Scuola Superiore
Sant'Anna

Distributed Video Signal Processing for Wireless Multimedia Sensor Networks

PhD Defence

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Retis
Real-Time Systems Laboratory

Outline

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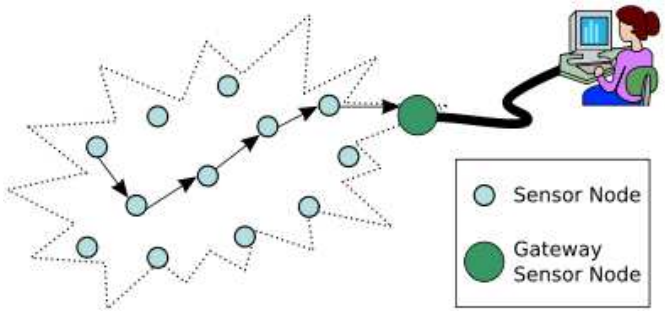
Wireless Sensor Networks

Networks of *autonomous* sensors specifically designed for *pervasive* applications.

- *autonomy*: sensing, computation, communication and self-powered
- *pervasiveness*: self-configurability, high scalability



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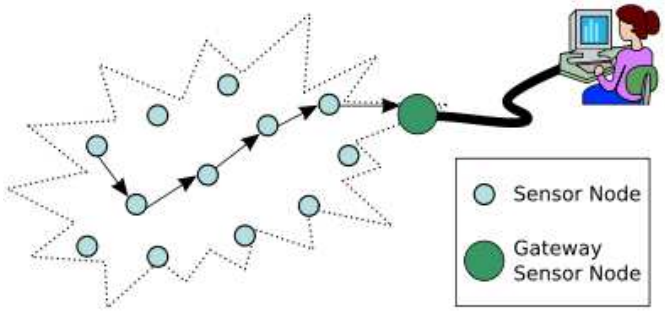
  - absolutely cheap nodes
  - thus scarce resources are available



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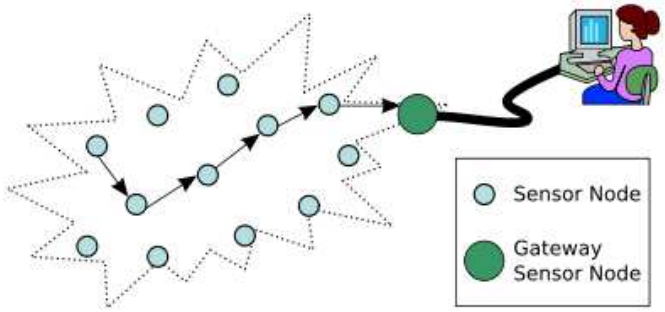


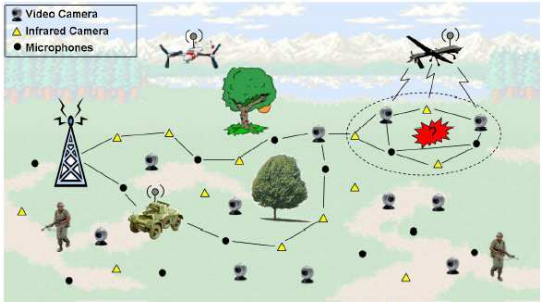
Typically... Scalar data (e.g. light, temperature, humidity)

Wireless Multimedia Sensor Networks

The way ahead... *Wireless Multimedia Sensor Networks*

Vectorial data (e.g. audio, **video**)

- high degree of information
- high volume of data...



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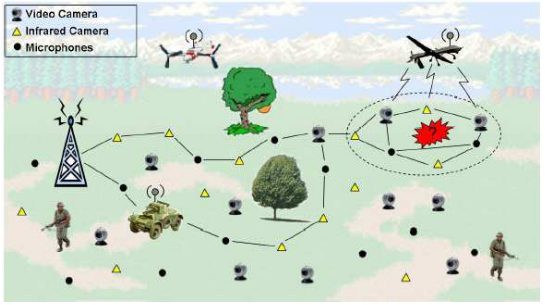

Challenges:

- Raw data cannot (always) be transfered
- Local processing required, but much more complex!

