بسم الله الرحمن الرحيم

Reliability Improvement of Distributed Detection in Clustered Wireless Sensor Networks

RELIABILITY IMPROVEMENT OF DISTRIBUTED DETECTION IN CLUSTERED WIRELESS SENSOR NETWORKS

PH.D. THESIS PRESENTED AT THE

DEPARTMENT OF ELECTRICAL ENGINEERING
SCHOOL OF ENGINEERING
FERDOWSI UNIVERSITY OF MASHHAD
MASHAD IRAN
HTTP://UM.AC.IR

PRESENTED BY:
S. HAMED JAVADI
UNDER THE SUPERVISION OF:
PROFESSOR ALI PEIRAVI

THIS THESIS WAS PRESENTED TO THE BOARD OF EXAMINERS ON MARCH 6, 2013:

1- Prof. Ali Peiravi THESIS ADVISOR - FERDOWSI UNIVERSITY OF MASHHAD
http://peiravi.profcms.um.ac.ir/

2- PROF. HAMIDREZA AMINDAVAR - AMIRKABIR UNIVERSITY OF TECHNOLOGY TEHRAN POLYTECHNIQUE
http://www.aut.ac.ir/official/main.asp?uid=hamidami

3- PROF. BEHZAD MOSHIRI - UNIVERSITY OF TEHRAN
http://ece.ut.ac.ir/en/users/moshiri?destination=user%2F12

4- PROF. MOHAMMAD-R. AKBARZADEH-T - FERDOWSI UNIVERSITY OF MASHHAD
http://akbazar.profcms.um.ac.ir/

5- ASSOCIATE PROF. SAAIED HOSSEINI KHAYAT - FERDOWSI UNIVERSITY OF MASHHAD
http://commeng.um.ac.ir/dslab/shk.html
6- ASSOCIATE PROF. H. HOSSEIN ZAMIRI JAFARIAN
http://hzamiri.profcms.um.ac.ir/

outline

- Wireless sensor networks and clustering
- Detection theorem
- Distributed detection in WSNs
- Reliability of a detector network
- Serial & Parallel detection
- Hybrid distributed detection (HDD)
- Weighted decision fusion (WDF)
- WDF in practice
- Conclusion and future works

WSN and clustering

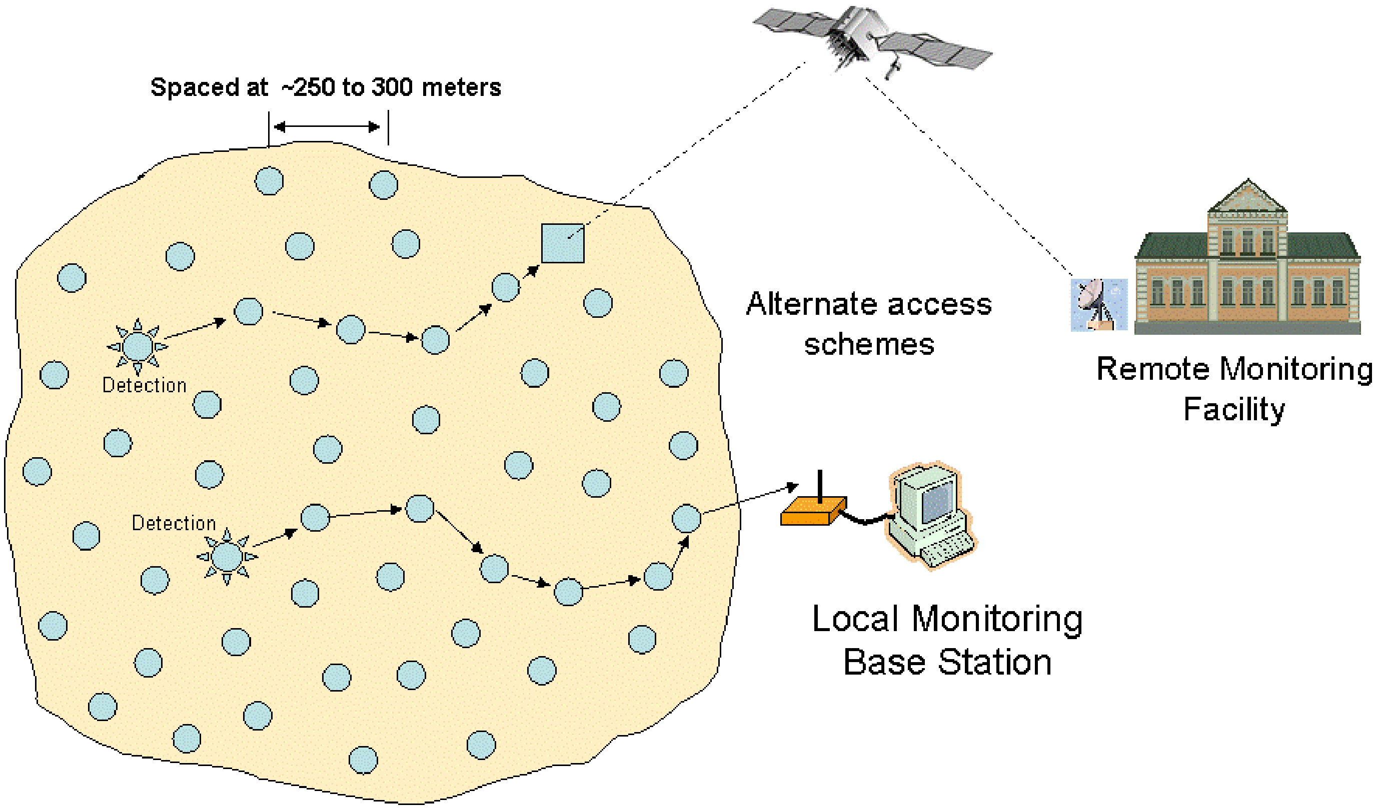
What is a wireless sensor network?

What are its challenges?

Why it should be clustered?

Wireless Sensor Networks

- A wireless Sensor Network (WSN):



WSN & clustering

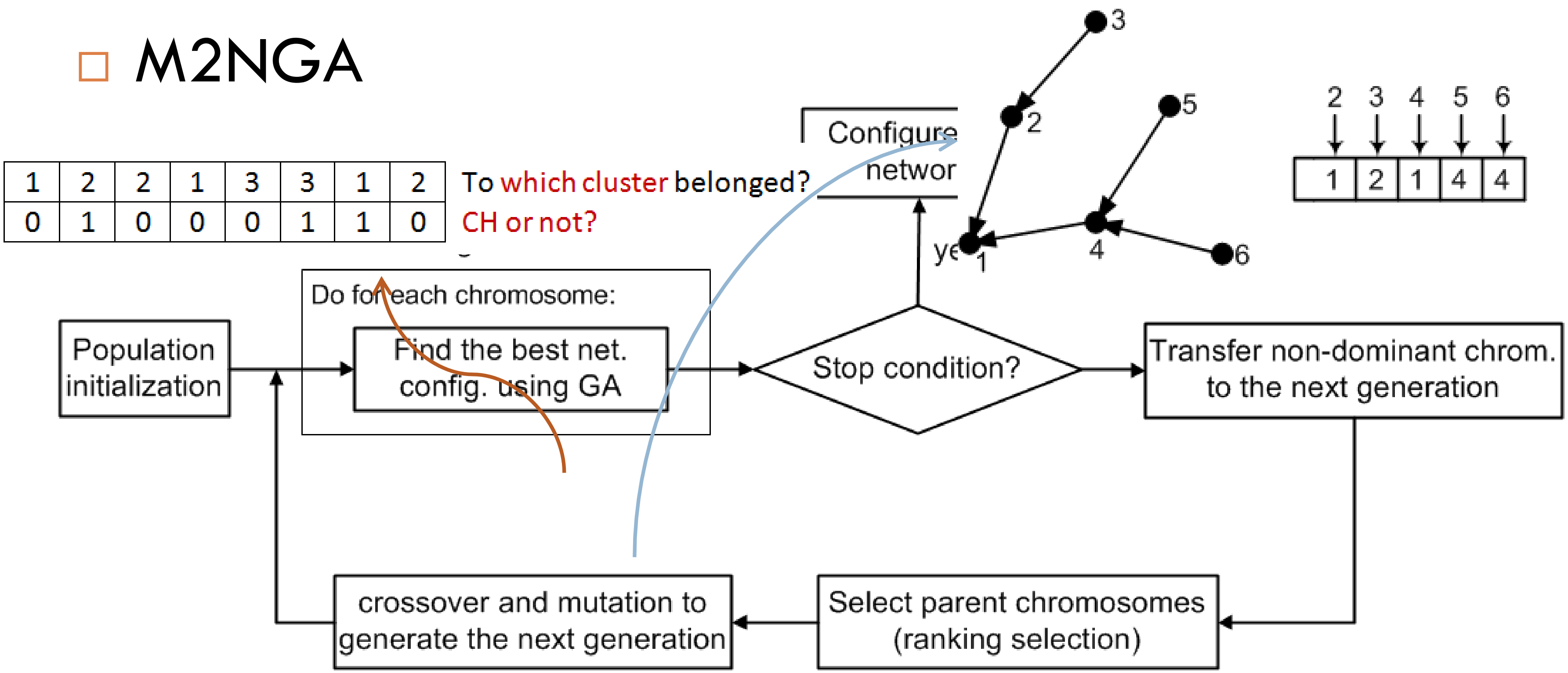
- Specific features of WSNs
  - Large number of nodes
  - Limited memory and computation resources
  - Limited energy resources
  - Usually tasked for surveillance of large environment
- Advantages of clustering
  - Improving the scalability of WSNs
  - Overcoming the limitations of memory and speed
  - Lower power consumption
  - Better surveillance

WSN & clustering

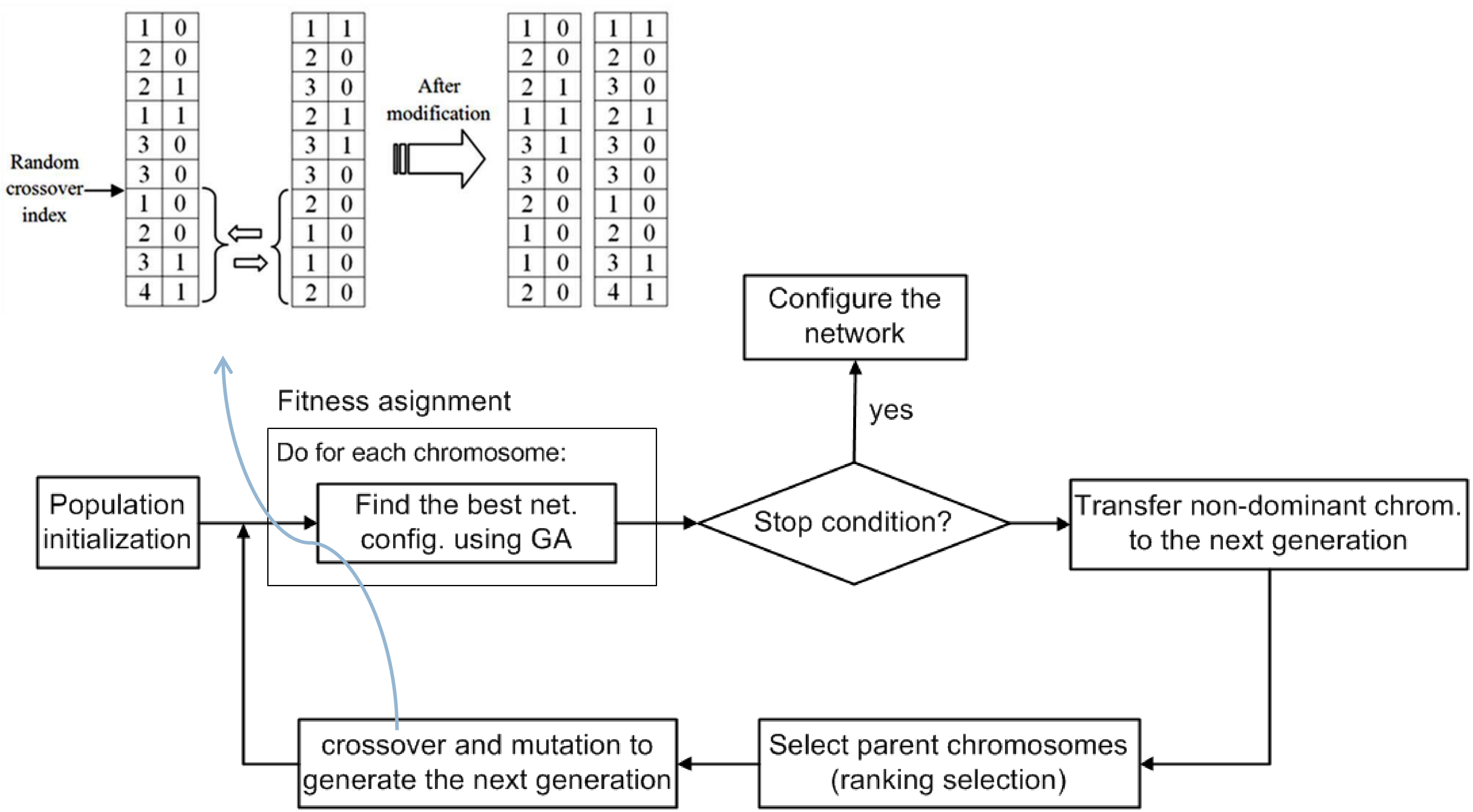
- Clustering sensor nodes s.t. maximize network lifetime and QoS parameters : *This is an optimization problem*
- M2NGA: A multi-objective evolutionary algorithm which simultaneously optimizes network lifetime and delay

