Distributed target tracking under realistic network conditions

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www.eecs.qmul.ac.uk/~andrea/wise-mnet.html

Context

- Wireless Sensor Networks (**WSNs**)
  - networks of *autonomous* sensors used for *pervasive* applications
  - large-number deployments, highly scalable
  - resource-constrained
  - scalar data (e.g. temperature, light, pressure)

The way ahead...

- Wireless Multimedia Sensor Networks (**WMSNs**)
  - vectorial data (e.g. audio, video)
  - raw data cannot (always) be transferred
  - local processing is required (but much more complex!)

Application: multi-sensor tracking

- Objective

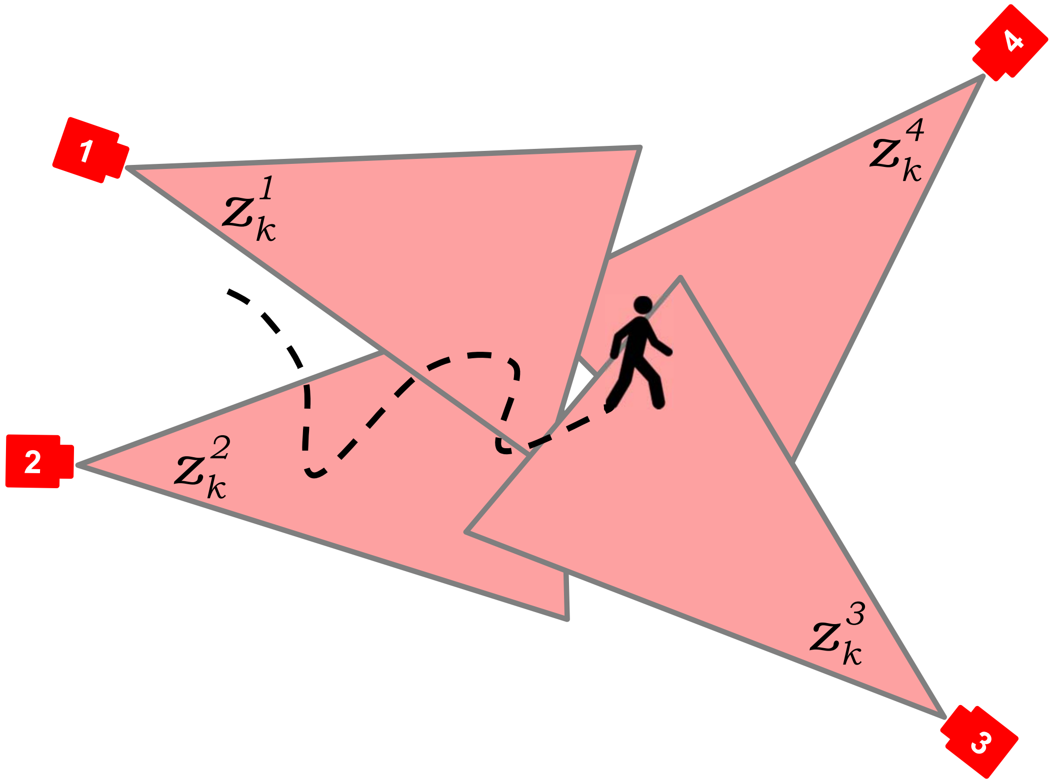
  Continuous *estimation* of the target state
  given a set of *measurements* (observations)
  obtained from spatially distributed sensing nodes.

