Source Extraction in Bandwidth Constrained Wireless Sensor Networks

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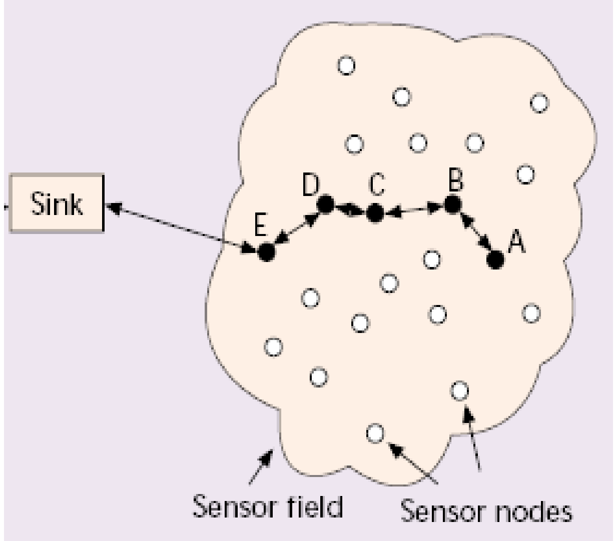
1 Sensor Networks

- A large number of small sensors, connected by wireless links, are densely deployed in a sensing field
- These sensors are energy-limited and has limited communication and computation capabilities
- Sensor observations would be corrupted by noise and distorted by wireless channels when transmitted

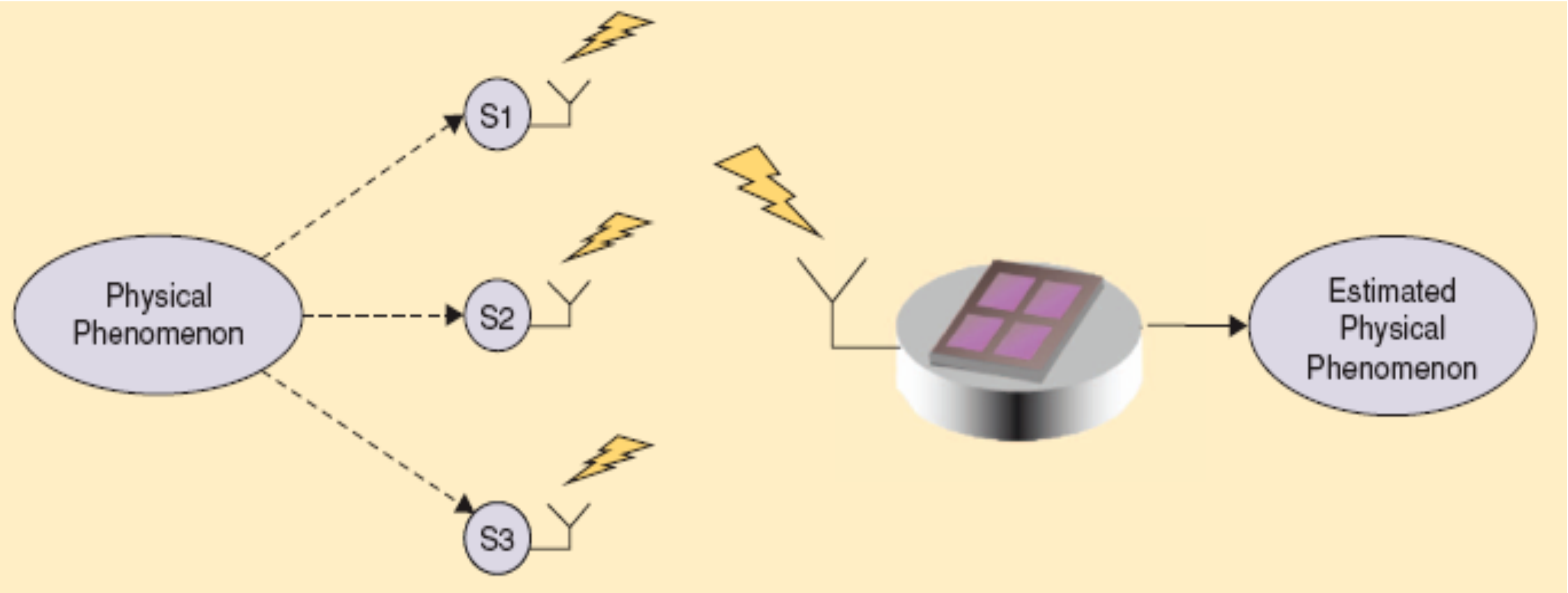


2 Distributed Estimation

- Detection, estimation, target tracking, etc
- Estimation
- **parameter estimation**
- **deterministic signal estimation**
- **random signal estimation**
- **blind source separation (extraction)**