WSN & clustering

- M2NGA

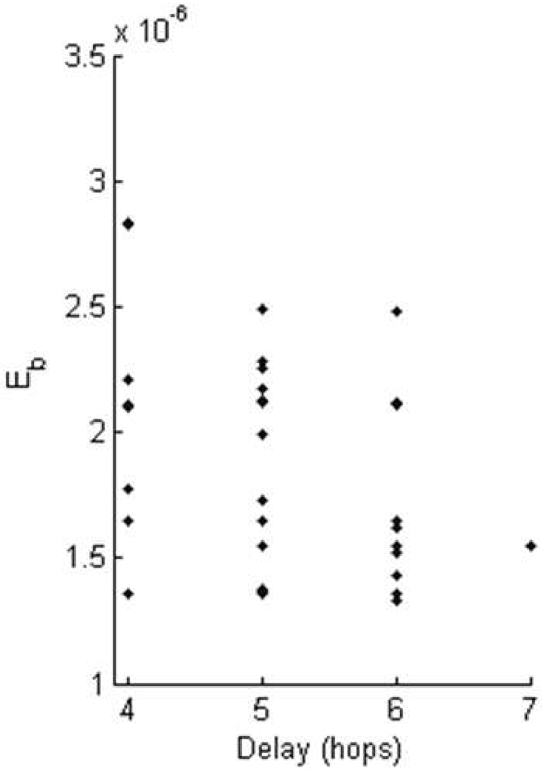


WSN & clustering



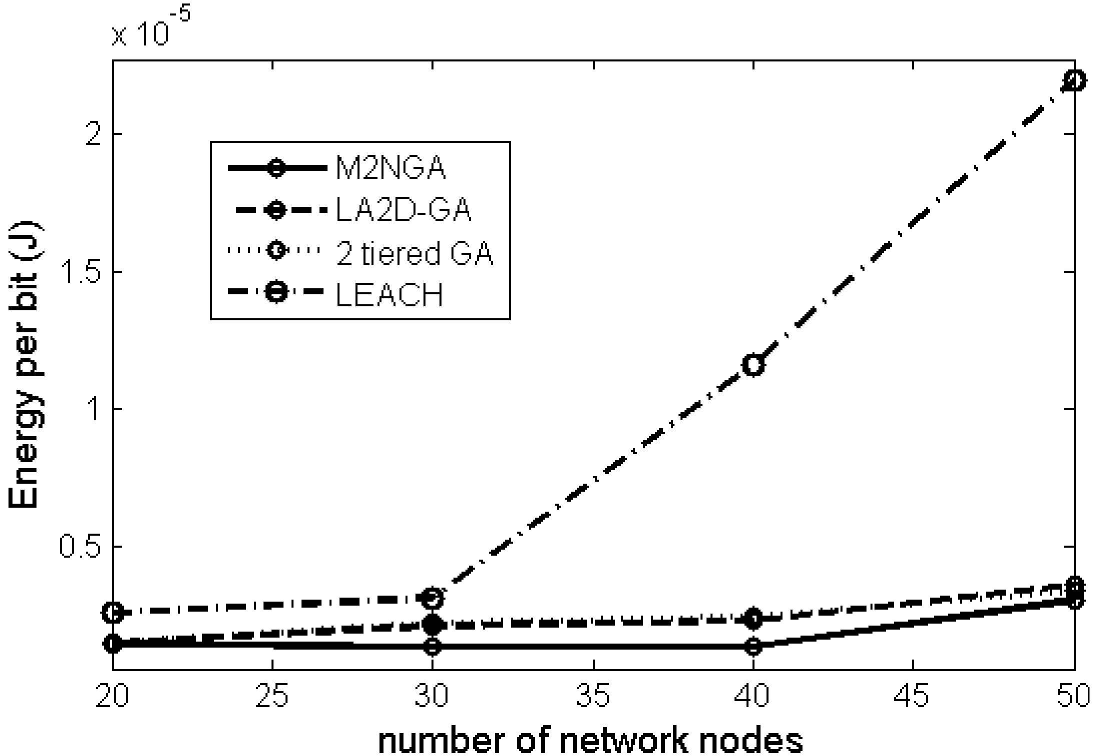
WSN & clustering

- M2NGA convergence



WSN & clustering

- Comparison



WSN & clustering

- M2NGA features:
  - The only algorithm which uses multi-objective optimization methods
  - Multi-hop intra-cluster data transmission
  - More energy-efficient clustering schemes

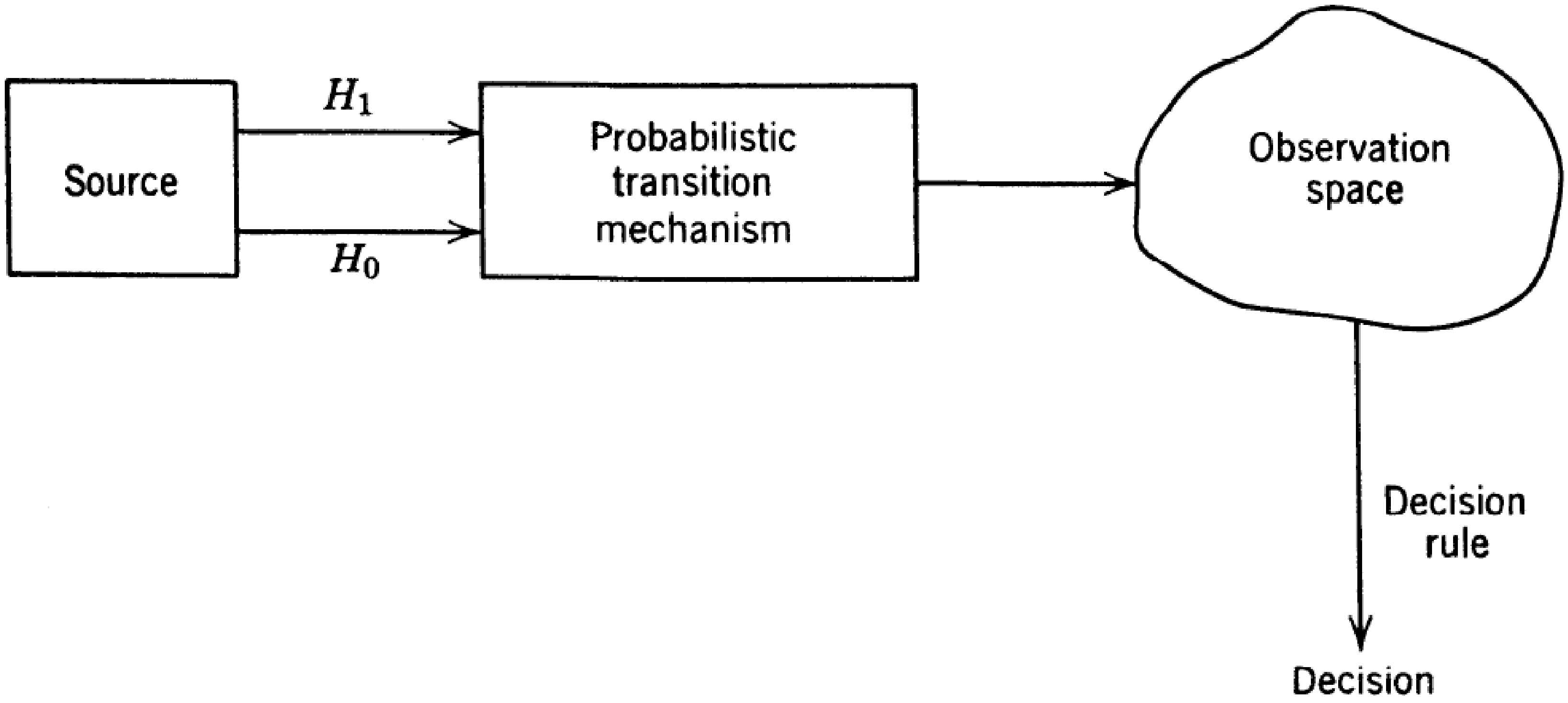
Detection theorem

Why is detection important?

What are detection methods?

Introduction

- A simple decision theory problem



Detection methods

- Three criterions:
  - Bayes
  - Neyman-Pearson (NP)
  - Maximize a Posterior (MAP)
- Result of criterions: an LRT (Likelihood Ratio Test)
- Other methods:
  - Minimax: unknown a priori probabilities
  - GLRT: unknown signal
  - LO: weak signal
  - f-divergence: information-theory-based method

Distributed detection in WSNs

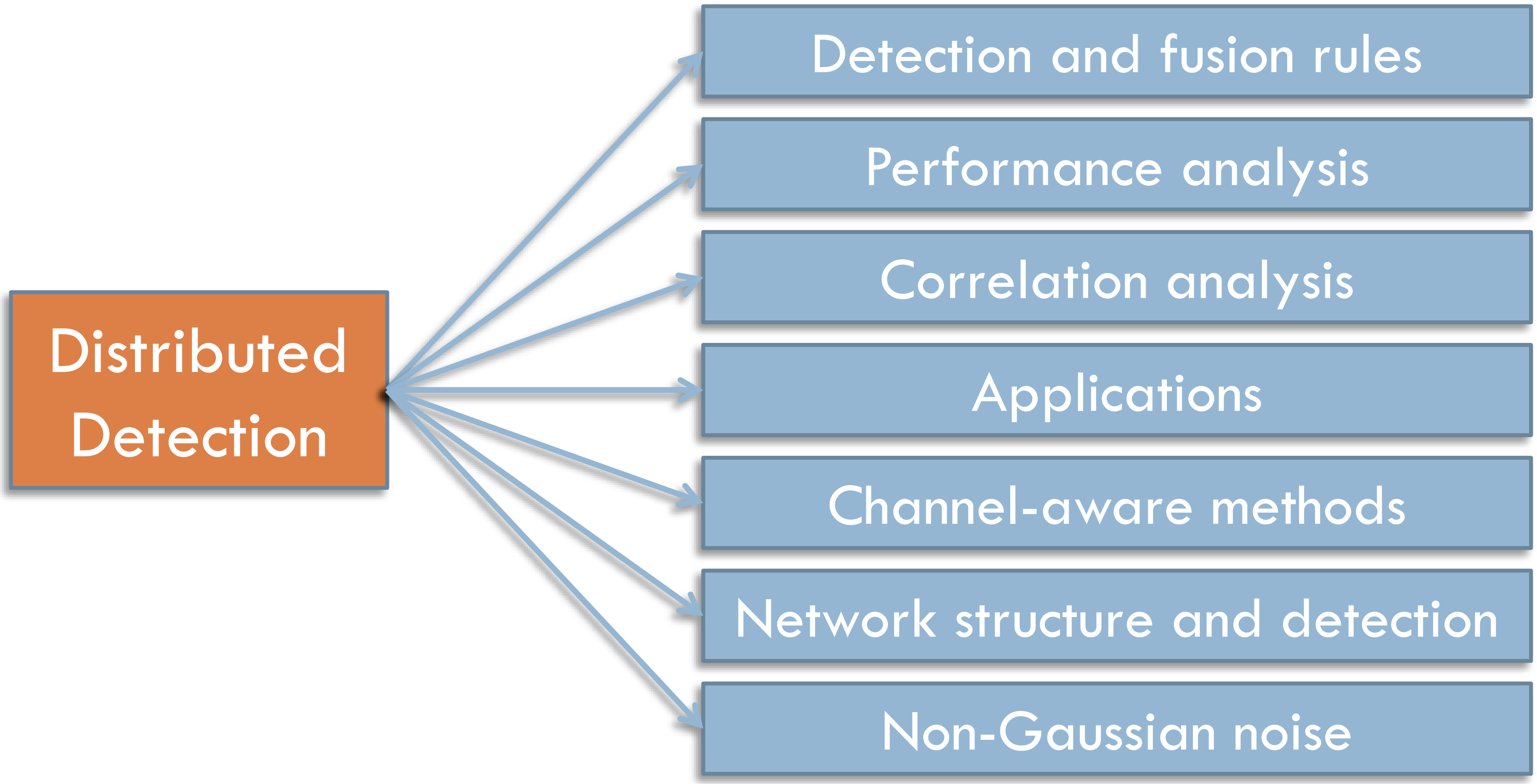
What is the problem?