$$Z_k = (z_k^1 \quad z_k^2 \quad \ldots \quad z_k^N)$$

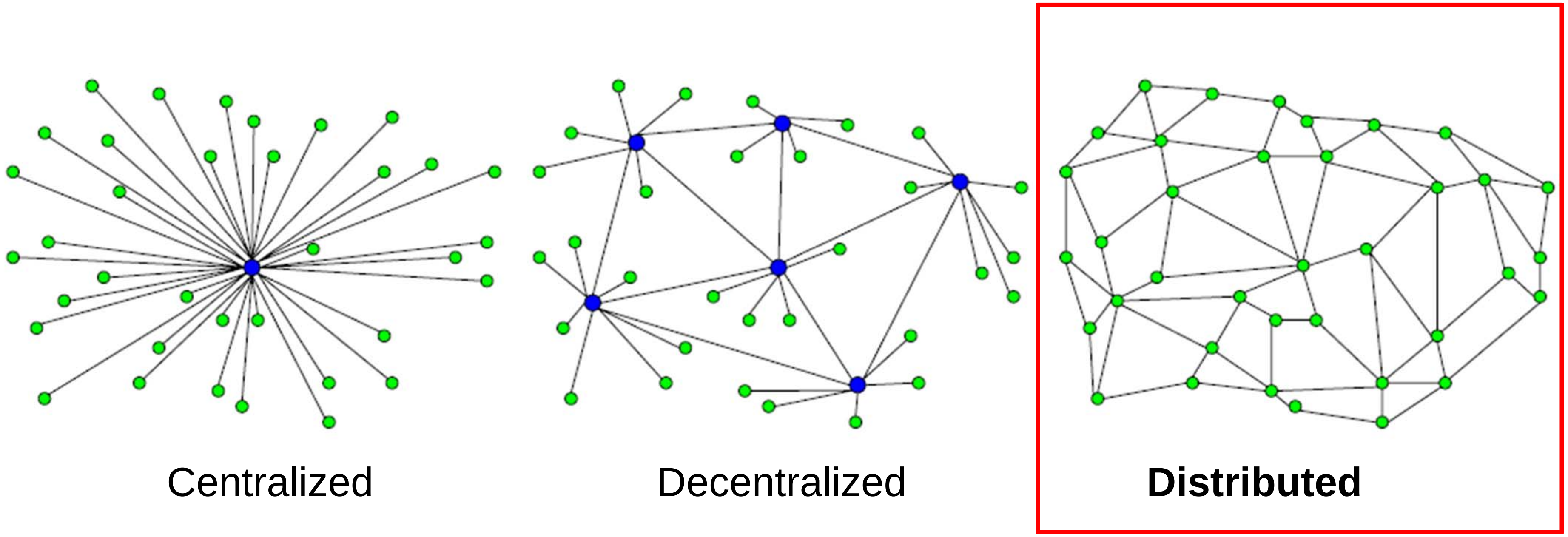
Measurements

$$x_k = f(Z_k, Z_{1:k-1}, x_{0:k-1})$$

State estimation



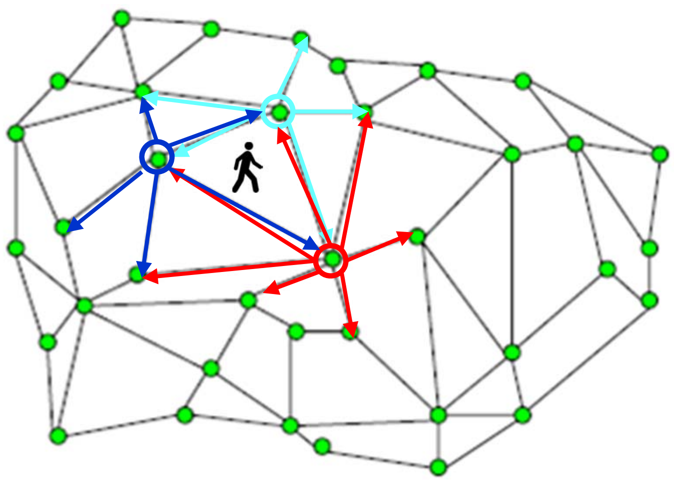
Approaches



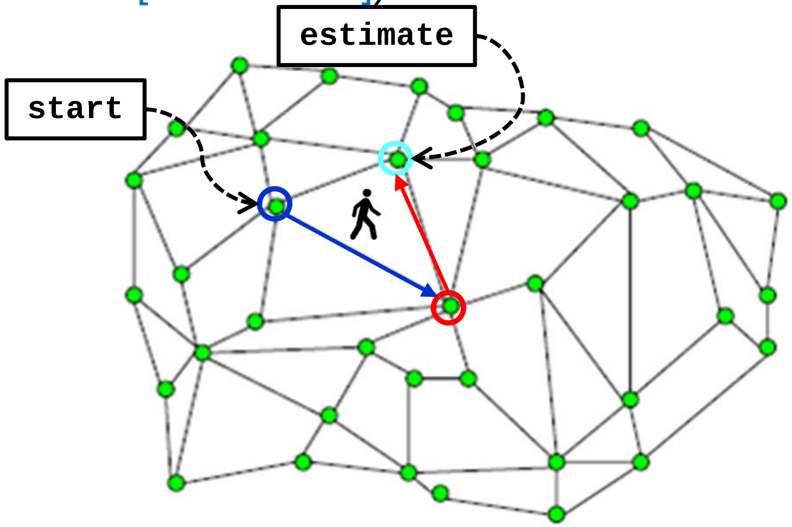
Distributed and decentralized multi-camera tracking
M. Taj, A. Cavallaro
IEEE Signal Processing Magazine, Vol. 28, Issue 3, May 2011