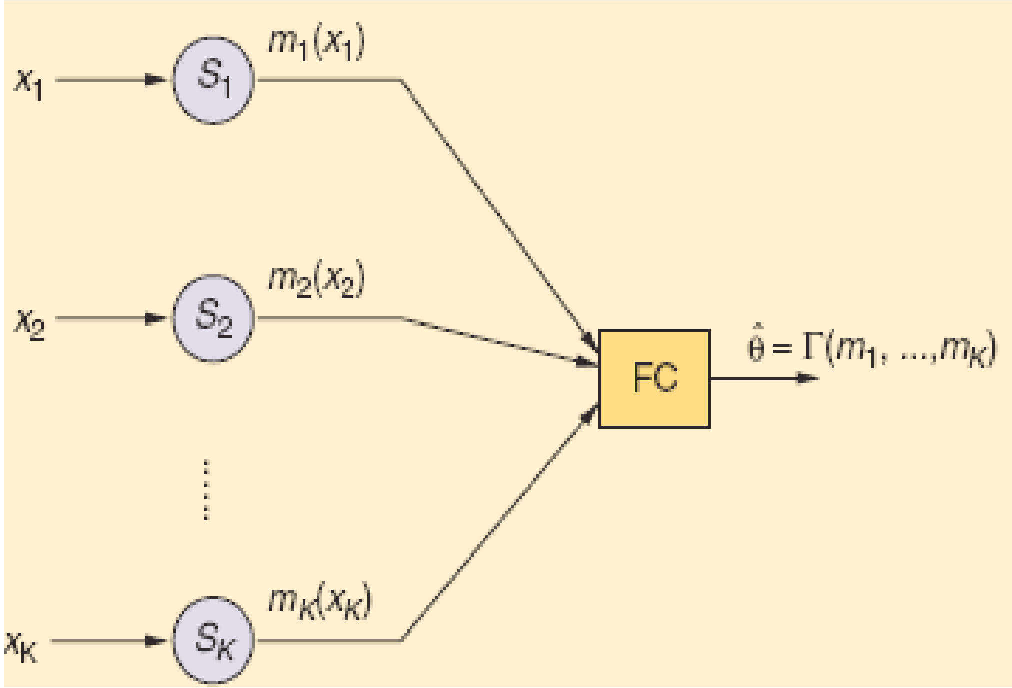
2 Distributed Estimation

- Sensor network with a fusion center



2 Distributed Estimation

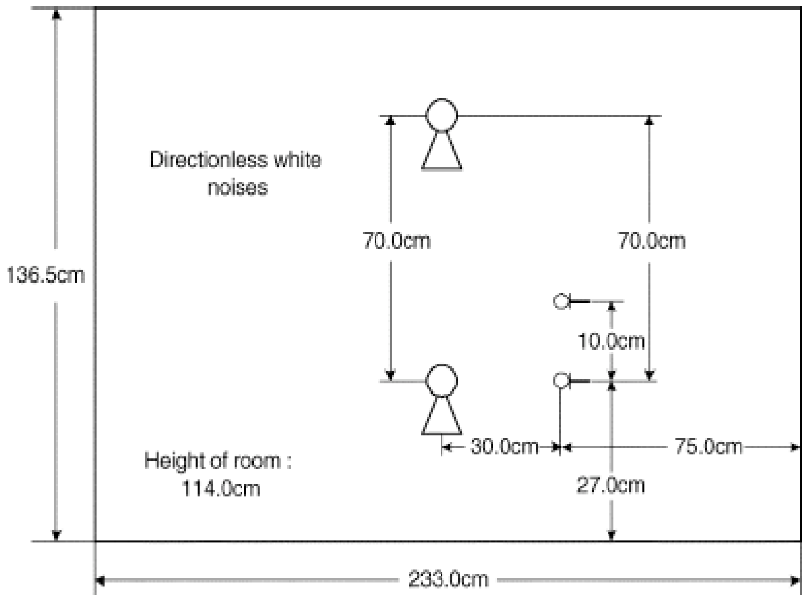
- Parameter estimation

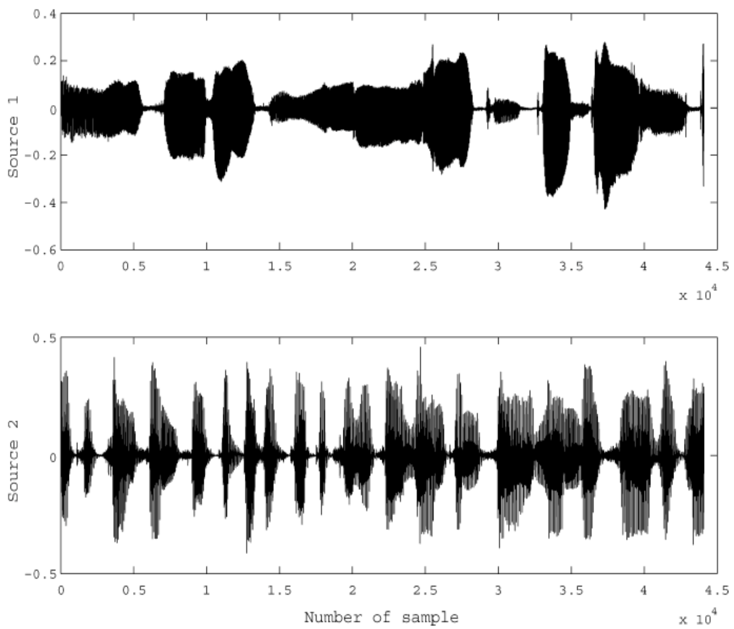


$$x_k = \theta + n_k, \qquad k = 1, 2, \ldots, K.$$

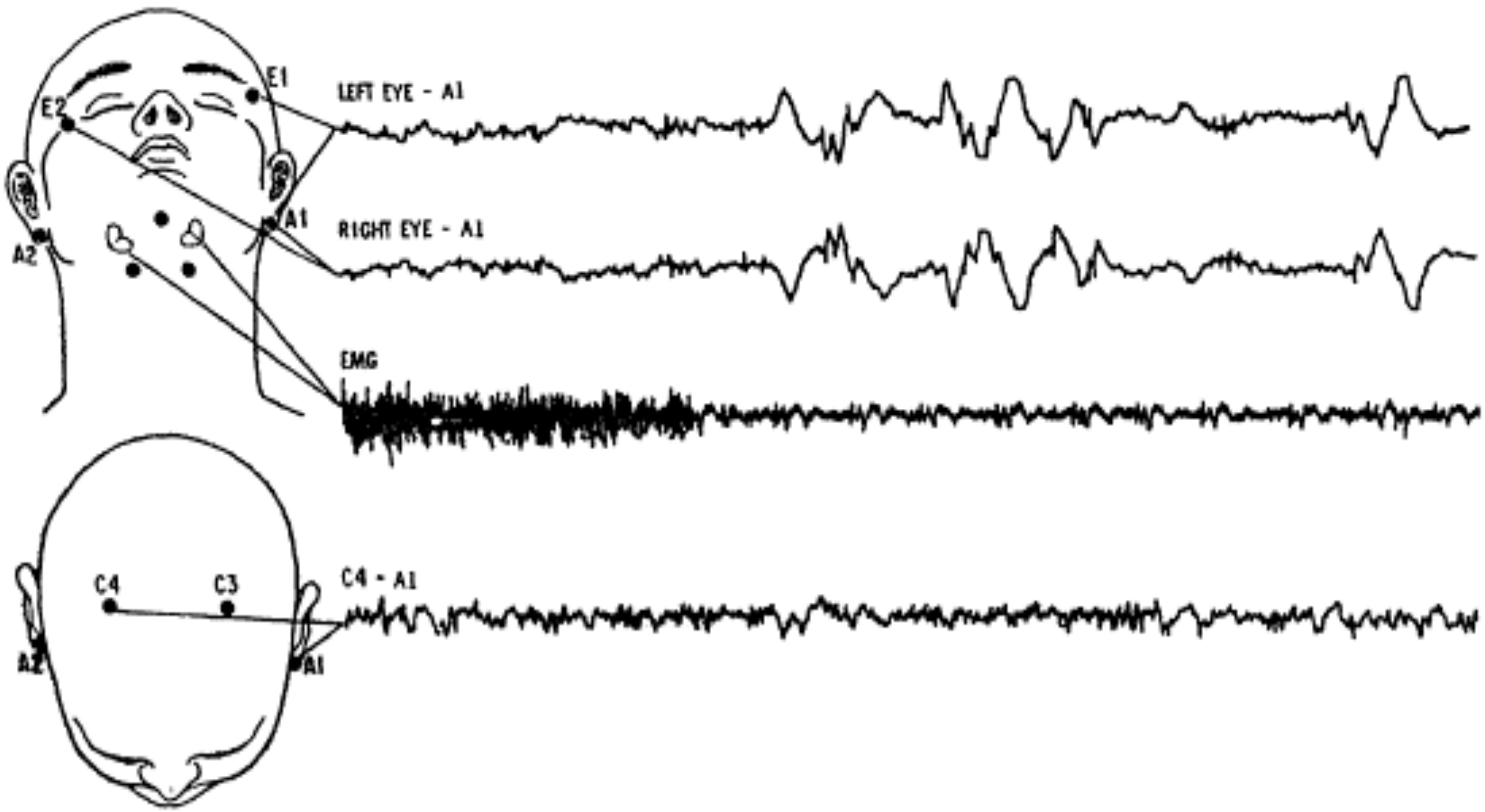
3 Blind Source Separation

- Applications
- **speech recognition, image restoration, biomedical engineering, and so on**





3 Blind Source Separation



3 Blind Source Separation

- Done by sensor arrays
- The simplest mixing model
- **instantaneous linear mixing**

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \boldsymbol{\nu}(t)$$

- More complicated mixing models
- **convolutive mixing and nonlinear mixing**

$$\boldsymbol{x}(t) = \sum_{\tau=0}^{q} \boldsymbol{H}(\tau)\boldsymbol{s}(t-\tau), \quad t = 0, \ldots, N-1$$

$$\mathbf{x}(t) = \boldsymbol{F}(\mathbf{s}(t))$$

3 Blind Source Separation

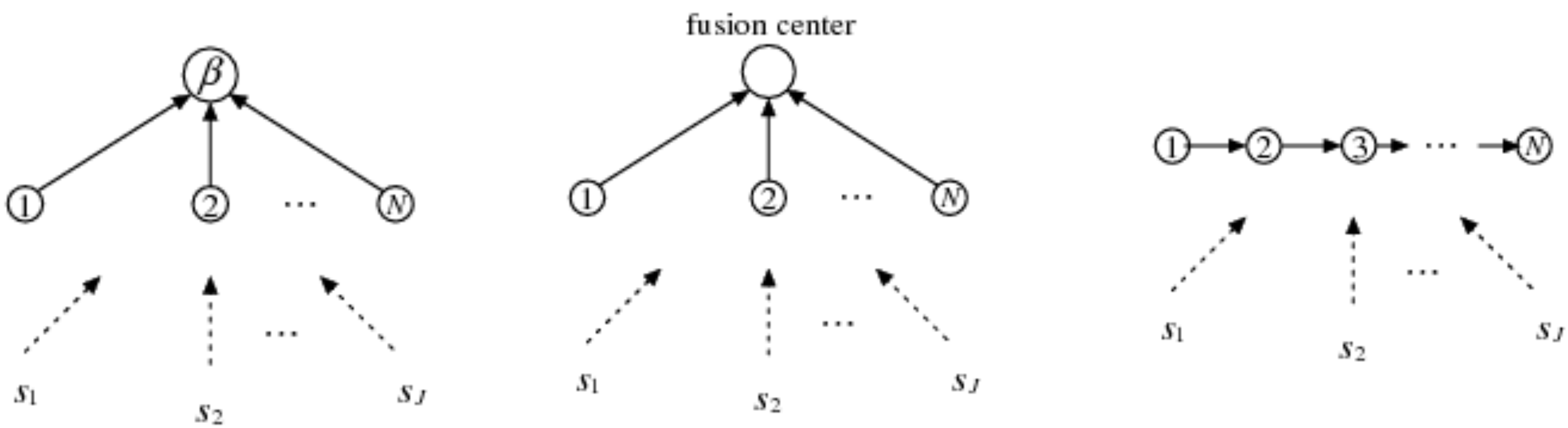
- Separation
- **simultaneous separation of all sources** $\mathbf{y}(t) = \mathbf{W}\mathbf{x}(t)$
- to determine the separation matrix $\mathbf{W}$
- Extraction
- **sequential extraction one by one**
- to determine the extraction vector w
- Contrast functions
- **principles: statistical, information-theoretic, geometric, etc**
- to recover the sources using only the observations

3 Blind Source Separation

- Intrinsic ambiguities
- **amplitude, order of sources**
- Assumptions
- **source, mixing matrix**
- the sources are mutually independent, zero mean, have unit variance and at most one of them is Gaussian
- the mixing matrix has full column rank
- the sources are stationary or nonstationary

4 Source Extraction in Wireless Sensor Networks

- Cluster-based sensor network, sensor network with a fusion center, sensor network for distributed extraction



4 Source Extraction in Wireless Sensor Networks

- Instantaneous linear mixing, possibly corrupted by noise
- **sensor observation model**

$$y_n(t) = \sum_{j=1}^{J} a_{nj}\, s_j(t) + w_n(t), \quad n = 1, \cdots, N$$

- J **is known *a priori* and** $N > J$
- **The communications are assumed to be error-free. The focus is on**
- the quantization effect of sensor observations