What are the methods?

Distributed detection in WSNs

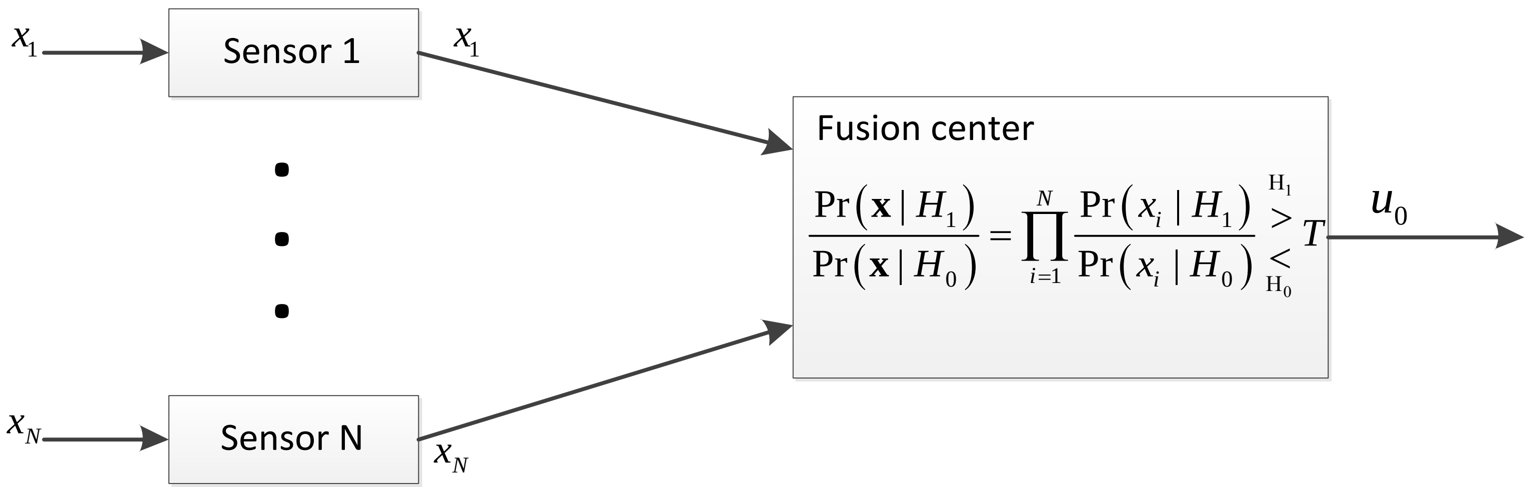
- Problem(s):
  - How to optimally decide s.t. the limitations of WSNs?
    - What are detection rules at sensors?
    - How to fuse the sensors' data?
    - How to meet the limitations of WSNs such as wireless nature, energy-efficiency and simple implementation?
    - How to design a detector network?
    - What's the matter with the noise?

Distributed detection in WSNs



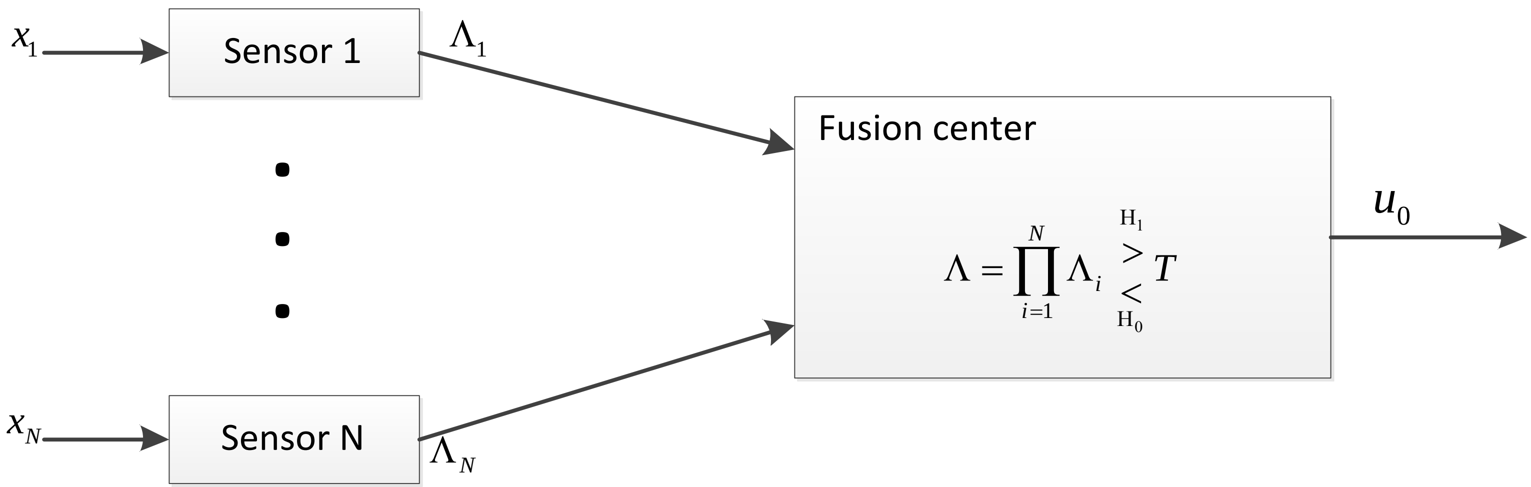
Detection methods in WSNs

- Centralized detection:



Detection methods in WSNs

- Independent likelihood pool:



Detection methods in WSNs

- Histogram fusion (HF):
  - Each sensor sends its local count values to the FC
  - The FC can compute the global LLR

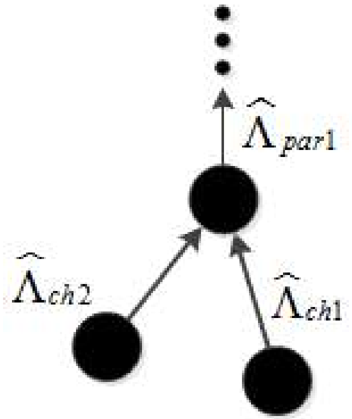
$$\Lambda = \sum_{i=1}^{N} \Lambda_i = \sum_{i=1}^{N} \frac{1}{M} \sum_{a=1}^{A} T_i(a) f(a)$$

$$= \sum_{a=1}^{A} \left[\sum_{i=1}^{N} \frac{T_i(a)}{M} \right] f(a)$$

K. Liu and A. M. Sayeed, "Type-Based Decentralized Detection in Wireless Sensor Networks," *IEEE Trans. Sign. Proc.*, vol. 55, no. 5 I, pp. 1899-1910, 2007.

Detection methods in WSNs

- Log-likelihood ratio Fusion (LF):
  - Each intermediate node obtains an estimate of the normalized LLR of all its descendants based on their quantized values.
  - More energy-efficiency vs. worse performance



W. Li and H. Dai, "Energy-Efficient Distributed Detection Via Multihop Transmission in Sensor Networks," *IEEE Signal Process. Lett.*, vol. 15, pp. 265-269, 2008.

Detection methods in WSNs

- Censoring technique:
  - Only informative information is transmitted

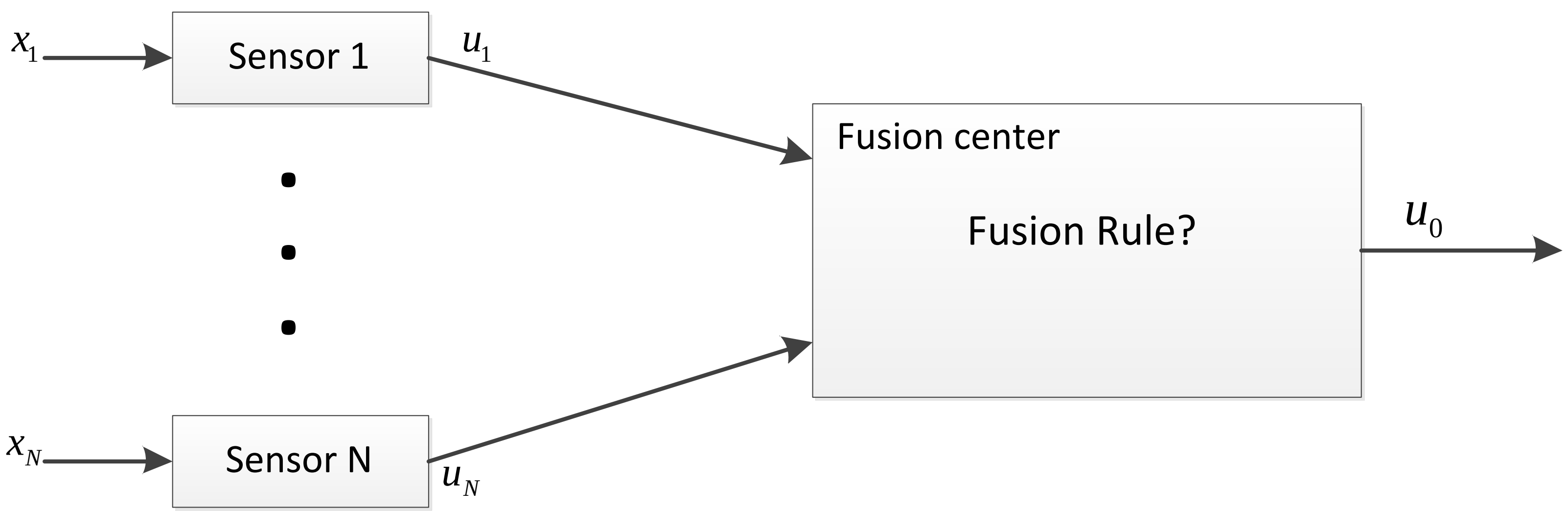
$$\Lambda = \prod_{i:\Lambda_i \in R_i} \Lambda_i \prod_{i:\Lambda_i \in \overline{R_i}} \frac{\Pr\left(\Lambda_i \in \overline{R_i} \mid H_1\right)}{\Pr\left(\Lambda_i \in \overline{R_i} \mid H_0\right)} \underset{H_0}{\overset{H_1}{\gtrless}} T$$

  - More energy-efficiency, no performance loss!

C. Rago, P. Willett and Y. Bar-Shalom, "Censoring Sensors: a Low-Communication-Rate Scheme for Distributed Detection," *IEEE Trans. Aerosp. Elect. Syst.*, vol. 32, no. 2, pp. 554-568, 1996.