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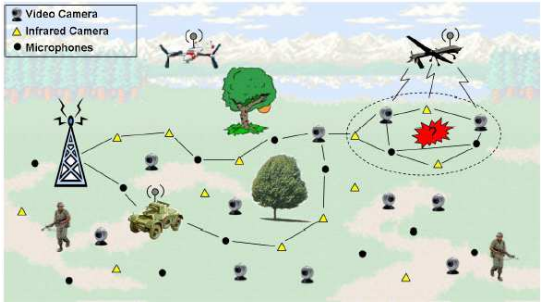

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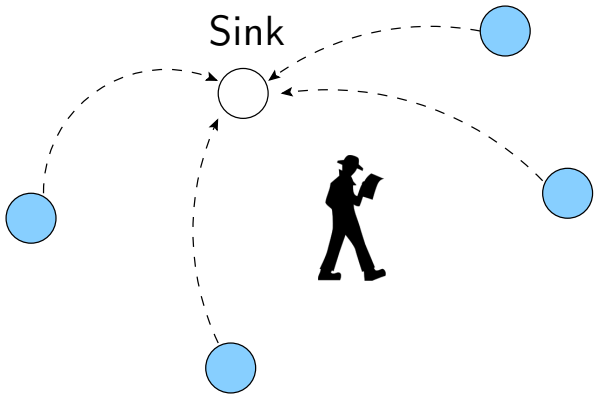
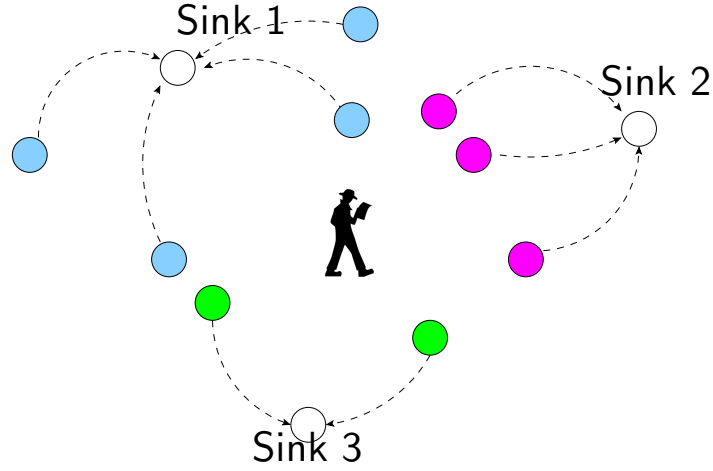
Two main research fields:

- streaming: transferring multimedia information
- **in-network processing**: making decision in the network

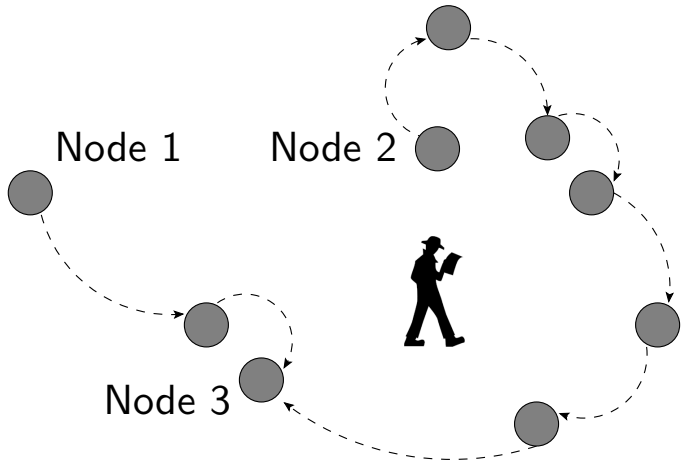
In-Network Processing



(a) Centralized



(b) Decentralized



(c) Distributed

Motivations

Why video sensors?

Motivations

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- Versatility

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Why WMSNs?

Motivations

Why video sensors?

- Versatility

Why WMSNs?