4 Source Extraction in Wireless Sensor Networks

- Basic idea
- **reconstruct the original mixtures at the cluster head or the sink**
- quantization of sensor observations
- **Suppose the sensor observations are bound to** $[-W, W]$
- **the quantization bit budget** M_i

$$\tilde{y}_i = (W + y_i)/2W.$$

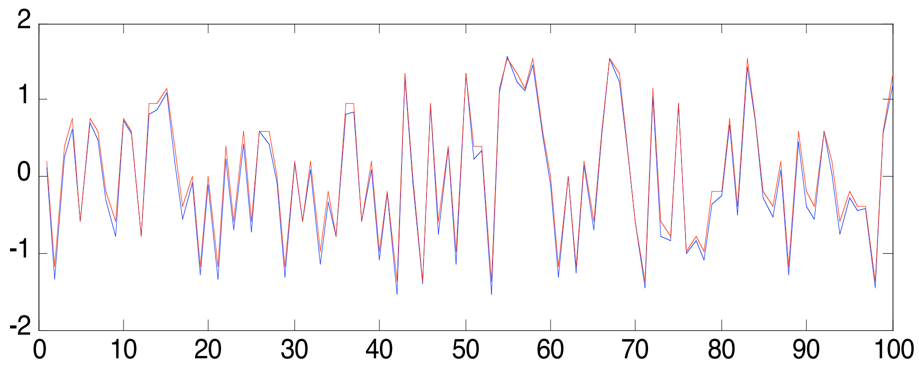
$$\begin{aligned}(\tilde{y}_i - q_i)|_t &= \sum_{k=1}^{M_i} b_k 2^{-k},\ b_k = 0, 1\\ F_i(\tilde{y}_i, M_i) &= b_1 \cdots b_{M_i},\end{aligned}$$

$$z_{i,k} = F_i(\tilde{y}_i, M_i)_k,\ k = 1, \cdots, M_i$$

$$\tilde{z}_i = 2W \sum_{k=1}^{M_i} z_{i,k} 2^{-k} - W.$$

4 Source Extraction in Wireless Sensor Networks

- Example: cluster-based sensor network
- **reconstruction of mixtures observed by the cluster members**



4 Source Extraction in Wireless Sensor Networks

- Information retrieval task
- **to extract one source each round at the sink**
- Source extraction algorithm
- **fast fixed-point algorithm with pre-whitening**
- **let** $Z = [y_\beta, \tilde{z}_1, \cdots, \tilde{z}_N]^T$
- **new mixing model**

$$Z = \mathrm{A}S + U$$

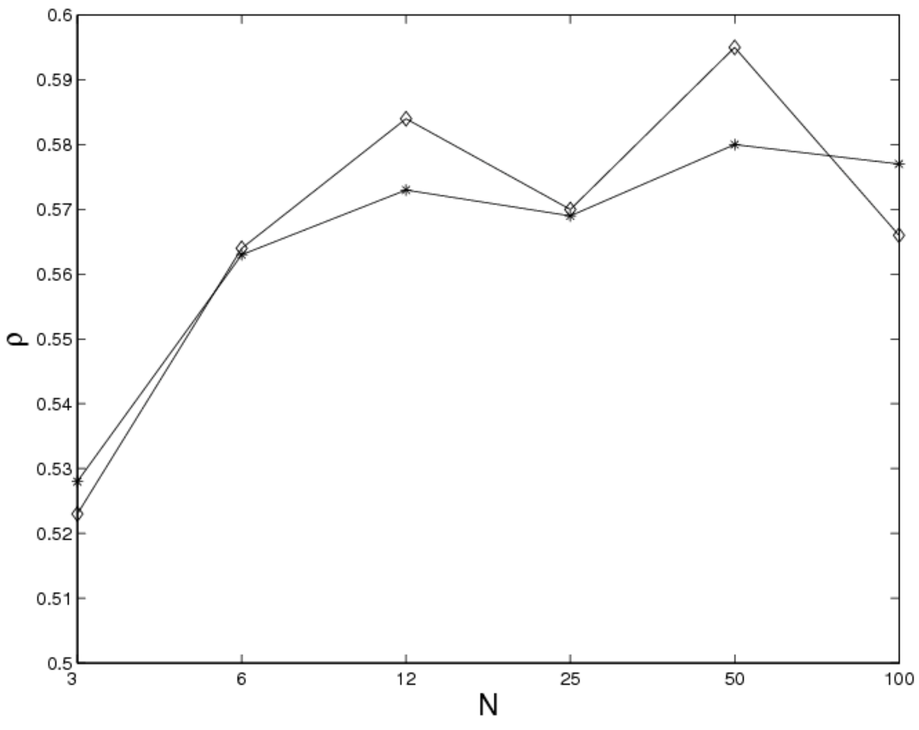
$$U = [w_\beta, w_1 - 2Wq_1, \cdots, w_N - 2Wq_N]^T$$

4 Source Extraction in Wireless Sensor Networks

- Simulation settings
- **cluster-based sensor network vs. benchmarking case**
- **sources: two chaotic signals, i.e., logistic map and Chebyshev map**
- **the mixing coefficients are randomly generated from the standard normal distribution**
- **the ambient noise levels and the number of quantization bits are assumed to be identical for all sensors**
- **the correlation coefficient is adopted to evaluate the performance**

