Wireless networks for spectrum sensing and source localization

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Radio sources in the 2.4GHz ISM band

Sources transmit signals that may overlap in time and frequency

Introduction

- Source activity is an on/off signal in time
- A network of sensors measures average received power in a frequency band with some time granularity (e.g. $T=20\mu s$)
- Sensor measurements are collected and processed using a centralized scheme

Radio sources and sensors

number of sensors $\geq$ number of sources

Objectives

Using the collected measurements we want to:

1. Determine the number of radio sources
2. Recover the source signal activities
3. Localize each detected source

Possible applications

- Monitoring of spectrum usage in a frequency band
- Detection and localization of interfering radio sources (cooperative spectrum sensing)

System model

- Source activity from different networks is modeled as statistically independent
- Sources from the same network transmit non overlapping signals in time
- Received signals are corrupted by additive noise only

Average received power

Approximate power at sensor j over interval [(k-1)T,kT]

$$p_{Rj}(k) = \sum_{i=1}^{M} g_{ji} p_i(k) + \sigma_j^2 \quad j = 1,\dots,N \quad k = 1,\dots,K$$

channel gain coefficient — g_{ji}

average power of the i-th source — $p_i(k)$

noise variance — σ_j^2

number of sensors — N

number of measurements — K

Blind signal separation model

We define zero-mean signals

$$p'_{Rj}(k) = p_{Rj}(k) - \frac{1}{K}\sum_{m=1}^{K} p_{Rj}(m) \qquad p'_i(k) = p_i(k) - \frac{1}{K}\sum_{m=1}^{K} p_i(m)$$

This leads to the blind signal separation model

$$\boldsymbol{p}'_R(k) = \boldsymbol{G}\boldsymbol{p}'(k) \quad k = 1,\ldots,K$$

$$\boldsymbol{p}'_R(k) = \left[p'_{R1}(k) \quad \cdots \quad p'_{RN}(k)\right]^T \qquad \boldsymbol{p}'(k) = \left[p'_1(k) \quad \cdots \quad p'_M(k)\right]^T$$

$$[\boldsymbol{G}]_{ij} = g_{ij}$$

Blind signal separation problem

Goal: recover gain matrix $\boldsymbol{G}$ and activity signals $\boldsymbol{p}'(k)$
from received power vectors $\boldsymbol{p}'_R(k)$

This can be solved if:

1. The number of sensors is at least equal to the number of sources

2. Gain matrix has full column rank

3. Source signals have special properties (different spectra, statistical independence, constant modulus, finite alphabet…)

Finite alphabet property

- If sources operate with constant power when they are on, then each source is characterized by an on/off signal

$$p_i(k) \in \{0,1\}$$

- Gain matrix and source signals are recovered by using this finite alphabet property

Existing finite alphabet algorithms

- Existing methods assume statistically independent signals
- Groups of non overlapping (statistically dependent) signals in time
  - Hence, existing methods are not directly applicable

Solution: prefiltering step

Number of sources is found as the rank of

$$P_R = \begin{bmatrix} p'_R(1) & \cdots & p'_R(K) \end{bmatrix} = U \Sigma V^T$$

Dimension reduction prefiltering

$$\tilde{p}_R(k) = \Sigma^{-1} U^T p'_R(k) = \Sigma^{-1} U^T G p'(k) = T p'(k)$$

$$T = \Sigma^{-1} U^T G$$

Restoring the finite alphabet property

- Source signals are recovered by finding the matrix W

$$\hat{p}'(k) = W^T \tilde{p}_R(k)$$

$$W^T = T^{-1}$$

- Enforcing the finite alphabet property (on/off) of the recovered signals
  - Leads to a generalized eigenvector problem for a unique W

Restoring the finite alphabet property: (generalized eigenvector problem)

Computation of the matrix W:

- For statistically independent source activity:
  - joint diagonalization of a set of matrices obtained from $\tilde{p}_R(k)$
- For groups of sources with non overlapping signals in time:
  - joint block diagonalization of a set of matrices obtained from $\tilde{p}_R(k)$

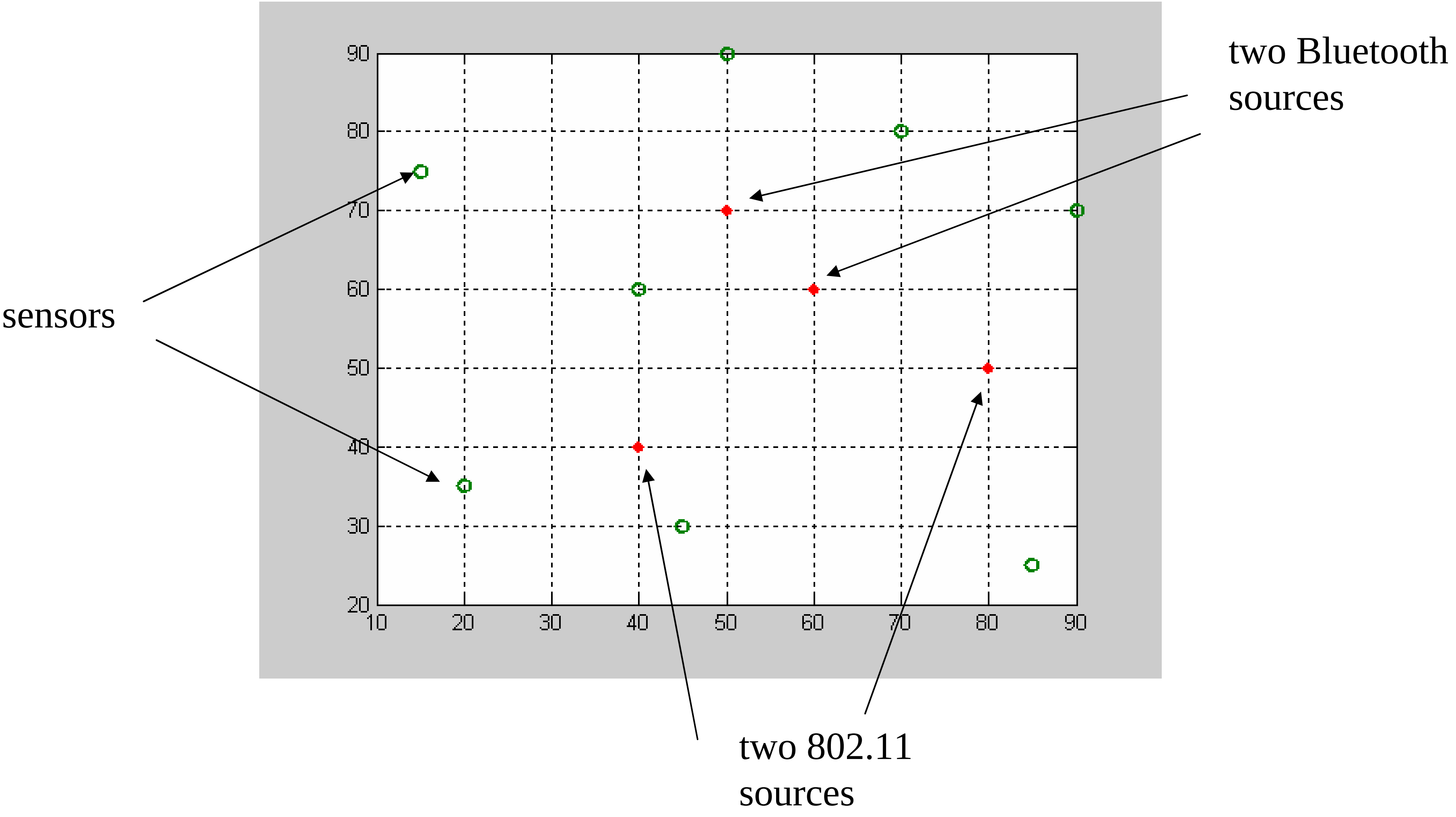
Solution

- Recovered signals are partitioned into groups

- Each group consists of source signals belonging to the same network (non overlapping signals in time)