Distributed Detection methods

- Distributed Detection:
  - Hard-decision fusion



Distributed Detection methods

- Chair-Varshney method:

$$\sum_{i \in A} \ln \frac{P_{d_i}}{P_{f_i}} + \sum_{j \notin A} \ln \frac{1 - P_{d_j}}{1 - P_{f_j}} \underset{H_0}{\overset{H_1}{\gtrless}} T$$

  - The FC must know each sensor's detection performance
  - Not practical

Z. Chair and P. K. Varshney, "Optimal Data Fusion in Multiple Sensor Detection Systems," *IEEE Trans. Aerosp. Elect. Syst.*, vol. AES-22, no. 1, 1986.

Distributed Detection methods

- Counting Rule Fusion (CRF):
  - FC counts '1's, then compares the result with a threshold

$$\Lambda = \sum_{i=1}^{N} u_i \underset{H_0}{\overset{H_1}{\gtrless}} T$$

  - Each sensor sends just one bit

R. Niu, P. K. Varshney, M. H. Moore and D. Klamer, "Decision Fusion in a Wireless Sensor Network With a Large Number Of Sensors," in *Proc. 7th IEEE Int. Conf. Inf. Fusion*, 2004.

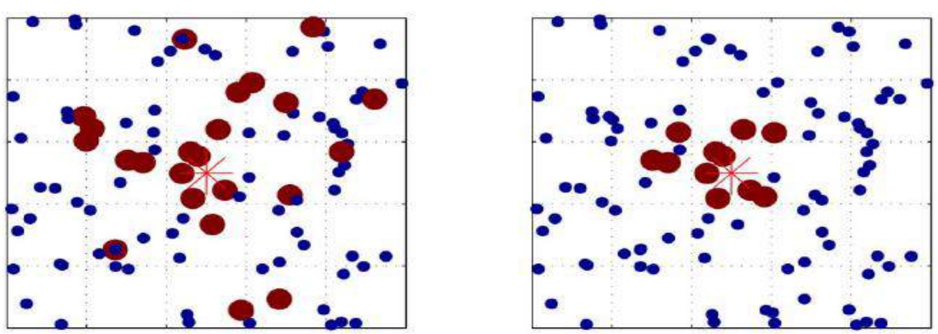
Detection methods in WSNs

- Distance-based decision fusion:
  - Event localization is performed prior to detection
  - Decision of the nearest node to the event is the most accurate one. Thus, choose that decision!

M. Duarte and Y. H. Hu, “Distance-Based Decision Fusion in a Distributed Wireless Sensor Network,” *Telecommun. Syst.*, vol. 26, no. 2-4, pp. 339-350, 2004.

Detection methods in WSNs

- Local Vote Decision Fusion (LVDF):
  - Sensors adjust their initial decisions with their neighbors prior sending it to the FC
  - Counting rule is performed at the FC to make the final decision



CRF LVDF

N. Katenka, E. Levina and G. Michailidis, "Local Vote Decision Fusion for Target Detection in Wireless Sensor Networks," *IEEE Trans. Signal Process.*, vol. 56, no. 1, pp. 329-338, 2008.

Reliability of a detector network

How the lifetime of a WSN is defined?

What's the definition of the reliability?

Reliability of a detector network

- Definitions of lifetime of a WSN:
  - ✓ The time until the first node dies
  - The time until some fixed ratio of nodes die
  - The time until the network is disconnected
  - The time until the network doesn't cover the ROI completely

Reliability of a detector network

- Reliability of distributed detection in a network with N_C clusters:

$$R_{DD} = \prod_{i=1}^{N_C} \left(1 - DEP_i\right)$$

- Reliability of a detector network:

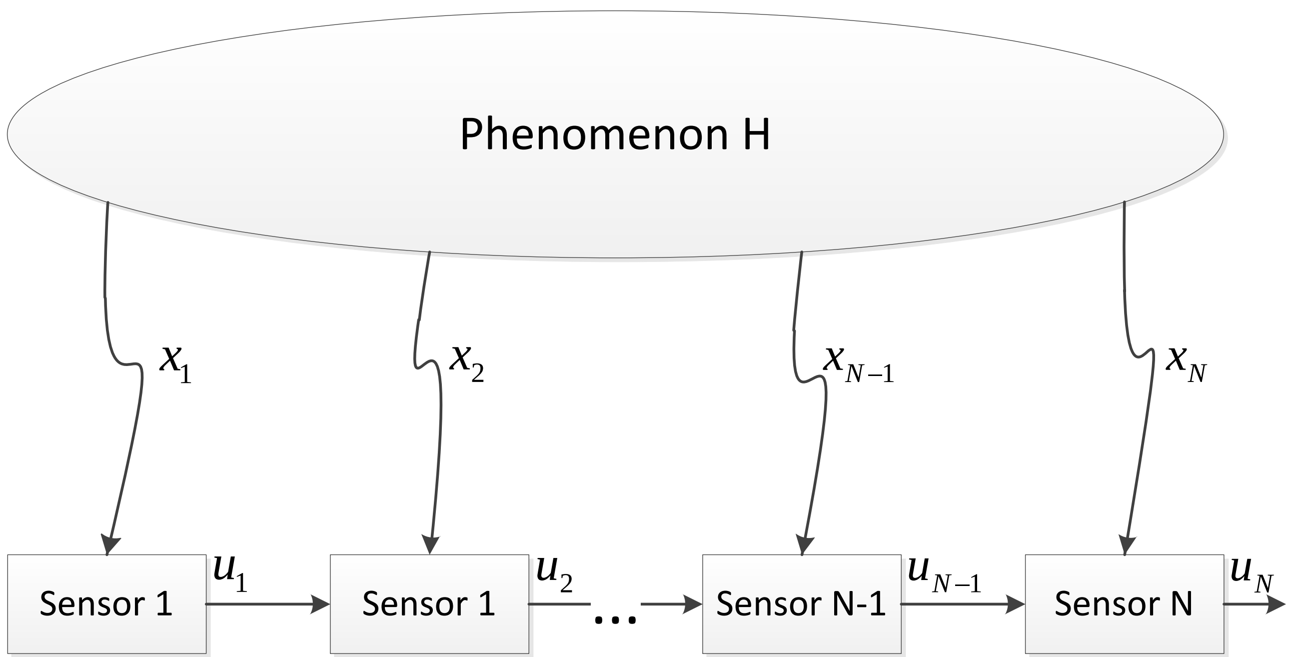
$$R_N = R_{DD} . \Pr\left(T_{network} \geq t\right)$$

Serial & Parallel Distributed Detection

Performance of distributed detection in serial and parallel configurations

Serial Distributed Detection

- Each sensor decides based on its own observation as well as its received decision.



Serial Distributed Detection

- Theorem: If each sensor's observation is assumed to be independent of its received decision, using a MAP-based detector:

$$P_{d_i} = P_{d_{i-1}} . \int_{x_i : \alpha(x_i, p_1) \geq \frac{P_{f_{i-1}}}{P_{d_{i-1}}}} \Pr(x_i \mid H_1) dx_i + (1 - P_{d_{i-1}}) . \int_{x_i : \alpha(x_i, p_1) \geq \frac{1-P_{f_{i-1}}}{1-P_{d_{i-1}}}} \Pr(x_i \mid H_1) dx_i$$

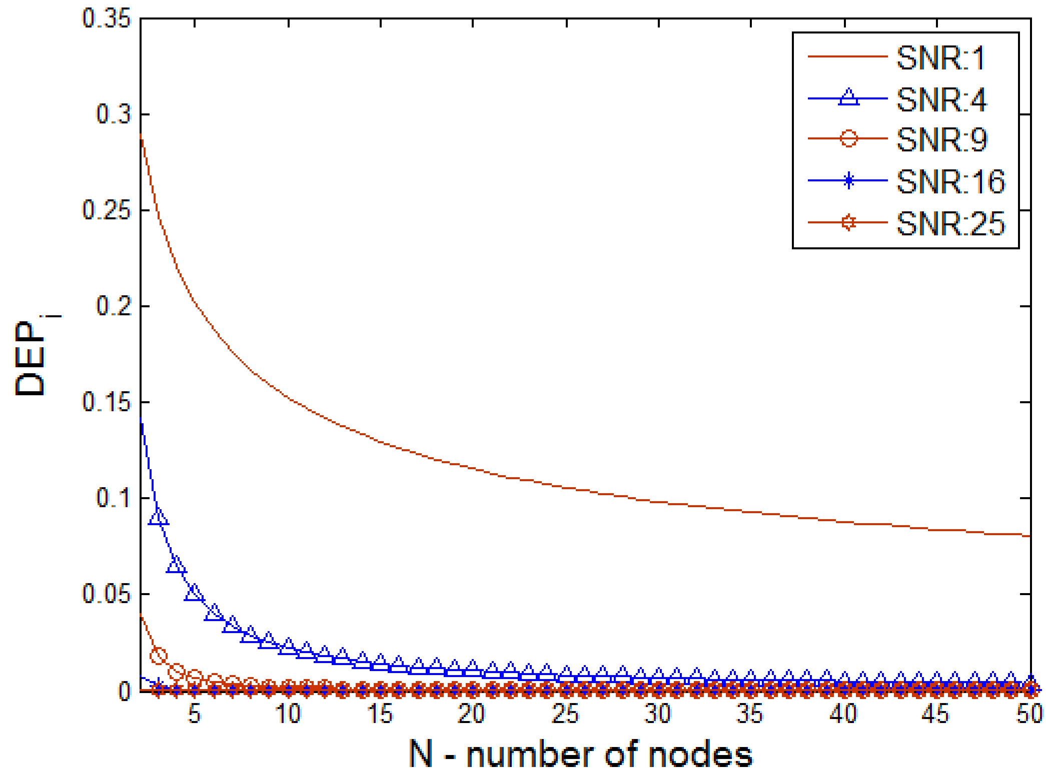
$$P_{f_i} = P_{f_{i-1}} . \int_{x_i : \alpha(x_i, p_1) \geq \frac{P_{f_{i-1}}}{P_{d_{i-1}}}} \Pr(x_i \mid H_0) dx_i + (1 - P_{f_{i-1}}) . \int_{x_i : \alpha(x_i, p_1) \geq \frac{1-P_{f_{i-1}}}{1-P_{d_{i-1}}}} \Pr(x_i \mid H_0) dx_i$$

in which:

$$\alpha(x_i, p_1) = \frac{\Pr(x_i \mid H_1)}{\Pr(x_i \mid H_0)} \times \frac{p_1}{1 - p_1}$$

Serial Distributed Detection

- Neglecting communication errors and assuming the Gaussian density for measurement noise of sensors:

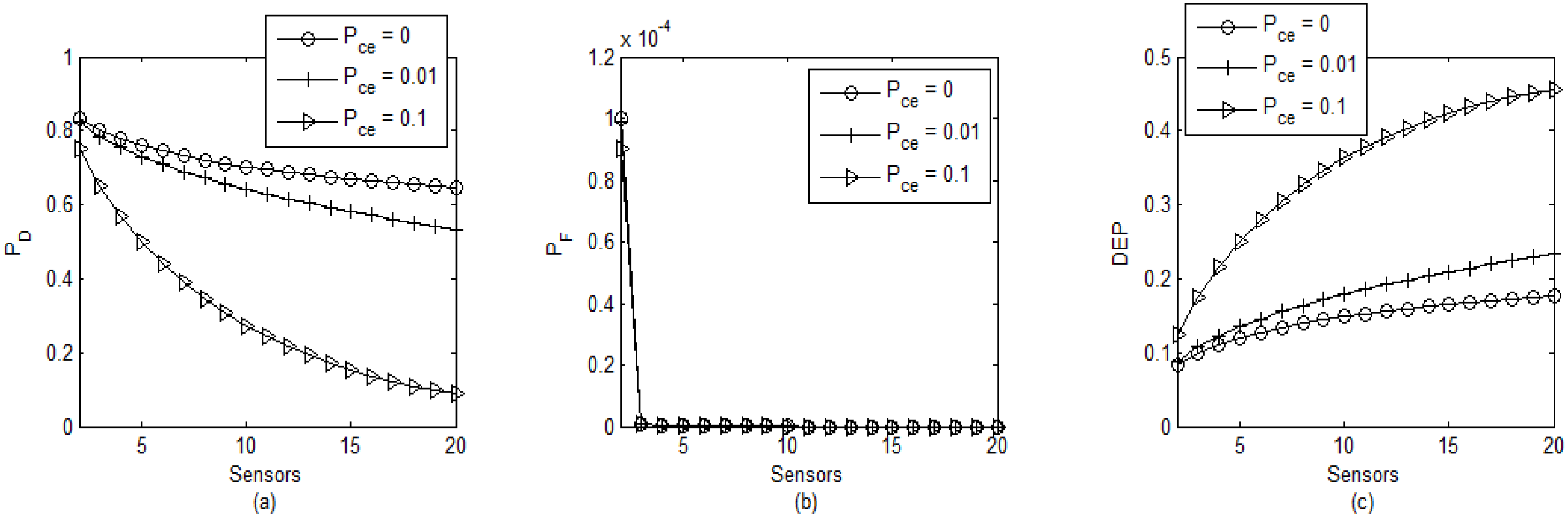


Serial Distributed Detection

- Considering communication error and correlation results in complicated detection rules when using MAP criterion
- Instead, each node of serial chain may use AND or OR fusion rule