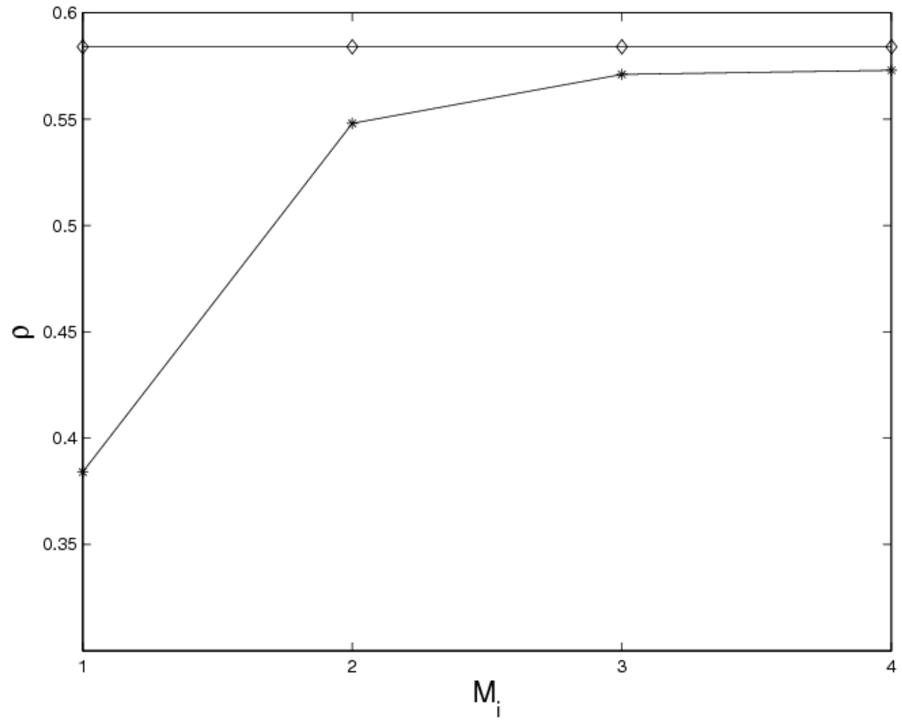
4 Source Extraction in Wireless Sensor Networks

- Simulation results (1)
- success rate ρ
- ρ versus N $M_i = 4$ SNR = 20 dB



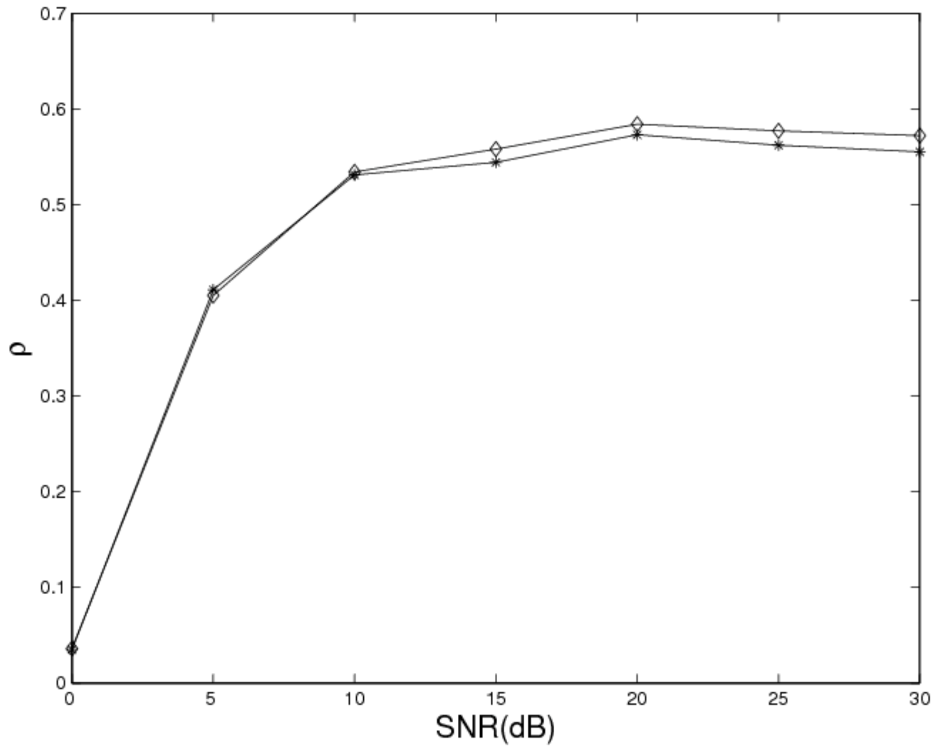
4 Source Extraction in Wireless Sensor Networks

- Simulation results (2)
- ρ versus M_i $N = 12$ SNR = 20 dB



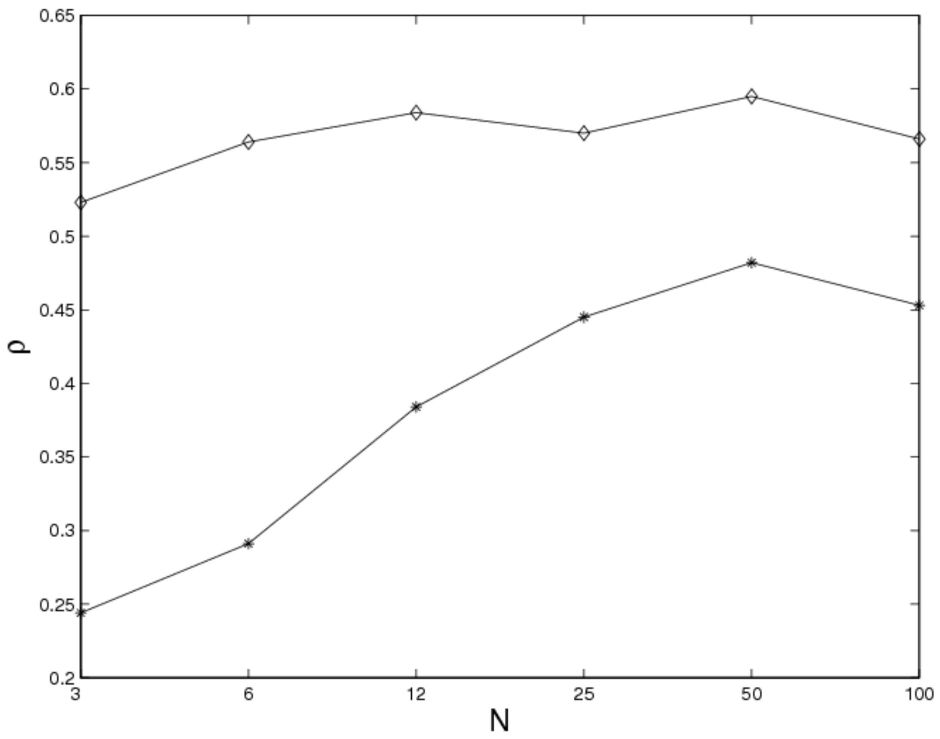
4 Source Extraction in Wireless Sensor Networks