- Large-scale deployments (thus coverage of large areas)
- Solve occlusion problems
- Fault-tolerance w.r.t. single-node failure
- Sensors diversity could be exploited

A Multi-Disciplinary Problem

WMSNs involve several disciplines...

- Networking (e.g timeliness, reliability, scalability)
- Signal Processing (e.g. cooperative algorithms)
- Computer Vision (e.g. light-weight algorithms)
- Embedded Systems Design
- ...

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Two fundamental approaches:

- **Simulation**: an integrated environment is necessary
- **Testbeds**: make things work in real cases!

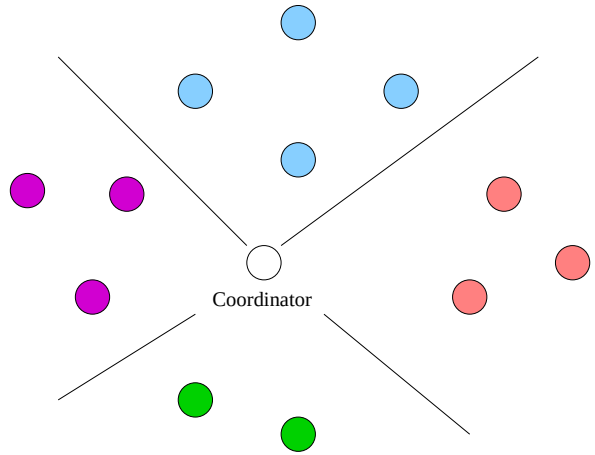
Outline

Application-Aware QoS

Bandwidth Allocation for Content-based Context-Aware Real-time ApplicaTions [NMS+10]

Scenario:

- redundancy of information
- real-time communication on top of the IEEE 802.15.4 with Guaranteed Time Slots (GTSs)



Basic Idea:

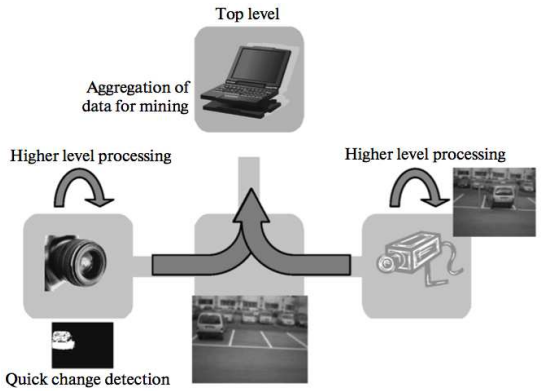
- Flow classification: *Guaranteed* and *Residual*
- EDF-like bandwidth allocation for Guaranteed flows
- Residual flows scheduled according to application requirements
- On-line real-time servers for temporal isolation

Extension to the network layer (cluster-tree) [SCN+10]

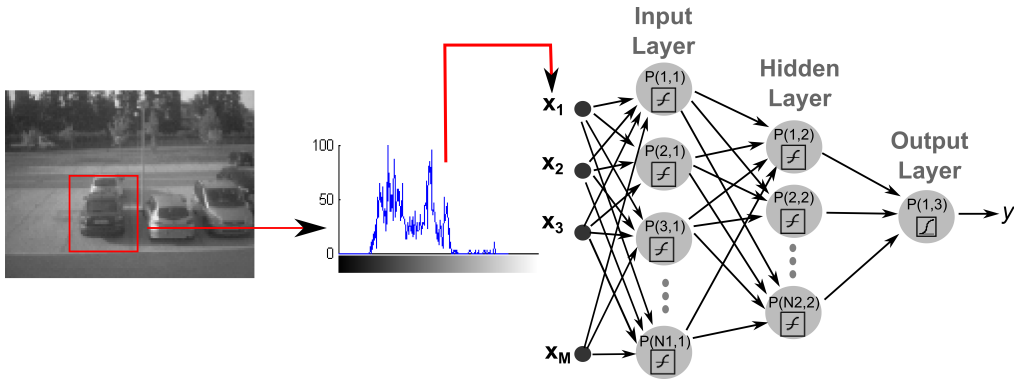
Local Processing

Image mining for monitoring applications: two approaches

- A multi-tier approach [MMN+11]
  - Fast change detection algorithm
  - Cascade of classifiers