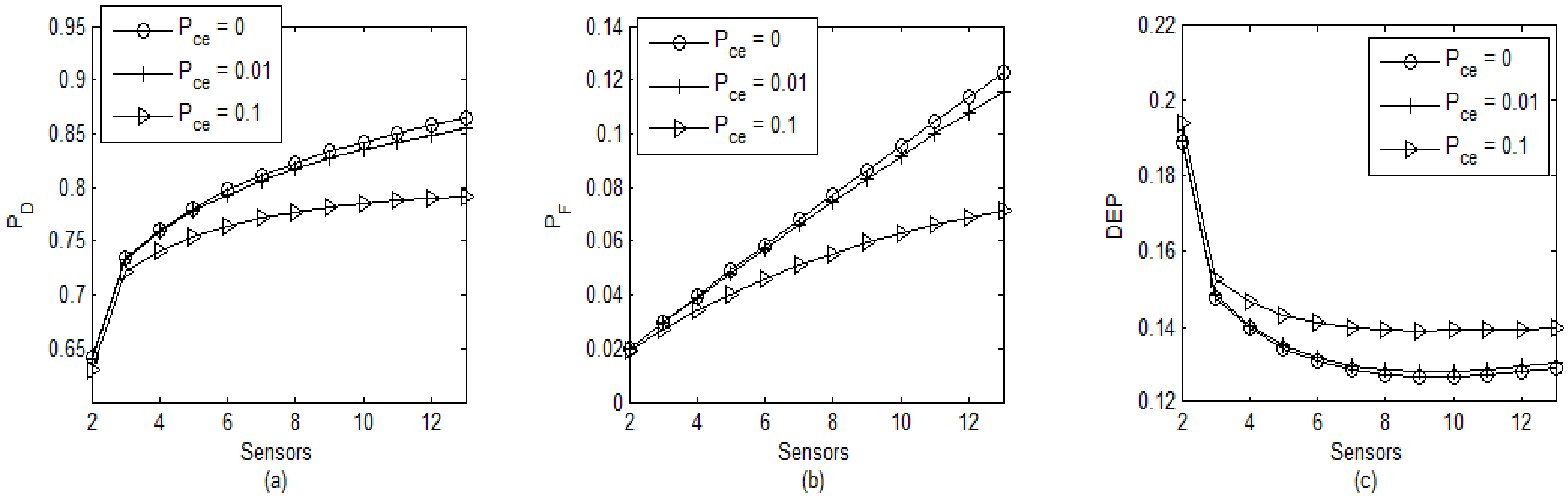
Serial Distributed Detection

- AND fusion rule in serial detection
  - v ~ *N*(5,4), standard normal noise, initial false alarm rate of sensors is kept at 0.01



Serial Distributed Detection

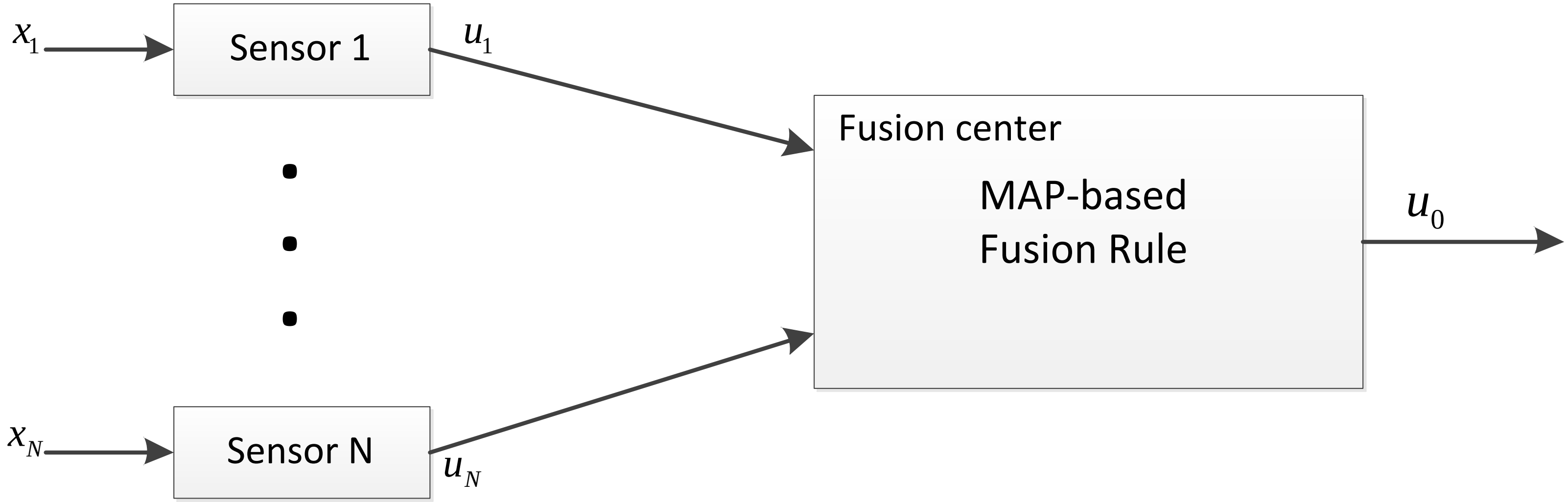
- OR fusion rule in serial detection
  - v ~ *N*(5,4), standard normal noise, initial false alarm rate of sensors is kept at 0.01



  - OR performs better than AND

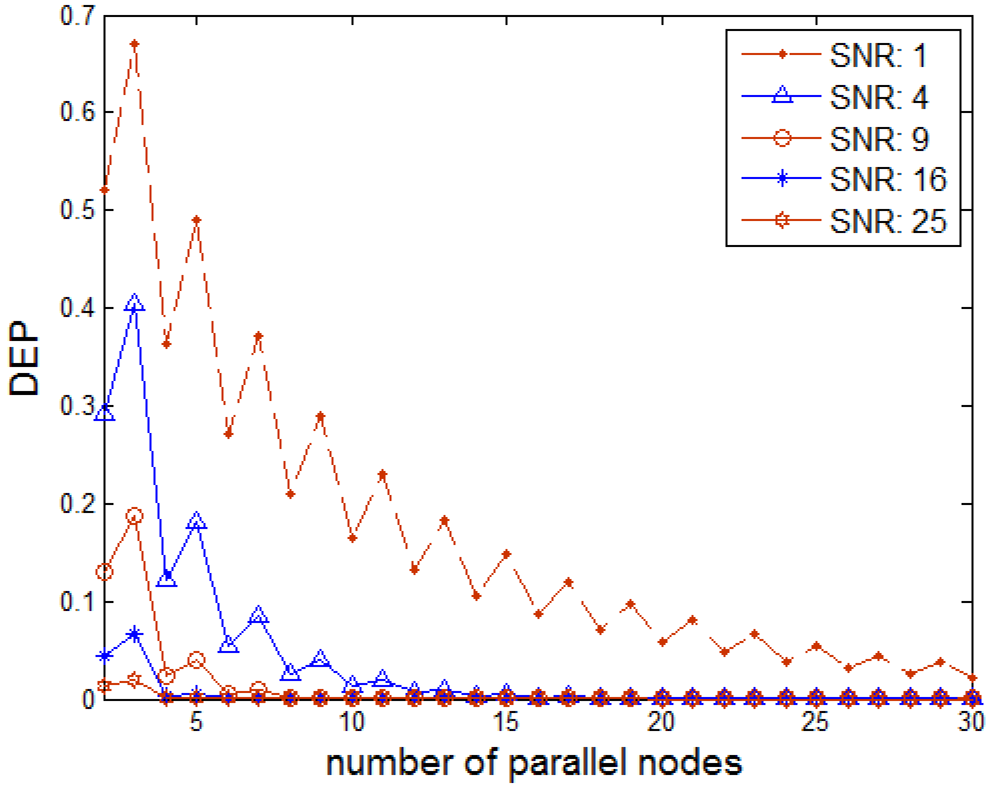
Parallel Distributed Detection

- The FC decides based on sensors decisions



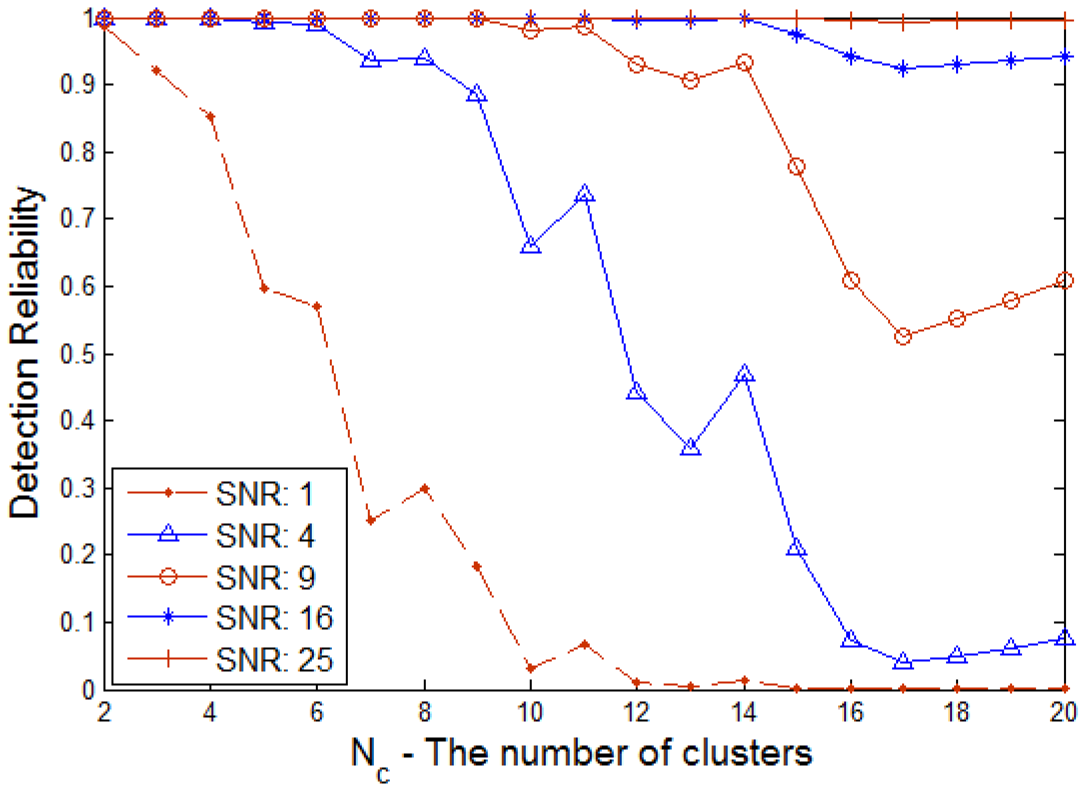
Parallel Distributed Detection

- Assuming i.i.d. sensor observations, no communication error and $P(H_0)=P(H_1)$