- Recovered signals from different groups are statistically independent

Simulation example

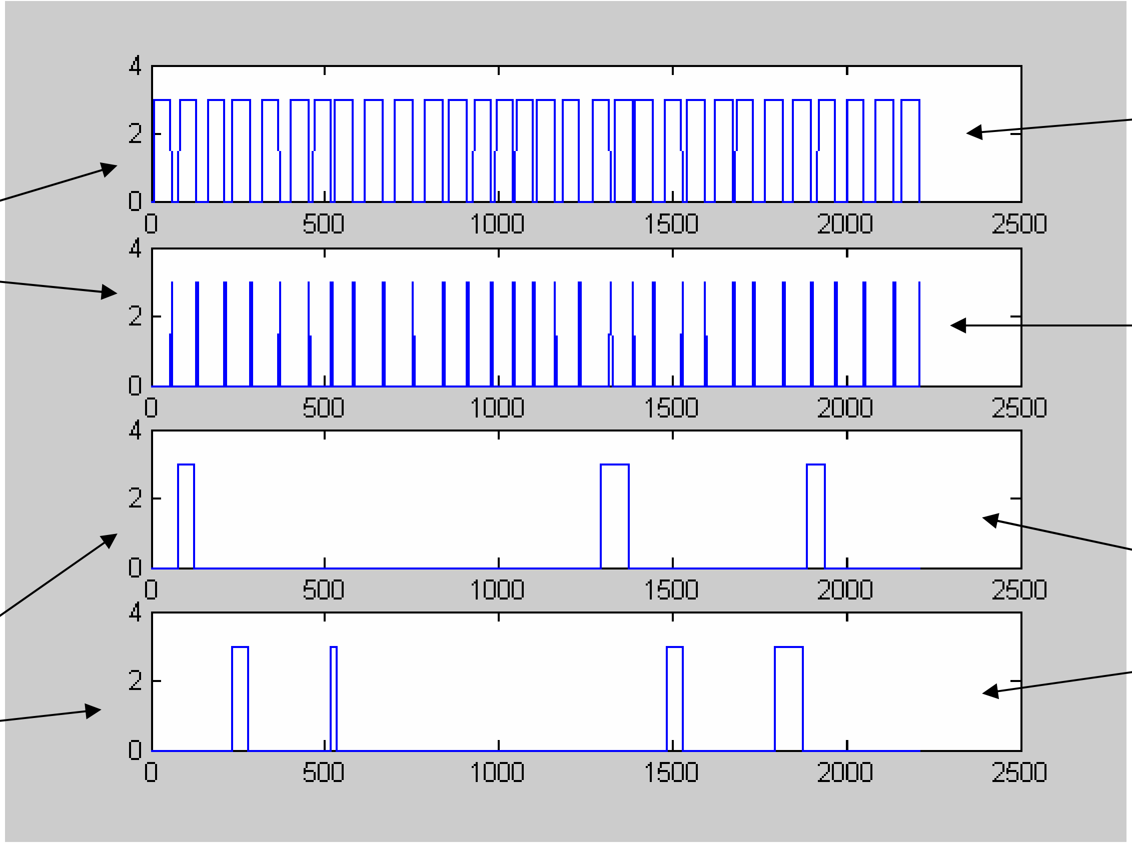


Original source signals

two 802.11 sources

sending packets

sending ACKs

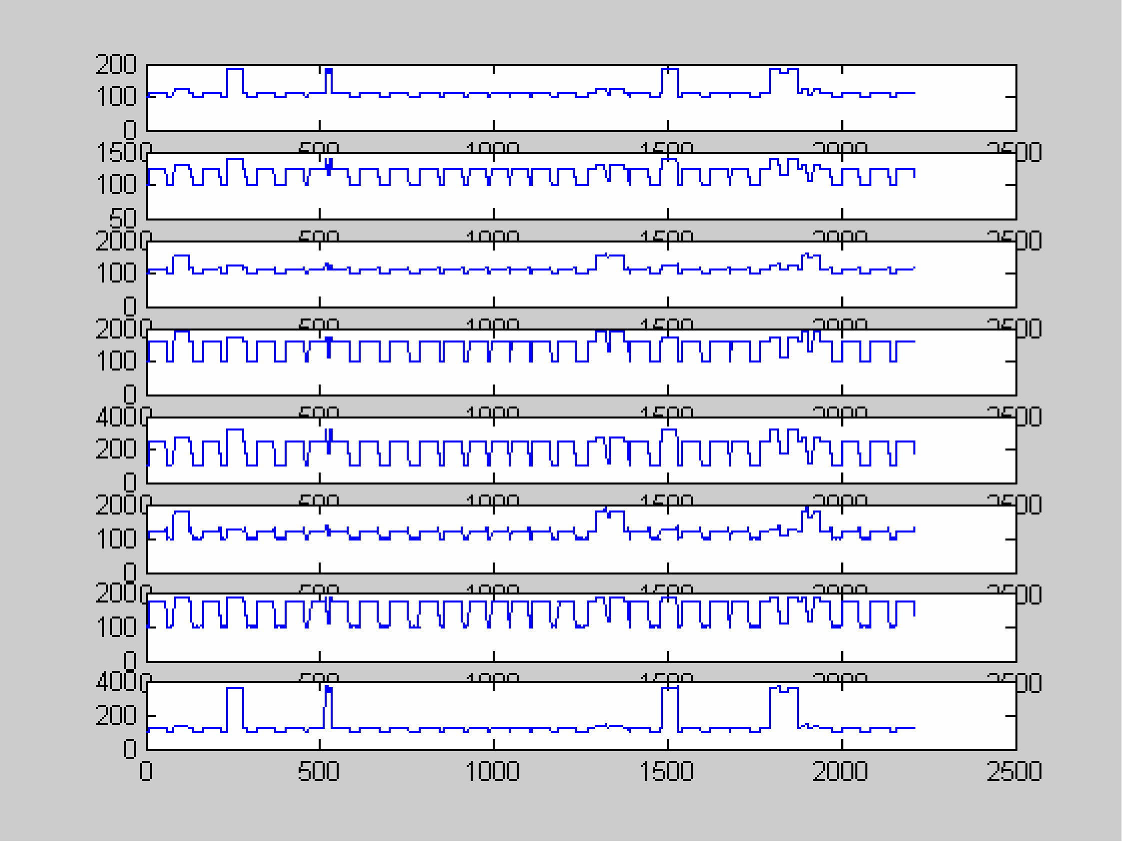


two Bluetooth sources

one WLAN channel
is used 25%
of the time

Source signal activities in one 20MHz wide WLAN channel

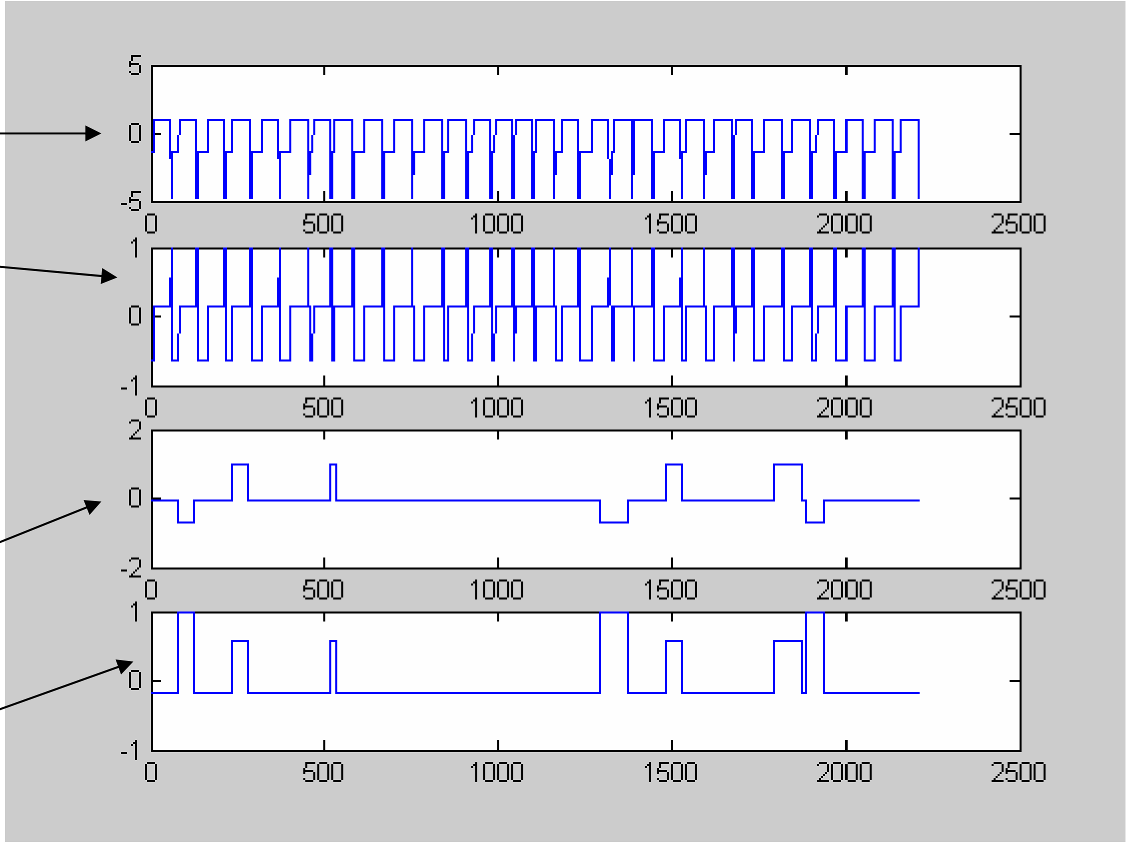