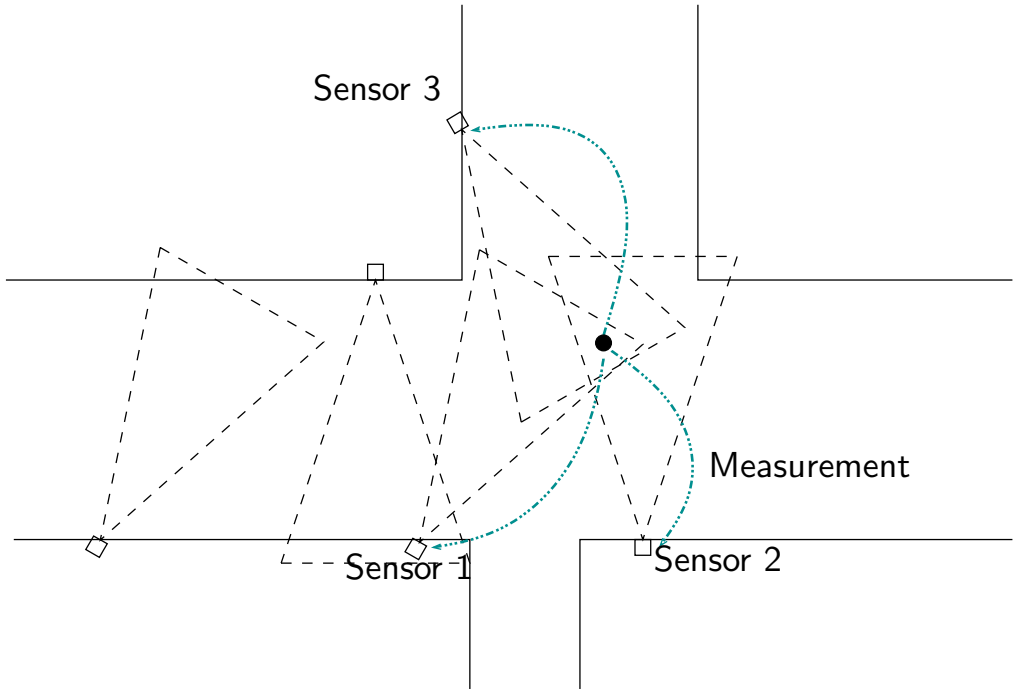


- A Neural Network approach



Distributed Processing

Distributed target tracking under realistic network conditions [NC11a]



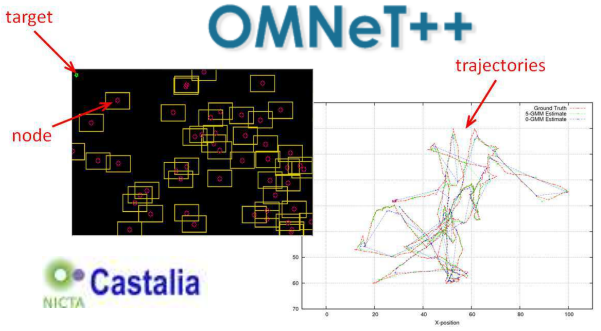
Multi-Sensor Tracking

- Bayesian formulation: *Distributed Particle Filter*
- Formulation for camera-based WMSNs
- Simulative approach: network simulator

Tools and Platforms

WiSE-MNet: an experimental environment for wireless multimedia sensor networks [NC11b]

- Based on OMNeT++ and Castalia
- Extension to support Multimedia Sensors
- Modular architecture: flexibility and extensibility