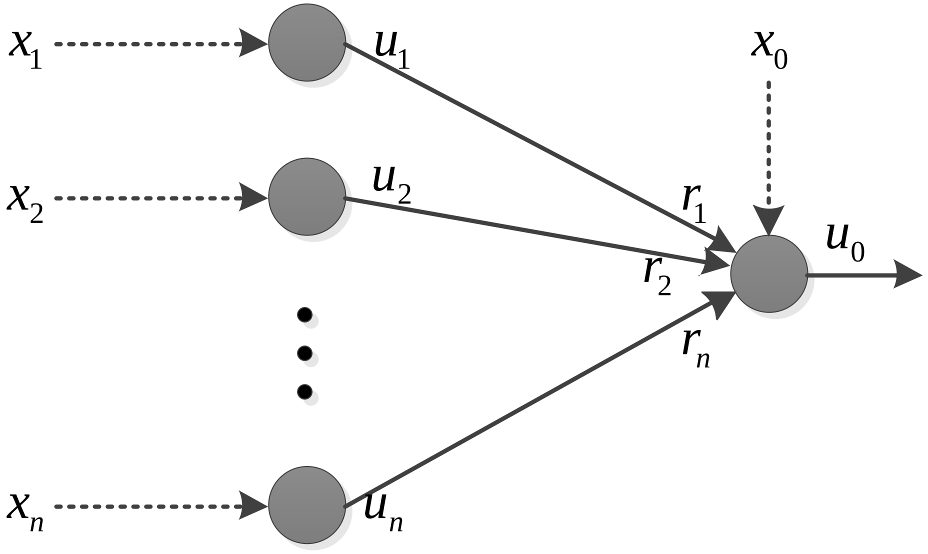
Parallel Distributed Detection

- Detection performance in a clustered WSN



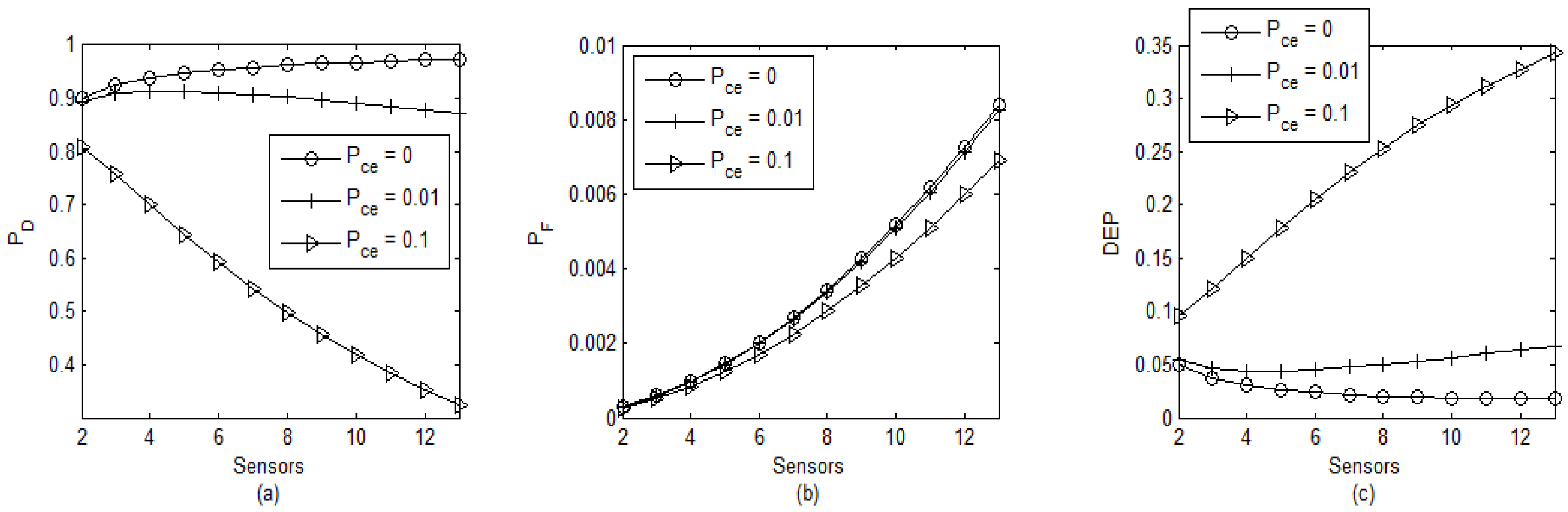
Parallel Distributed Detection

- Considering communication error and correlation



Parallel Distributed Detection

- Using counting rule at node 0
  - v ~ $N(5,4)$, standard normal noise, initial false alarm rate of sensors is kept at 0.01



Hybrid Distributed Detection (HDD)

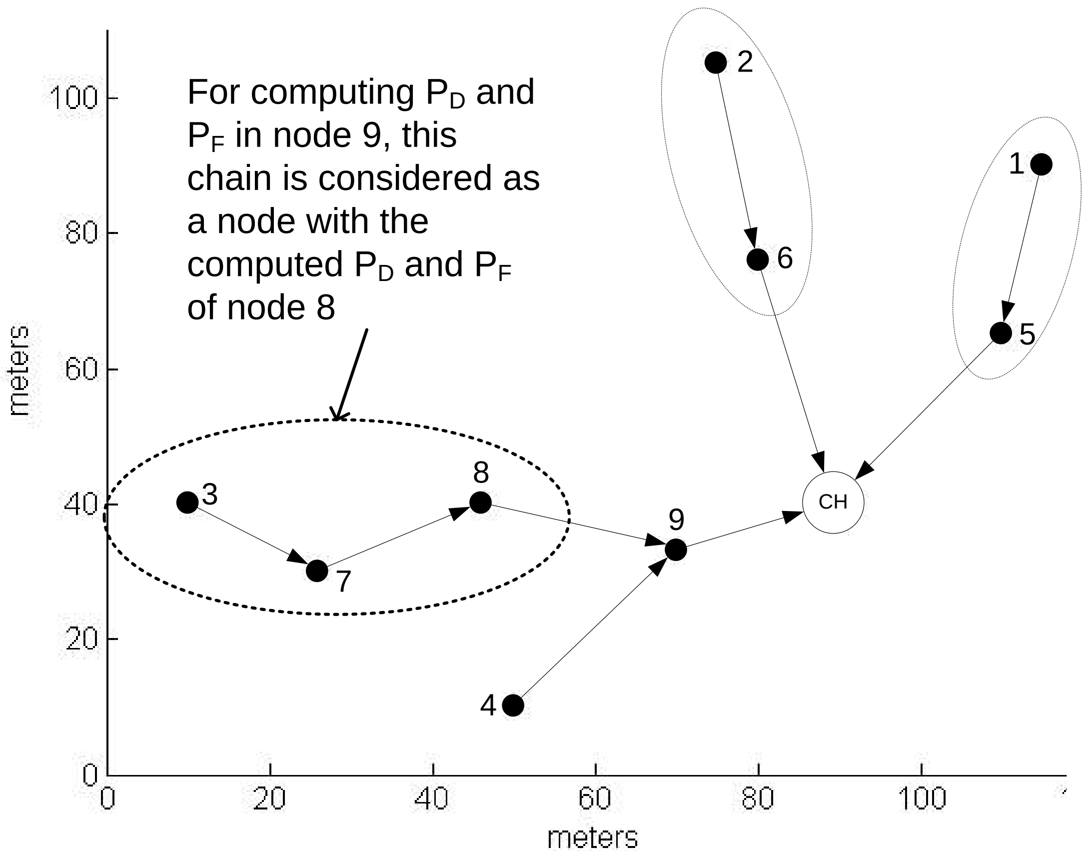
Novel suggestion #1

Hybrid Distributed Detection

- In a multi-hop WSN, decision fusion can be performed during transmission of sensors' decisions to the FC
- Combination of serial and parallel distributed detection
  - Nodes in regular WSN → router (relay)
  - Nodes in HDD method → router *and* a local FC

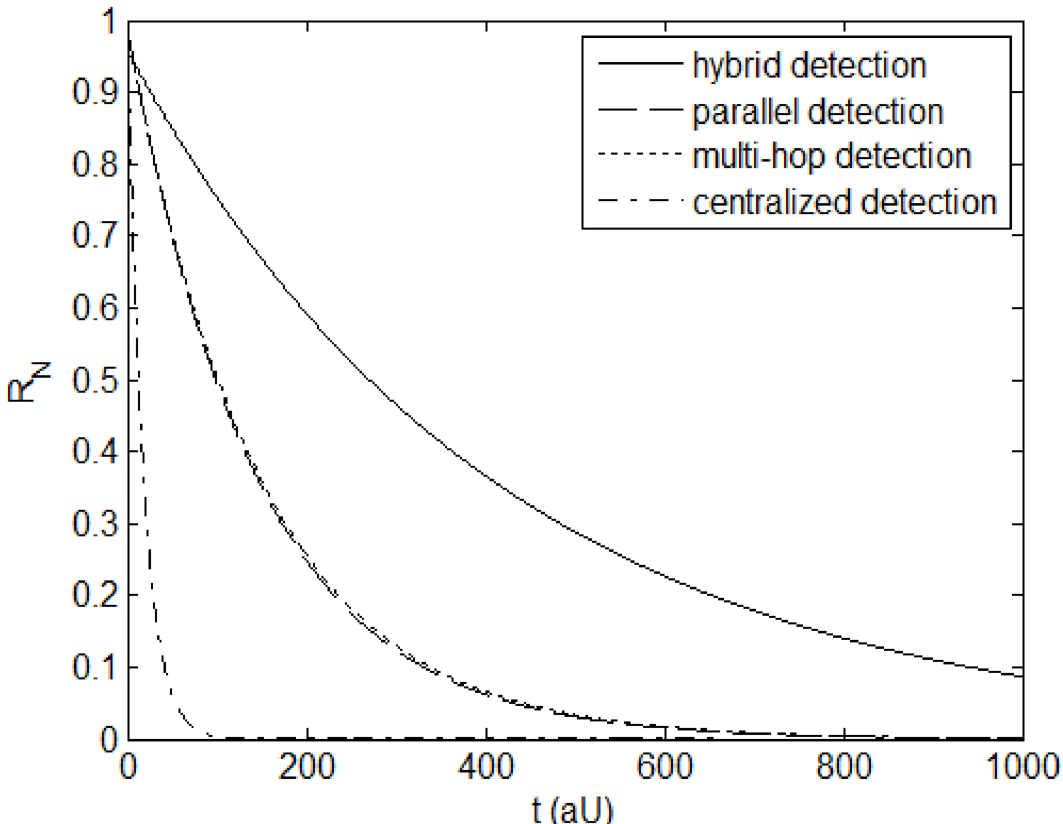
Hybrid Distributed Detection

- HDD in a cluster of a WSN



Hybrid Distributed Detection

- Reliability comparison: $D = 0.8$, $F = 0.2$, AWGN with unit variance, 8-bit data for centralized method



Weighted Decision Fusion (WDF)

Novel suggestion #2

Weighted Decision Fusion

- Chair-Varshney fusion rule:
  - Detection performance of sensors must be known to obtain optimal detection performance
  - Not compatible with WSN limitations
- Counting rule fusion:
  - All decisions are treated equally
  - Compatible with WSN limitations *But* far from the optimal detection performance

Weighted Decision Fusion

- WDF:
  - A minimum detectable SNR (S_{min}) is defined for sensors
  - An LRT is performed in each node
  - Upon detection in a node, it estimates SNR
  - If the estimated SNR is more than S_{min}, it is quantized and sent to the FC
  - The FC weighs each sensor's decision based on its quantized SNR

Weighted Decision Fusion

- WDF fusion rule:

$$\Lambda = \sum_{i=1}^{n_A} S_i \underset{H_0}{\overset{H_1}{\gtrless}} \tau$$

$$\tau \,\Box\, f\left(n_A; \alpha, \xi, k_1, T\right)$$

α : CFAR at sensors

k_1 :A parameter related to sensors' miss probability

ξ: a parameter

$$T = \ln\left(\frac{p_0}{p_1}\right)$$

- Simplifying Chair-Varshney rule:

$$\tau \,\Box \left[\frac{1}{\xi}\left(\ln\frac{\alpha}{1-\alpha} + k_1\right) + S_i^m\right] n_A + \frac{N}{\xi}\left(\ln\left(1-\alpha\right) - k_1\right) + \frac{T}{\xi}$$