Distributed tracking: strategies

- Distributed target tracking
  - need a collaborative information exchange mechanism
  - consensus-based algorithms
    - Parallel (e.g. Kalman Consensus Filter [Olfati-Saber2005], Distributed Particle Filters [Gu2007])
  - data aggregation algorithms
    - Sequential (e.g. Distributed Particle Filters [Hlinka2009])



consensus



aggregation

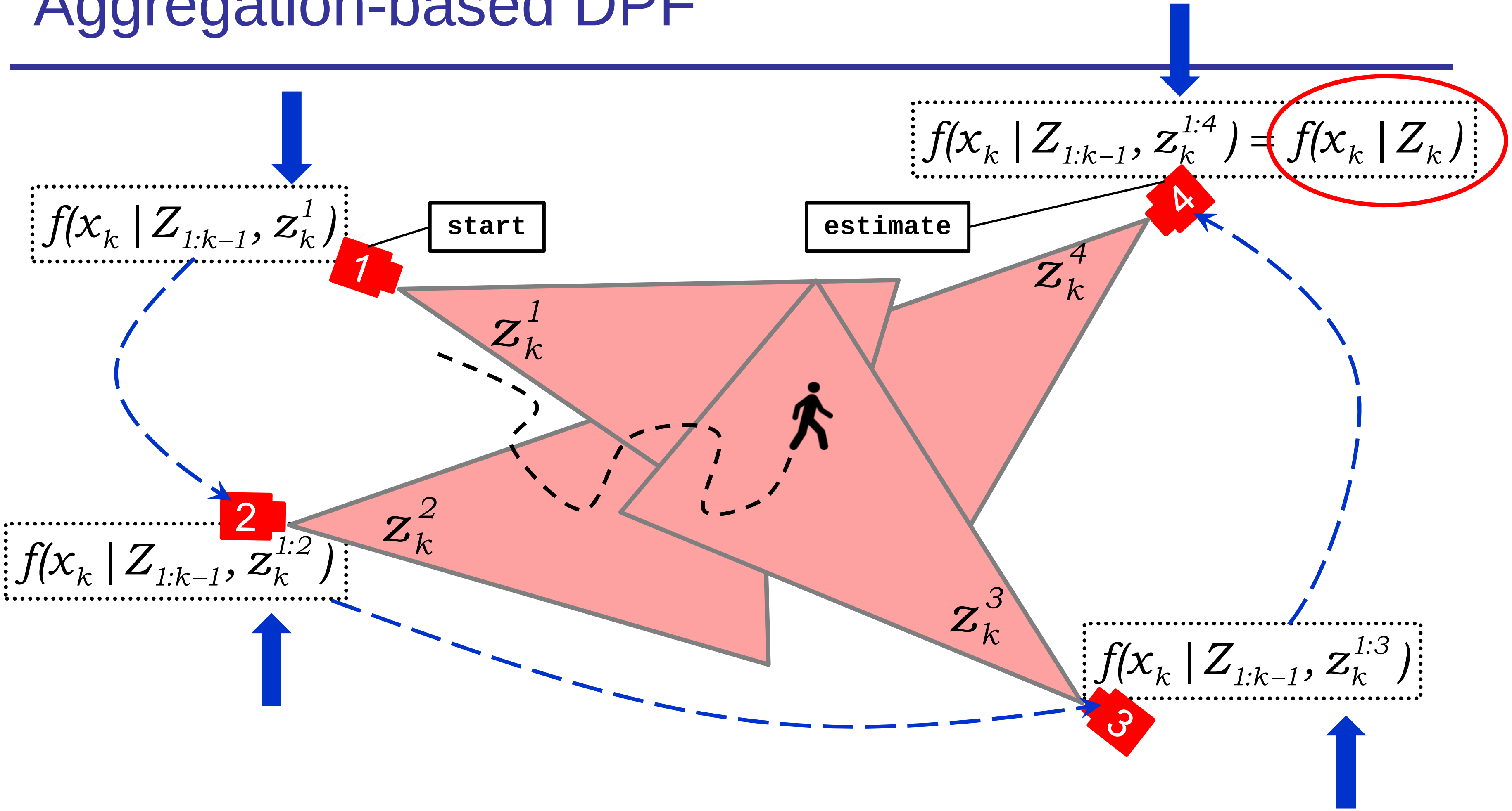
Distributed Particle Filters (DPFs)