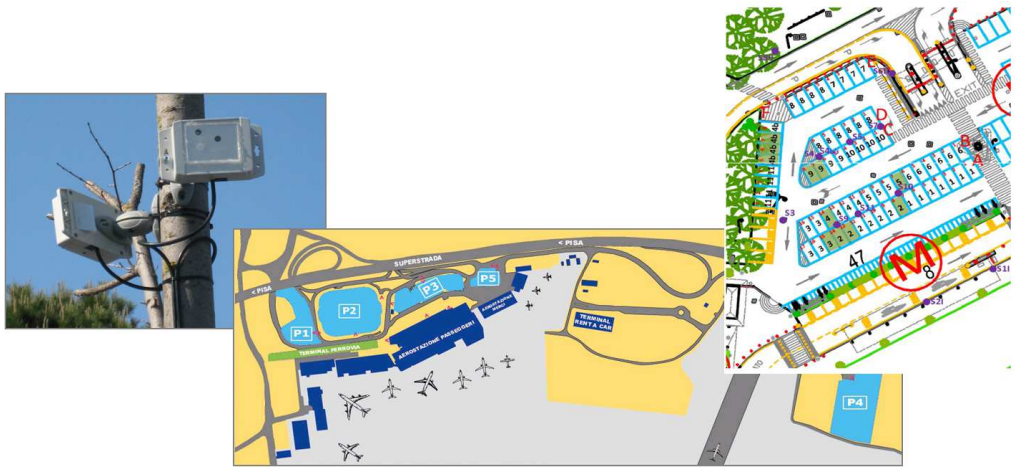


SeedEye: a camera-based platform for WMSNs

- Porting ERIKA RTOS to the PIC32 architecture
- uWireless: a portable light-weight IEEE 802.15.4 compliant stack
- uCV: a light-weight computer vision library for micro-controllers

Real Testbed

- IPERMOB: Regional project (3.3 MEur total cost, 670 KEur SSSA)
- Infrastructure to control Urban Mobility in Real-Time
- The testbed at the Pisa International Airport:
  - Parking lots occupancy
  - Traffic flow measurement