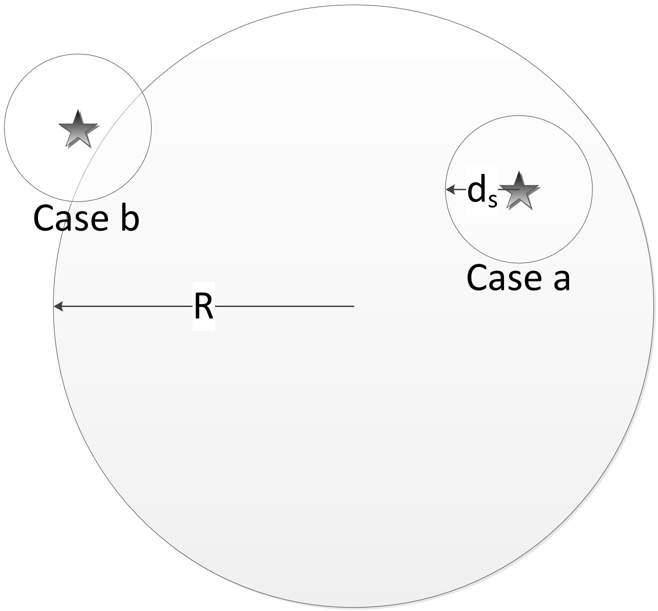
Weighted Decision Fusion

- Expected advantages:
  - Imposing a condition for transmission results in more network reliability and lower false alarm rate
  - Detection performance is improved by weighting the sensors' decisions and using an adaptive threshold at the FC
  - The bandwidth is used more efficiently

WDF analysis

- Analysis of detection performance of a system is essential to answer these questions:
  - Which method?
  - How?
- Assumptions:
  - Measurement noise of sensors is i.i.d.
  - Sensors' decisions are independent conditioned on each hypothesis
  - Communication channels are BSC with constant communication error p_{ce}

WDF analysis



$$P_F = \sum_{n_A=1}^{N} \frac{G\left(\frac{\max(\tau, n_A S_{min}) - \mu_{\Lambda|H_0}}{\sigma_{\Lambda|H_0}}\right)}{G\left(\frac{n_A S_{min} - \mu_{\Lambda|H_0}}{\sigma_{\Lambda|H_0}}\right)} \Pr(n_A \mid H_0)$$

$$P_D = P_a \Pr(\Lambda > \tau \mid H_1, a) + P_b \Pr(\Lambda > \tau \mid H_1, b)$$

$$\Pr(\Lambda > \tau \mid H_1, a) = \sum_{n_A=1}^{N} \frac{G\left(\frac{\max(\tau, n_A S_{min}) - \mu_{\Lambda,a}}{\sigma_{\Lambda,a}}\right)}{G\left(\frac{n_A S_{min} - \mu_{\Lambda,a}}{\sigma_{\Lambda,a}}\right)} \Pr(n_A \mid H_1, a)$$

$$n_A \mid H_0 \sim Binomial(N, \alpha_1)$$

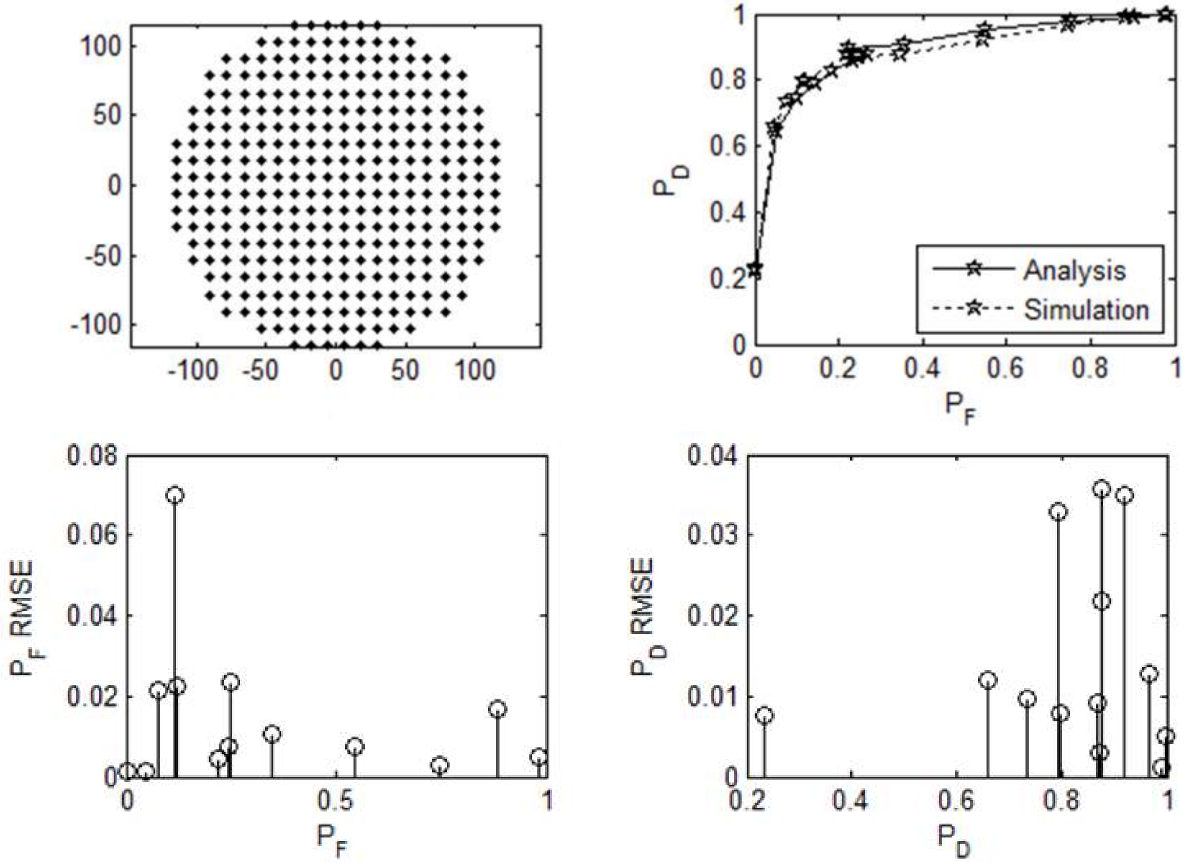
$$\alpha_1 = \alpha \Pr(S_i > S_{min} \mid \Lambda_i > \tau_i)(1 - p_{ce})$$

$$n_A \mid (H_1, a) \sim Binomial(N, \beta_a)$$

$$\beta_a = P_{isr}^a E(P_{d_i})(1 - p_{ce}) + (1 - P_{isr}^a)\alpha \Pr(S_i > S_{min} \mid H_0, \Lambda_i > \tau_i)$$

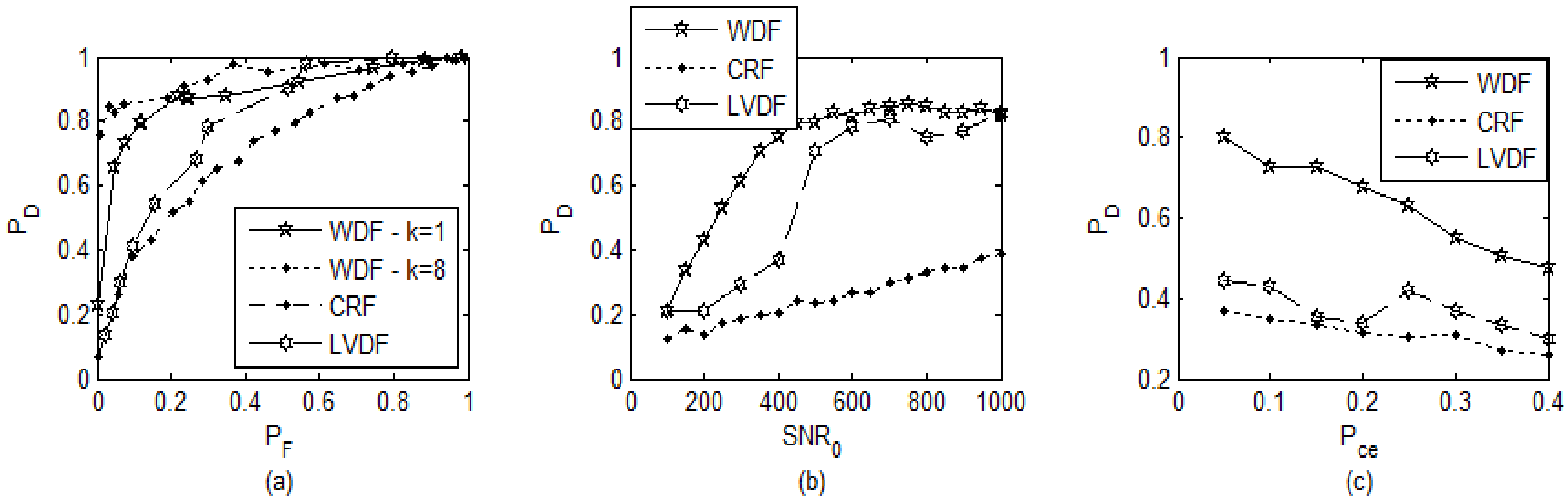
WDF analysis accuracy

- N = 316, R = 120m, S_0 = 300, p_{ce} = 0.02 , 5000 runs of Monte-Carlo



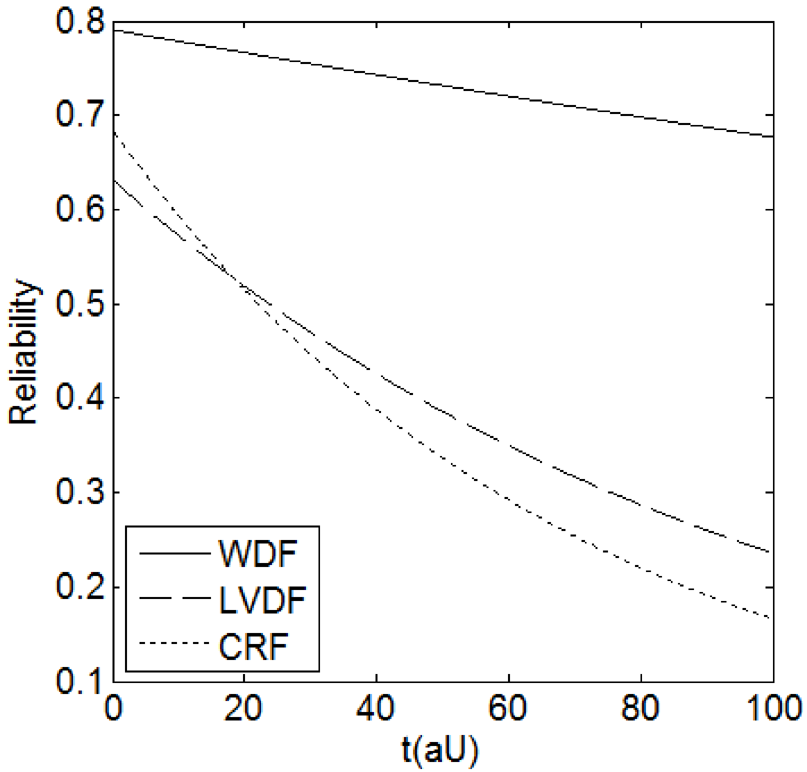
WDF vs. CRF and LVDF

- R = 120m, N = 316, grid network,
  - (a) S_0 = 300, p_{ce} = 0.02
  - (b) p_{ce} = 0.05, P_F = 0.1
  - (c) S_0 = 300, P_F = 0.1



WDF vs. CRF and LVDF

- R = 120m, S_0 = 300, p_{ce} = 0.05, P_F = 0.1, N = 316, grid network



WDF in practice

Practical implementation of WDF method in a radiation detection application

WDF in practice

- Practical data of the project “SensorScope” at the EPFL university is used for validation
- The SensorScope object is to collect parameters related to natural variation of environment using wireless sensor networks
- 97 sensors deployed at the EPFL campus to report several parameters to the base station