- Basic ideas:
  - each node executes a local Particle Filter (PF)
  - measurements are synchronized, calibration is known
  - some information is exchanged

- Likelihood sharing [Coates2004]
  - exchange information to have a common model of the likelihood
  - random number generators are synchronized

- Posterior sharing
  - the network has a common knowledge of the posterior *pdf*
  - *consensus*-based approach [Sheng2005, Gu2007]
  - *aggregation*-based approach [Sheng2005, Hlinka2009]
    - spatial sequence of aggregation steps
    - Partial Posterior (PP) is exchanged among the nodes

Aggregation-based DPF



Problem: Particle dissemination is not feasible!

Solution: Gaussian Mixture Model of the Partial Posterior (GMM-PP)

Independence from the # of particles

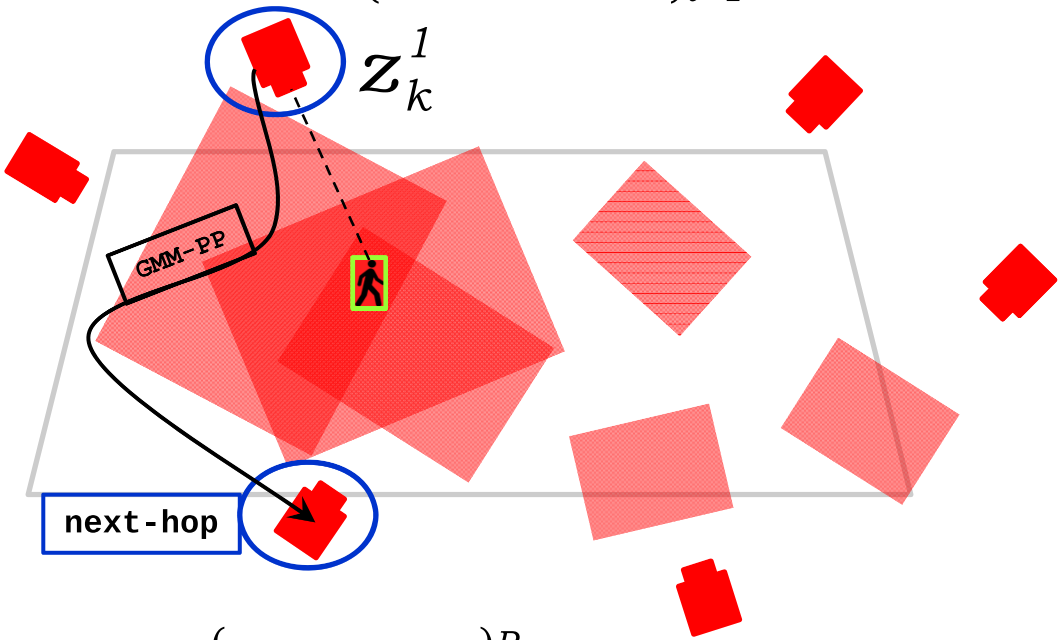
How to extend this tracking approach from WSNs to WMSNs?