- Simulation results (3)
- ρ versus SNR $N = 12$ $M_i = 4$



4 Source Extraction in Wireless Sensor Networks

- Simulation results (4)
- ρ versus N $\qquad M_i = 1 \qquad \mathrm{SNR} = 20\ \mathrm{dB}$



5 Minimizing Effective Energy Consumption in Multi-Cluster Sensor Networks for Source Extraction

- Performance
- **success rate** ρ multi-cluster
- Total energy consumption E_{total}
- **sensing, computation and communication**

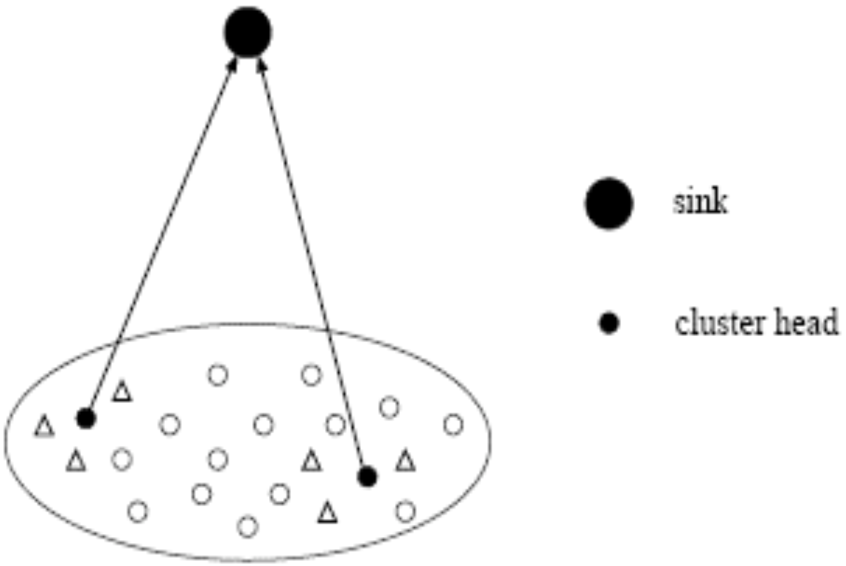
$$
\begin{aligned}
E_{h,\text{total}}^{k} &= E_{h,s}^{k} + E_{h,\text{comp}}^{k} + E_{h,\text{comm}}^{k} \\
&\approx LE_{\text{se}} + \beta_1 E_c + \beta_2 E_c N_k^2 \\
&+ LME_{\text{elec}}(N_k - 1) \\
&+ 8L(E_{\text{elec}} + \epsilon_{\text{mp}}\, d_{s,k}^4).
\end{aligned}
$$

$$
E_{\text{nh,total}}^{k,i} \approx LE_{\text{se}} + \beta_3 E_c + LM(E_{\text{elec}} + \epsilon_{\text{fs}}\, d_{c,k,i}^2).
$$

$$
E_{\text{total}} = \sum_{k=1}^{K} E_{h,\text{total}}^{k} + \sum_{k=1}^{K} \sum_{i=1}^{N_k-1} E_{\text{nh,total}}^{k,i}.
$$

5 Minimizing Effective Energy Consumption in Multi-Cluster Sensor Networks for Source Extraction

- Cluster formation strategy
- **to minimize the energy consumption relating to distance**
- **PSO algorithm**



5 Minimizing Effective Energy Consumption in Multi-Cluster Sensor Networks for Source Extraction

- Effective energy consumption
- **definition:** $\frac{E_{\text{total}}}{\rho}$
- Optimal number of clusters K_{opt}
- **criteria: minimizing effective energy consumption**
- Analysis
- **the existence and the uniqueness of** K_{opt}
- **The simulation results coincide with the theoretical ones**

5 Minimizing Effective Energy Consumption in Multi-Cluster Sensor Networks for Source Extraction

- Simulation settings
- **the energy parameters (J)**
- **the system parameters**

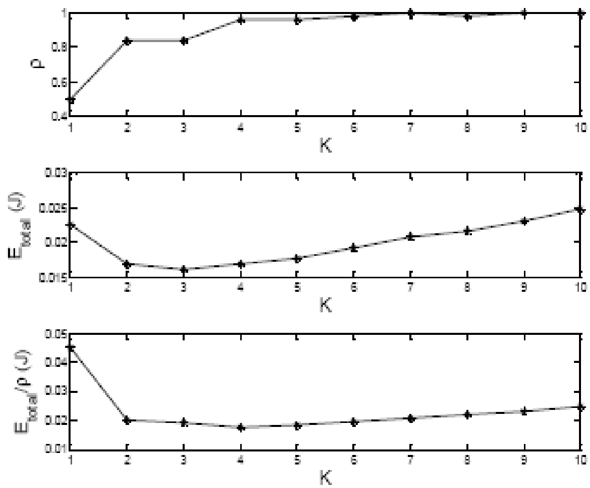
$M = 4$

- **the sensor network deployment**
- the cluster members are uniformly distributed over a 100 m×100 m area centered at the origin. The sink is placed over the origin and is 200 m away from the area.