WDF in practice

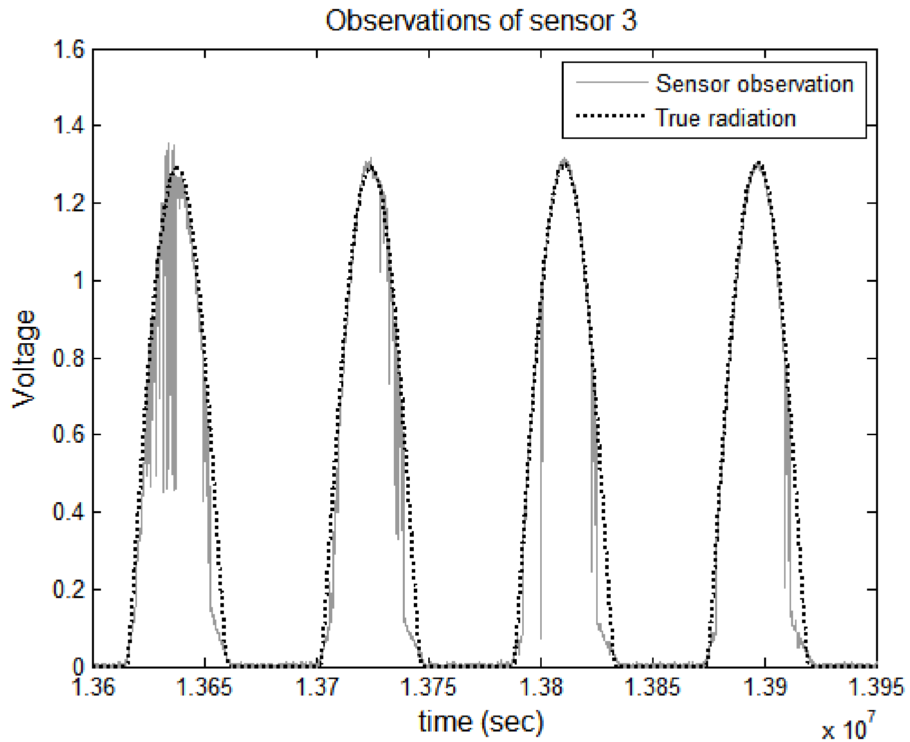
- Sensors deployment in SensorScope

WDF in practice

- Radiation data is used for practical validation of WDF
- Radiation detection may be applicable in precision agriculture to avoid irrigation in day time
- Hypotheses:
  - H_1: Day time
  - H_0: Night time

WDF in practice

- Comparison between expected radiation and sensors' data:



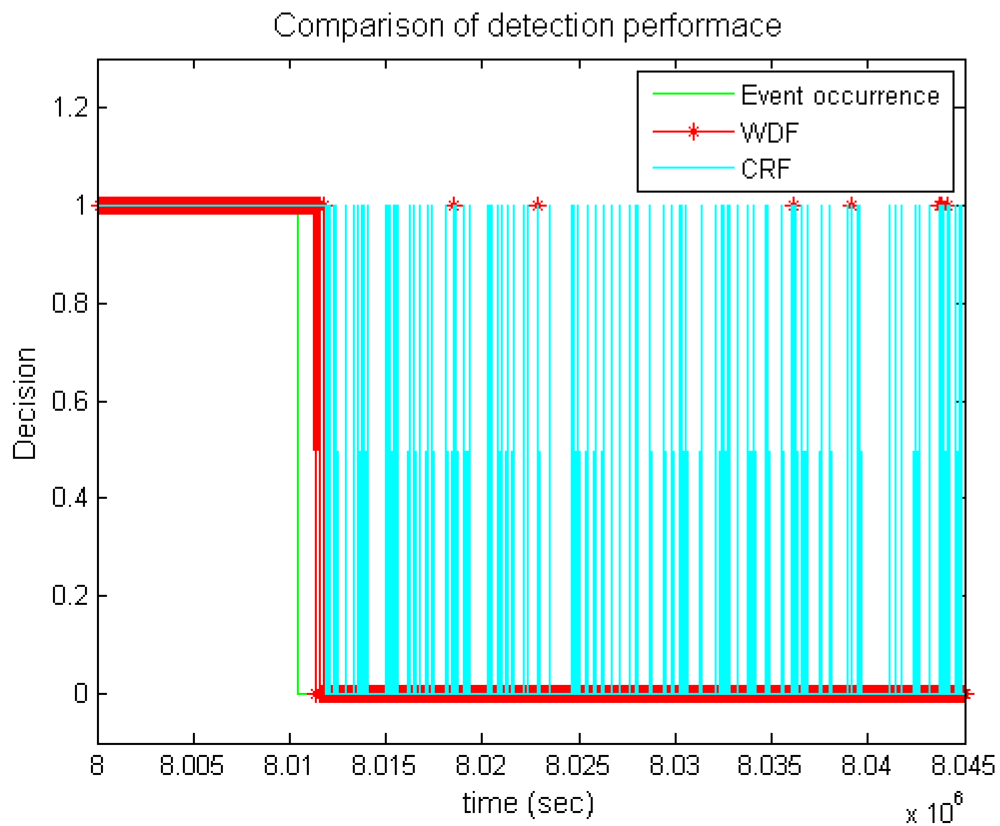
WDF in practice

- Comparison of detection performance in WDF and CRF

	CRF	WDF
P_F	0.07	0.0302
P_D	0.9363	0.9334

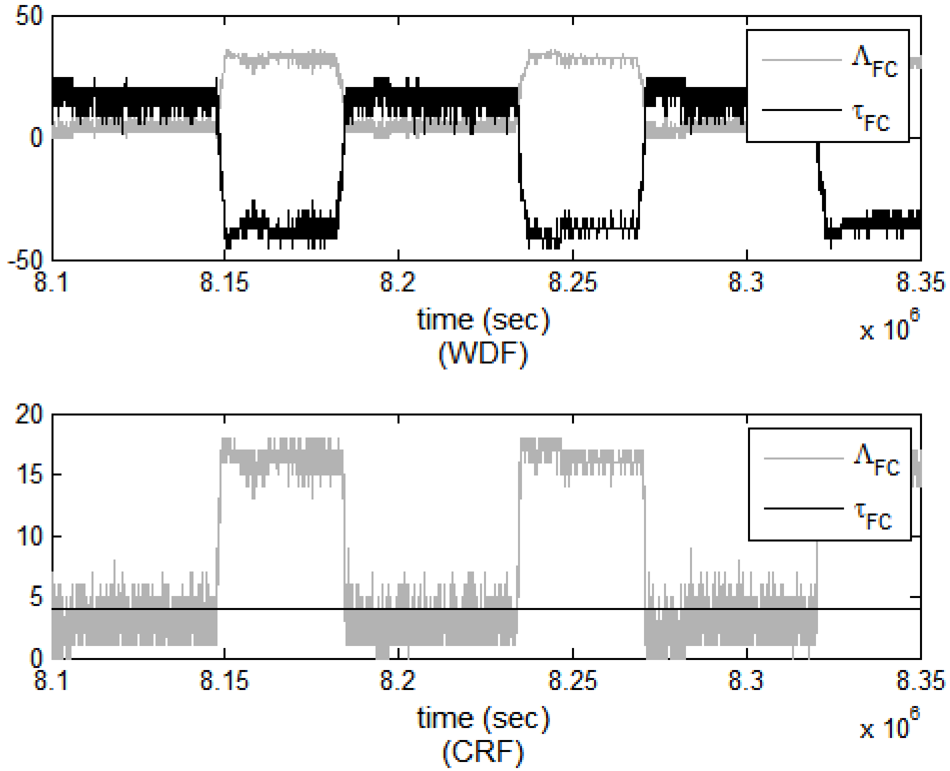
WDF in practice

- Comparison of decisions



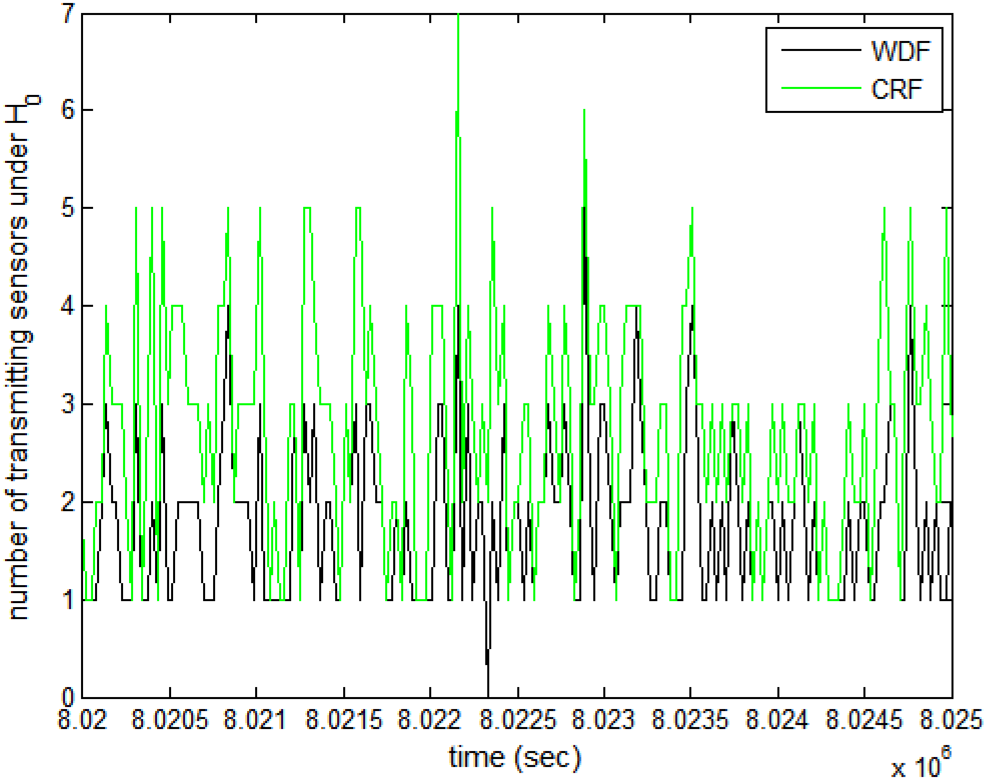
WDF in practice

- Comparison of hypothesis test at the FC



WDF in practice

- Comparison of number of transmitting sensors



Conclusion and future works

What are the contributions of this dissertation?

Which subjects would be more underscored?

Conclusion and future works

- Analysis results:
  - Assuming i.i.d. observations and negligible communication error, serial detection outperforms parallel detection
  - Serial detection results in more energy saving and less delay compared to multi-hop detection
  - Parallel detection outperforms serial detection when using simple fusion rules (AND, OR, …)
  - Serial OR detection outperforms serial AND detection

Conclusion and future works

- HDD:
  - Decision fusion may be carried out during transmission to the FC
  - More reliability in multi-hop WSNs
- WDF:
  - Weighting and adaptive fusion threshold improve detection performance
  - Transmission threshold lessens FA and energy
  - More reliability
  - Fits NP criterion

Conclusion and future works

- The contributions of this dissertation:
  - A novel clustering method ➔ *Wiley Int. J. Commun. Syst.*, vol. 26, no. 1, 2013.
  - A comprehensive survey on distributed detection literature and its classification ➔ publishable
  - Performance analysis of serial and parallel distributed detection ➔ *IET Signal Processing*, vol. 6, no. 8, 2012
  - Considering communication error and correlation effect in serial and parallel detection ➔ publishable
  - Weighted decision fusion ➔ submitted to *Elsevier Information Fusion*

Conclusion and future works

- Suggestions for future works:
  - Application-aware clustering methods
  - Combining LVDF and WDF
  - Temporal correlation of sensors and the FC decisions
  - Channel-aware distributed detection
  - Inference with correlated decisions
  - Multi-modal detection
  - Distributed detection in mobile ad-hoc networks

THANK YOU

- Any question?