Proposed approach

- Objective
  - Distributed tracking under realistic conditions in camera-based WMSNs
- Problems
  - existing approaches are theoretical and designed for WSNs
  - need adaptation for limited Field-Of-View sensors (cameras)
    - detection miss
    - target hand-over
    - target loss
  - need mechanisms for the definition of the aggregation chain
    - first node (starts iteration)
    - intermediate nodes (aggregate local measurement to the PP)
    - last node (performs estimation)
  - a network-simulator environment is required

First node

$$\left\{ x_{k-1}^{(i)}, w_{k-1}^{(i)} \right\}_{i=1}^{P}$$

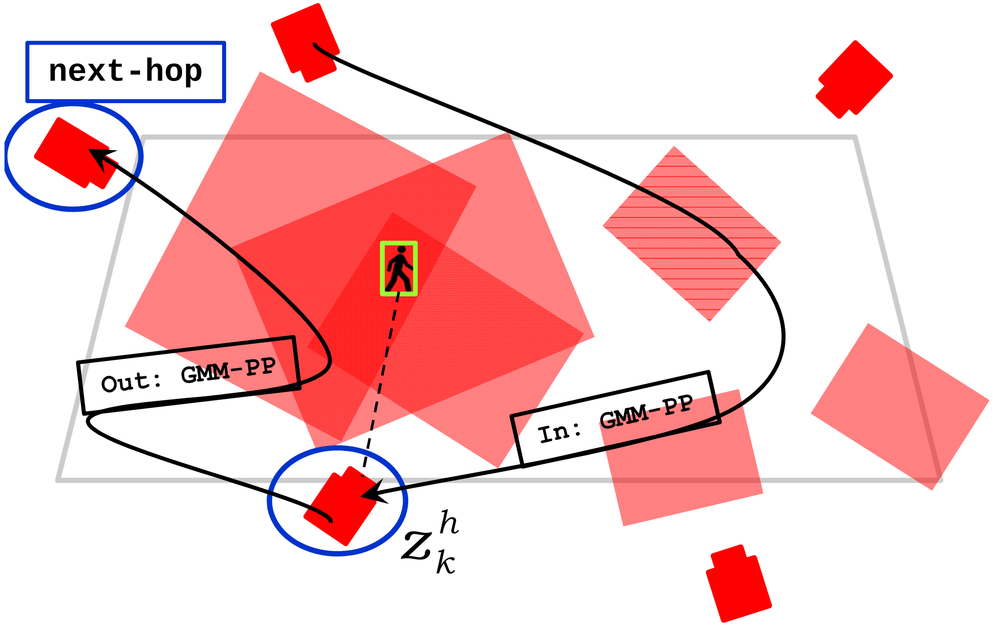


$$\left\{ \bar{x}_{k-1}^{(i)}, \bar{w}_{k-1}^{(i)} \right\}_{i=1}^{P}$$

$$\left.\begin{aligned} x_k^{(i)} &\sim f(x_k \mid \bar{x}_{k-1}^{(i)}) \quad \forall i = 1,\dots,P \\ w_k^{(i)} &= \frac{f(z_k^1 \mid x_k^{(i)})}{\sum_{j=1}^{P} f(z_k^1 \mid x_k^{(j)})} \quad \forall i = 1,\dots,P \end{aligned}\right\} \left\{ x_k^{(i)}, w_k^{(i)} \right\}_{i=1}^{P} \longrightarrow f_{GMM-PP}^{1}$$

1. Knows previous posterior and local measurement
2. Prediction and Update:
   - re-sampling
   - draw from state-transition
   - weight update from likelihood
3. GMM-PP creation
4. Next-hop selection
5. Sends GMM-PP

Intermediate node h



1. Receives PP from node h-1
2. Importance sampling:
   - use the incoming PP as importance function $g()$
   - draw from importance function
   - weight update: CONDENSATION
3. GMM-PP creation
4. Next-hop selection
5. Sends GMM-PP