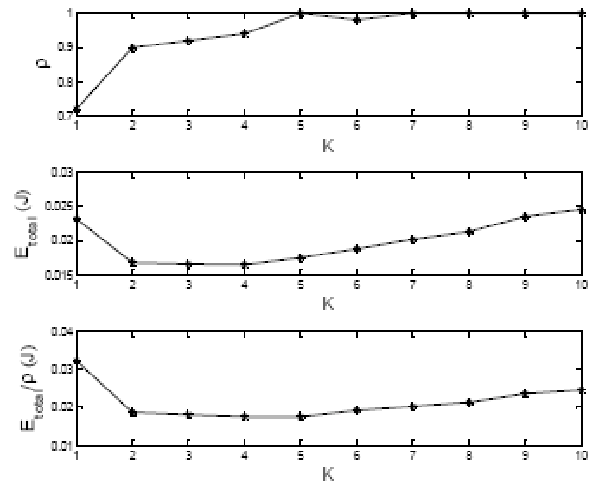
5 Minimizing Effective Energy Consumption in Multi-Cluster Sensor Networks for Source Extraction

- Simulation results (1)
- **parameter setting**

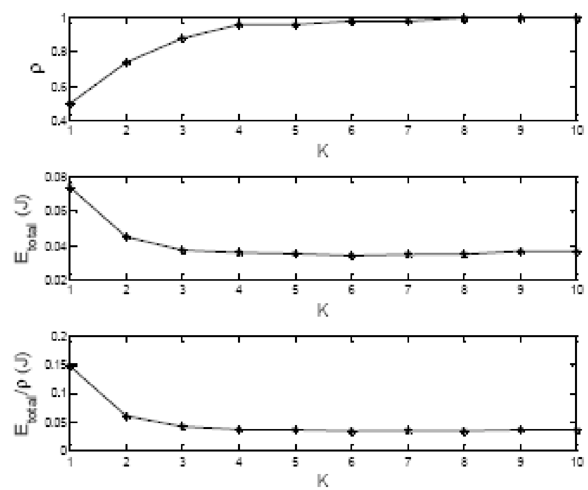
(a) $J = 2$, $N = 120$, $L = 100$. (b) $J = 3$, $N = 120$, $L = 100$. (c) $J = 2$, $N = 240$, $L = 100$. (d) $J = 2$, $N = 120$, $L = 200$.


ρ
K
E_total (J)
K
E_total/ρ (J)
K

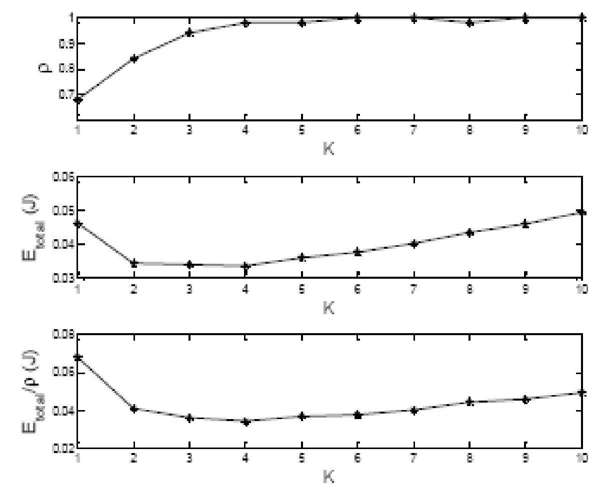
(a)


ρ
K
E_total (J)
K
E_total/ρ (J)
K

(b)


ρ
K
E_total (J)
K
E_total/ρ (J)
K

(c)

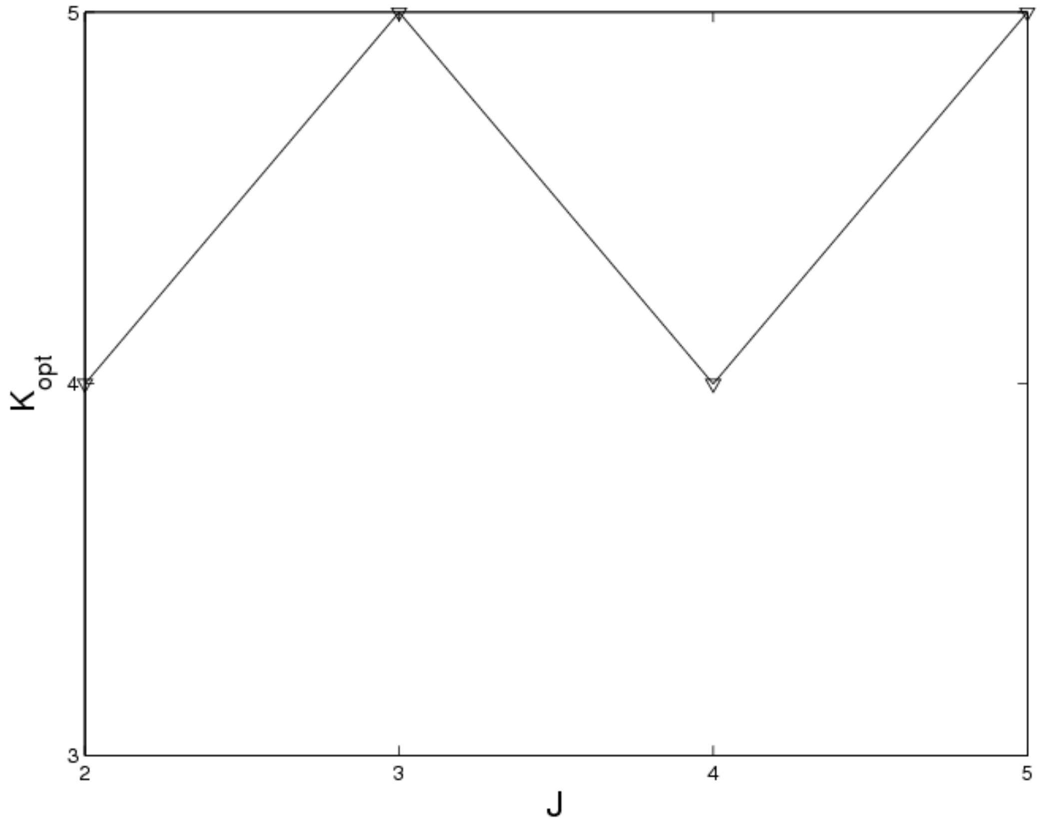

ρ
K
E_total (J)
K
E_total/ρ (J)
K

(d)

5 Minimizing Effective Energy Consumption in Multi-Cluster Sensor Networks for Source Extraction

- Simulation results (2)

