol{G}, \widehat{\boldsymbol{G}}) \triangleq \frac{1}{mn} \sum_{i=1}^{n} d^{H}(g_{:,i}, \widehat{g}_{:,i})$$

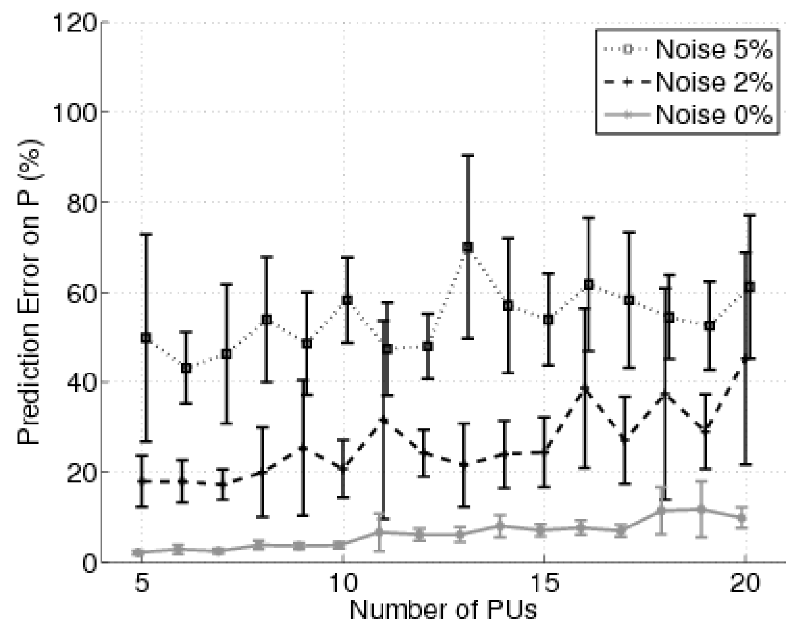
2. Root Mean Square Error Ratio

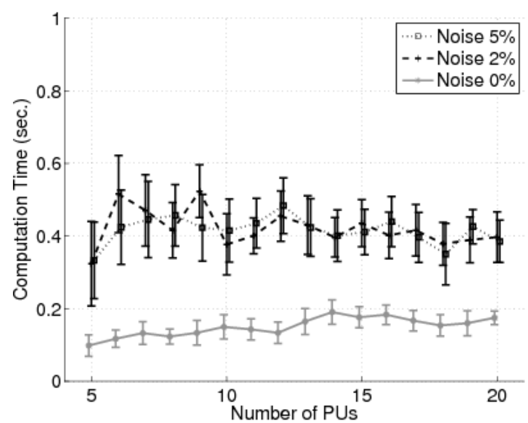
$$\bar{P} \triangleq \sqrt{\frac{\sum_{i=1}^{n} (\widehat{p}_i' - p_i)^2}{n}} \Big/ \frac{\sum_{i=1}^{n} p_i}{n}$$

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