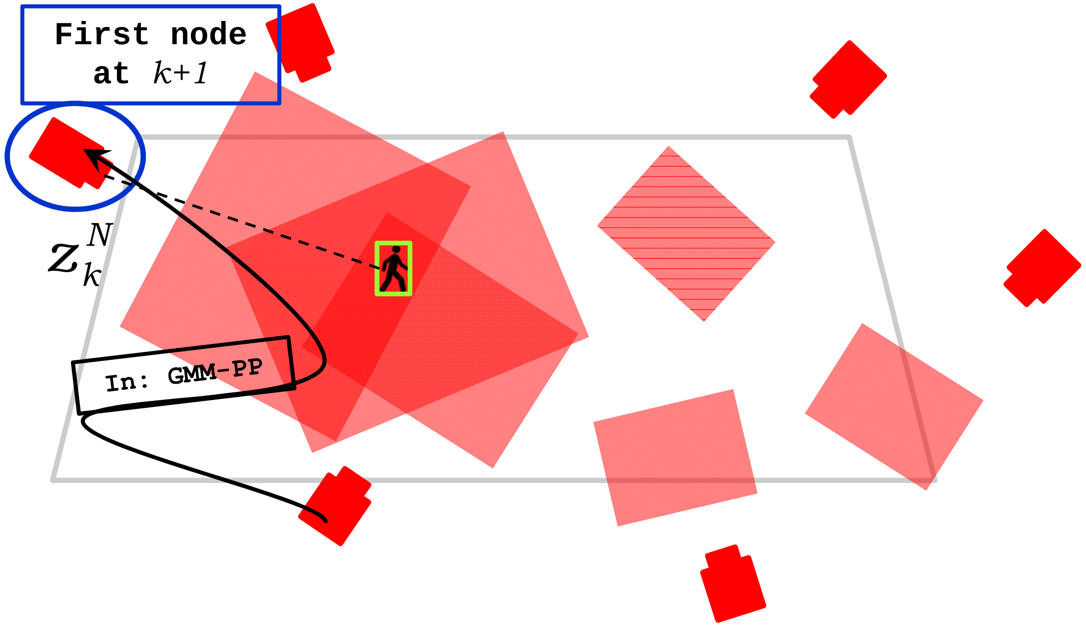
$$g(x_k) = f_{GMM\text{-}PP}^{1:h\text{-}1}(x_k \mid z_k^{1:h\text{-}1})$$

$$x_k^{(i)} \sim f_{GMM\text{-}PP}(x_k \mid z_k^{1:h\text{-}1}) \quad \forall i = 1,\dots,P$$

$$w_k^{(i)} = \frac{f(z_k^h \mid x_k^{(i)})}{\sum_{j=1}^{P} f(z_k^h \mid x_k^{(j)})} \quad \forall i = 1,\dots,P$$

$$\left\{ x_{k\text{-}1}^{(i)}, w_{k\text{-}1}^{(i)} \right\}_{i=1}^{P} \longrightarrow f_{GMM\text{-}PP}^{1:h}$$

Last node



1. Receives PP from node N-1
2. Importance sampling as for intermediate nodes
3. Last PP is also the global PP
4. Target state estimation
5. *Next tracking step starts here!*

After importance sampling: $f_{PP}^{1:N} = f(x_k \mid Z_k)$

Estimation: $\hat{x}_k = \sum_{i=1}^{P} w_k^{(i)} \cdot x_k^{(i)}$

Experimental setups

- Simulations
  - number of nodes: N = 10, 50, 100, 300, 500, 700, 1000
  - number of particles: P = 100, 300, 500

  - DPF with different GMM configurations
    - No GMM approximation: *DPF-0*
    - Variable number of GMM components: *DPF-1*, *DPF-5*

  - realistic network conditions

Simulator: *WiSE-MNet* **www.eecs.qmul.ac.uk/~andrea/wise-mnet.html**

Simulation setup

- Network
  - T-MAC protocol, BW = 250 kbps
  - request-to-send/clear-to-send mechanism
  - acknowledged-transmission mechanism
  - number of retransmissions: 10
- Cameras
  - Covering 6000 sqm (random uniform distribution)
  - Top-down facing cameras: 6m from the ground plane (FOV is 10m X 6m)
  - Frame rate = 1fps
- 100 simulation runs, each of 10 minutes

What do we measure?