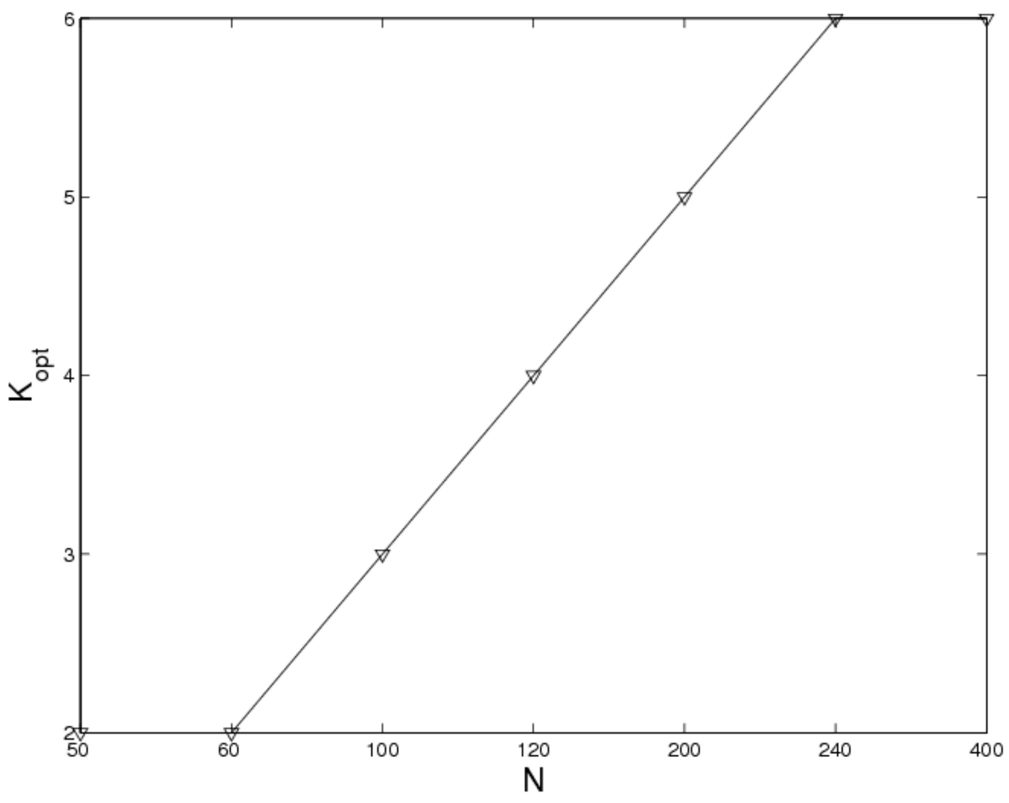
K_{opt} versus J, with $N = 120$, $L = 100$.



5 Minimizing Effective Energy Consumption in Multi-Cluster Sensor Networks for Source Extraction

- Simulation results (3)

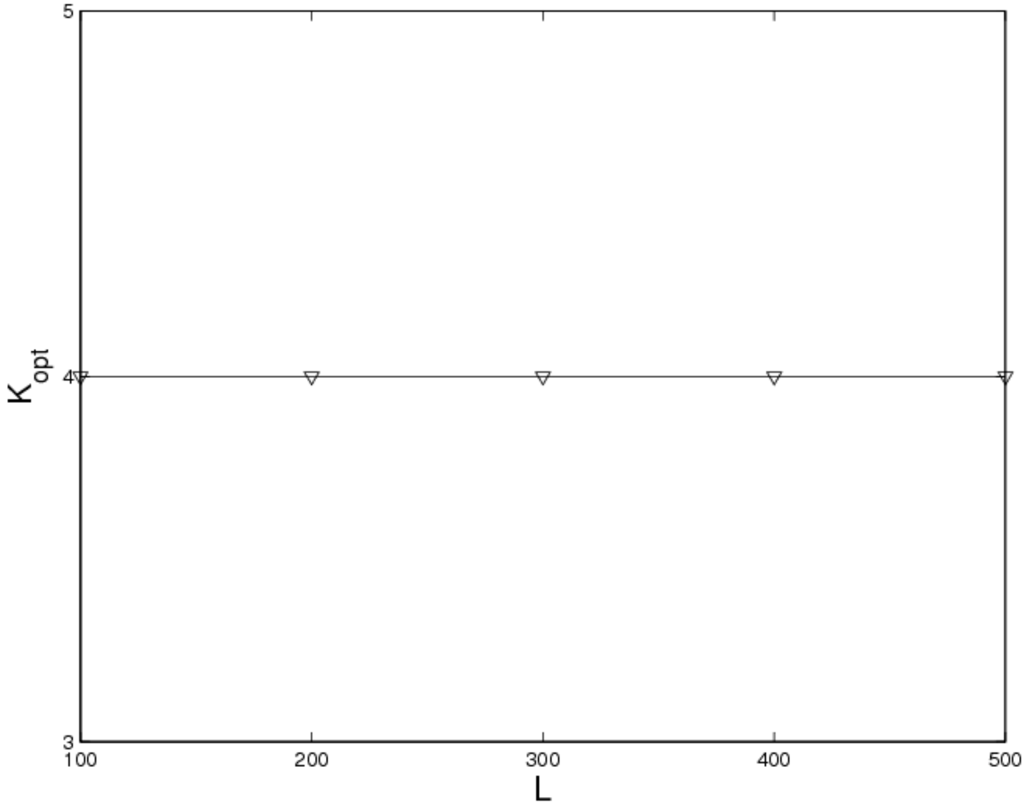
K_{opt} versus N, with $J = 2$, $L = 100$.



5 Minimizing Effective Energy Consumption in Multi-Cluster Sensor Networks for Source Extraction

- Simulation results (4)

K_{opt} versus L, with $J = 2$, $N = 120$.



6 Future Works

- Source Extraction in Heterogeneous Wireless Sensor Networks

  different local signal-to-noise-ratios, sensor observations are bounded to different intervals

- Source Extraction in a Correlated Sensing Field
- Analysis

  to identify the conditions under which the sources can be separated, which are related to the number of sensors, the number of quantization bits, and so on

Thank you