Signals measured by sensors



Average power is measured with time granularity T=20μs

Signals recovered after joint block diagonalization

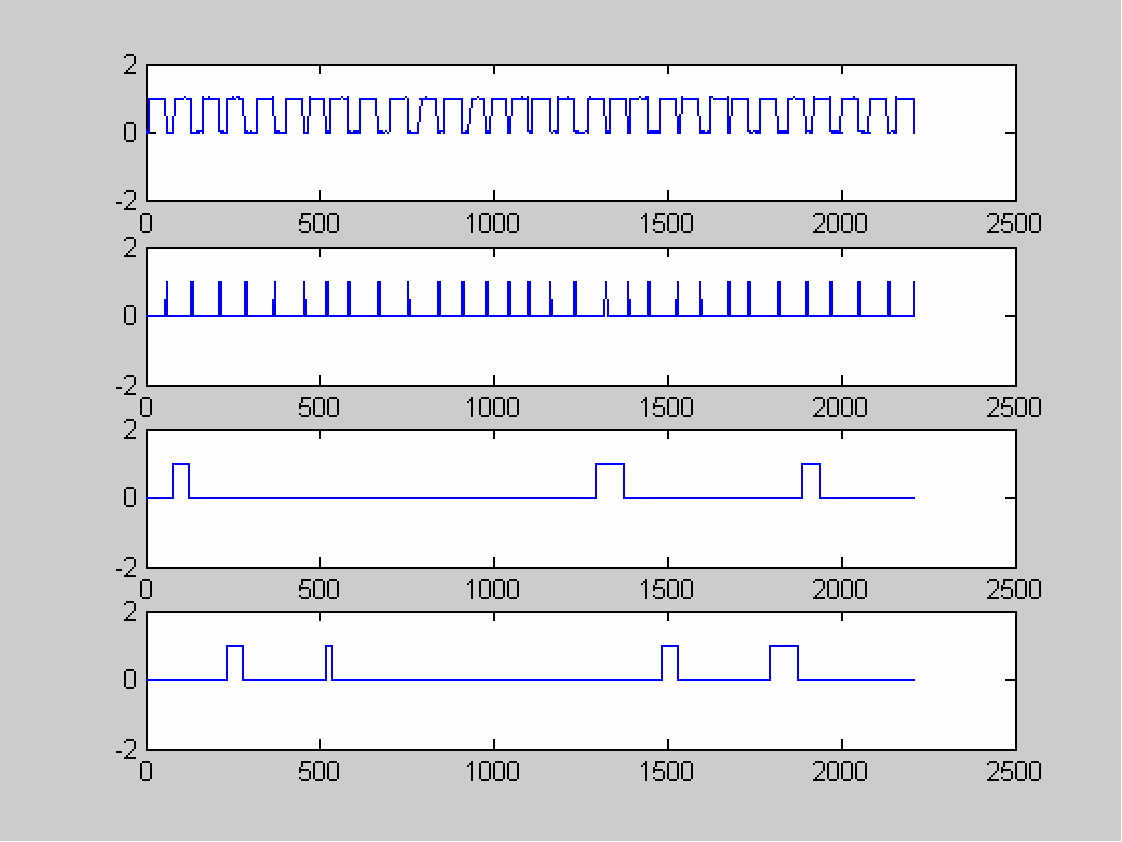
linear combinations of 802.11 signals

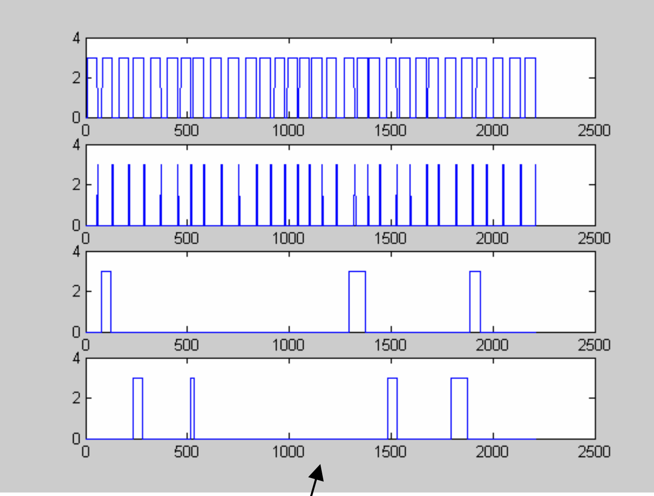


linear combinations of Bluetooth signals

Recovered signals are partitioned into two independent groups

Final recovered signals





Original source signals

Source localization

Gain matrix entries for path loss coefficient 2

$$[\boldsymbol{G}]_{ij} = g_{ij} = \frac{c}{(x_{r,i} - x_j)^2 + (y_{r,i} - y_j)^2}$$

Location
of the i-th sensor

Location of the j-th source

Source localization

For known sensor locations the j-th source can be localized by solving

Estimated gain matrix coefficients

$$\frac{\hat{g}_{ij}}{\hat{g}_{i+1,j}} = \frac{(x_{r,i+1} - x_j)^2 + (y_{r,i+1} - y_j)^2}{(x_{r,i} - x_j)^2 + (y_{r,i} - y_j)^2}$$

$$i = 1, \ldots, N-1$$

Conclusion

- Source signals can be recovered by
  - exploiting their finite alphabet property and
  - spatial diversity provided by the network of sensors

- If the path loss coefficient and sensor locations are known detected sources can be localized