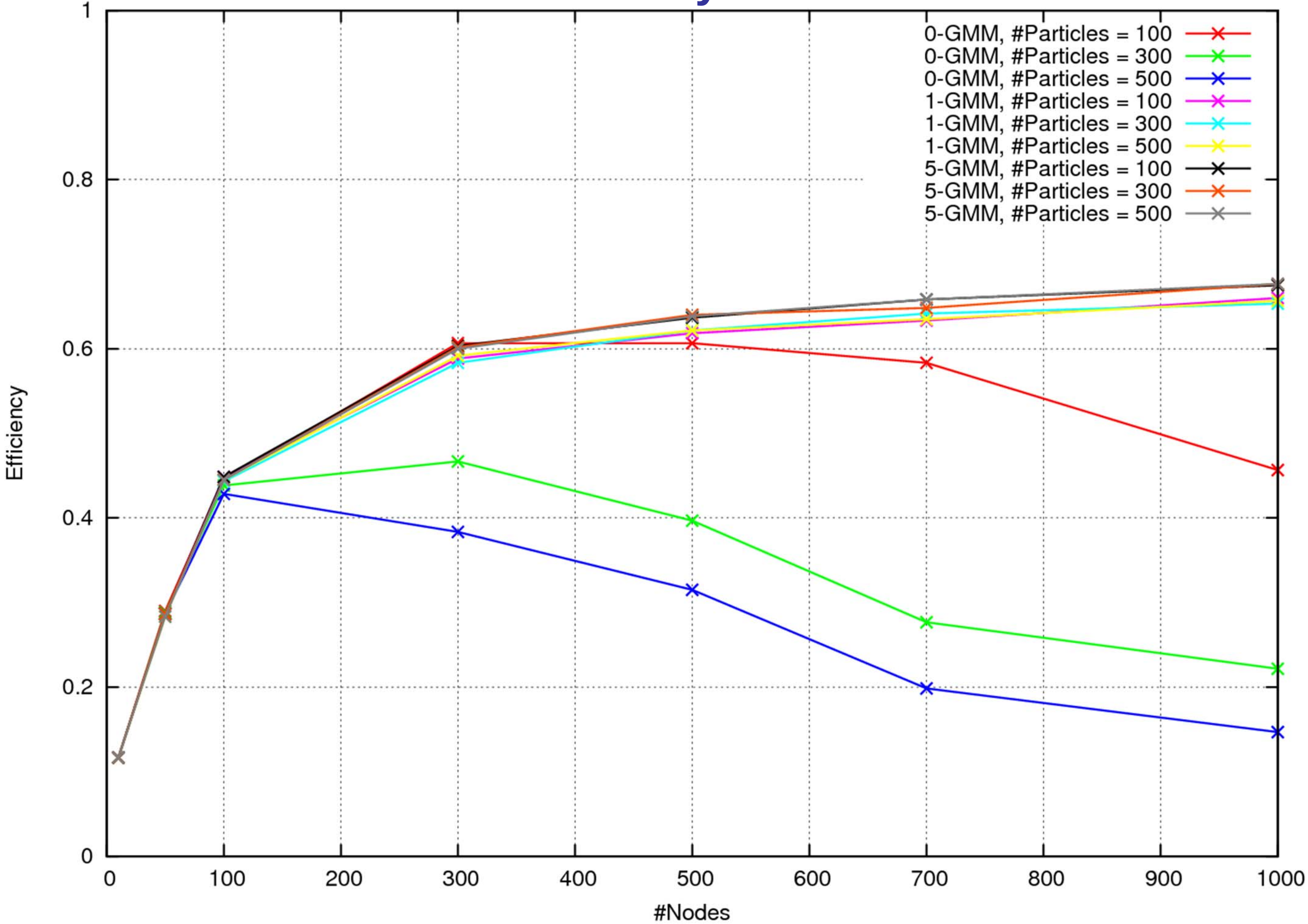
- Estimation efficiency $$\boxed{E = \frac{K_{tr}}{K}}$$

  K_{tr} # of estimations (detected events)
  K # of observations (all the events)

- Average estimation delay $$\boxed{\overline{D} = \frac{1}{K_{tr}} \sum_{i=1}^{K_{tr}} d(k)}$$

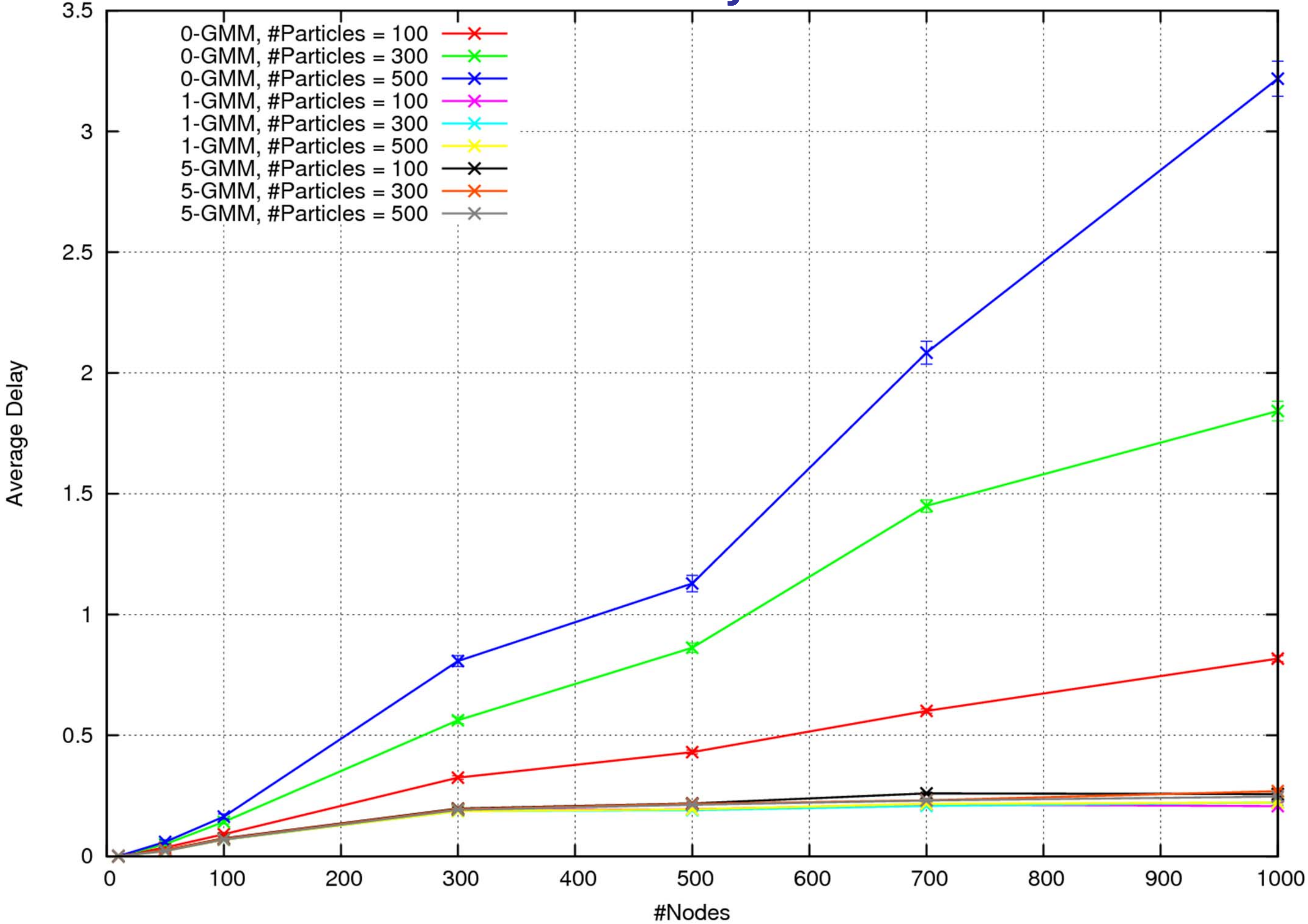
  $d(k)$: Estimation delay for the k-th tracking step

Efficiency



0-GMM, #Particles = 100
0-GMM, #Particles = 300
0-GMM, #Particles = 500
1-GMM, #Particles = 100
1-GMM, #Particles = 300
1-GMM, #Particles = 500
5-GMM, #Particles = 100
5-GMM, #Particles = 300
5-GMM, #Particles = 500
Efficiency
#Nodes
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
700
800
900
1000

Network Delay



Conclusions

- Conclusions
  - distributed target tracking for camera-based WMSNs with a DPF
    - Dealing with limited-FOV sensors
    - Operating on a network-simulator environment
  - importance of co-design between tracking algorithms and communication protocols

Simulator available as open source at
www.eecs.qmul.ac.uk/~andrea/wise-mnet.html

- Future work
  - Comparing other state-of-the-art protocols (e.g. consensus-based)
  - Using the full vision-pipeline: more complex features