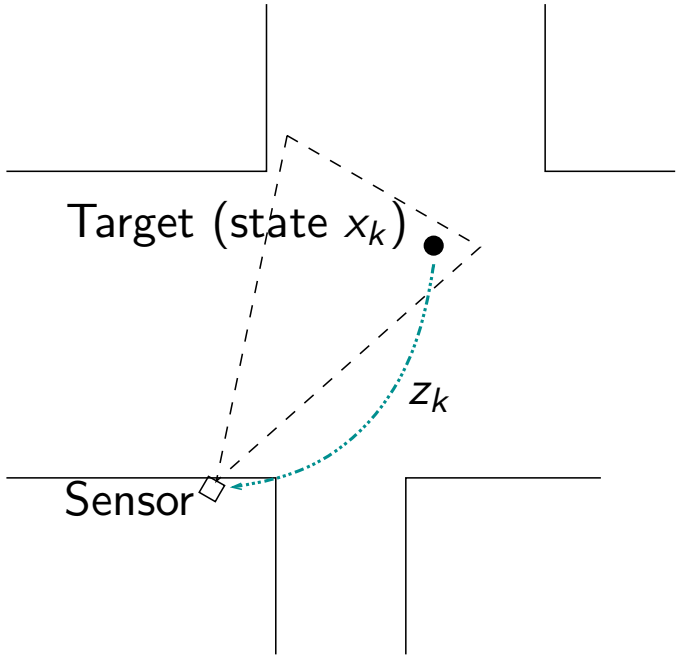


Outline

Problem Formulation

x_k Unknown State of the target at time k

z_k Noisy Measurement of the target at time k



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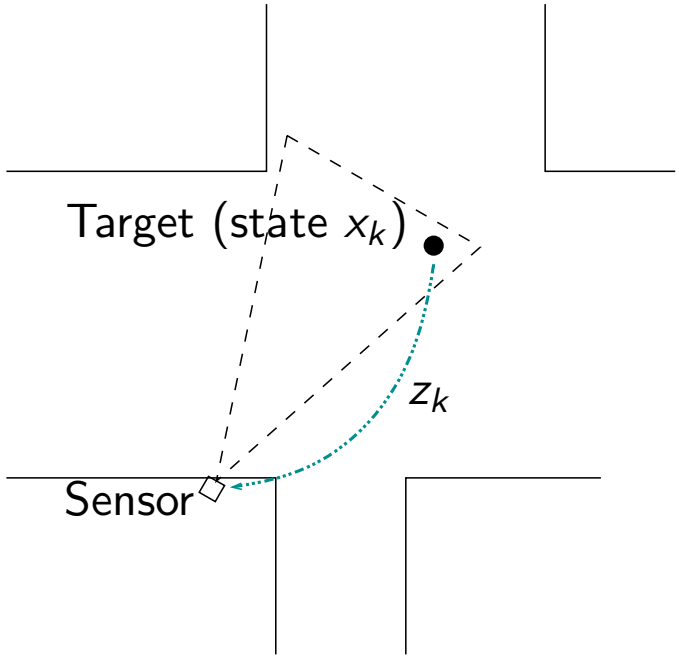
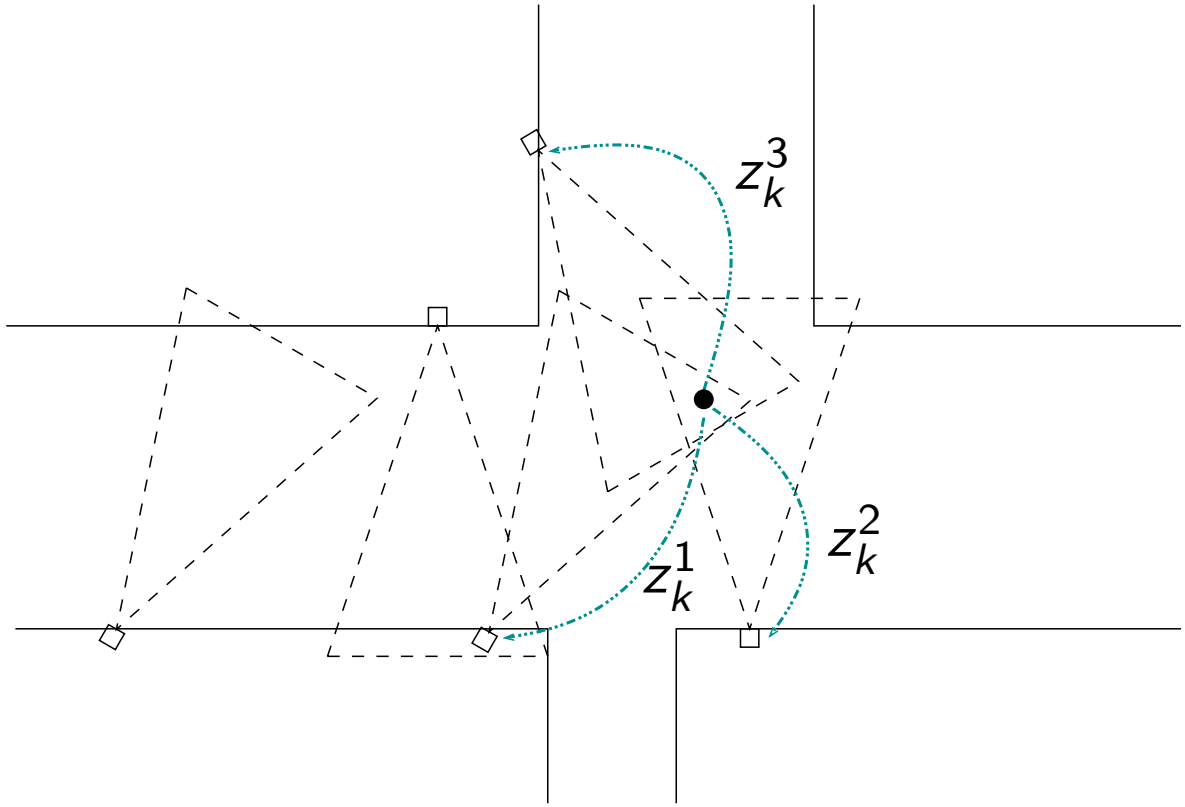


Aim: Continuous *estimation* of a target state given a sequence of noisy obeservations or *measurements* of the state.

Multi-Sensor Tracking

Measurements obtained by spatially distributed sensors



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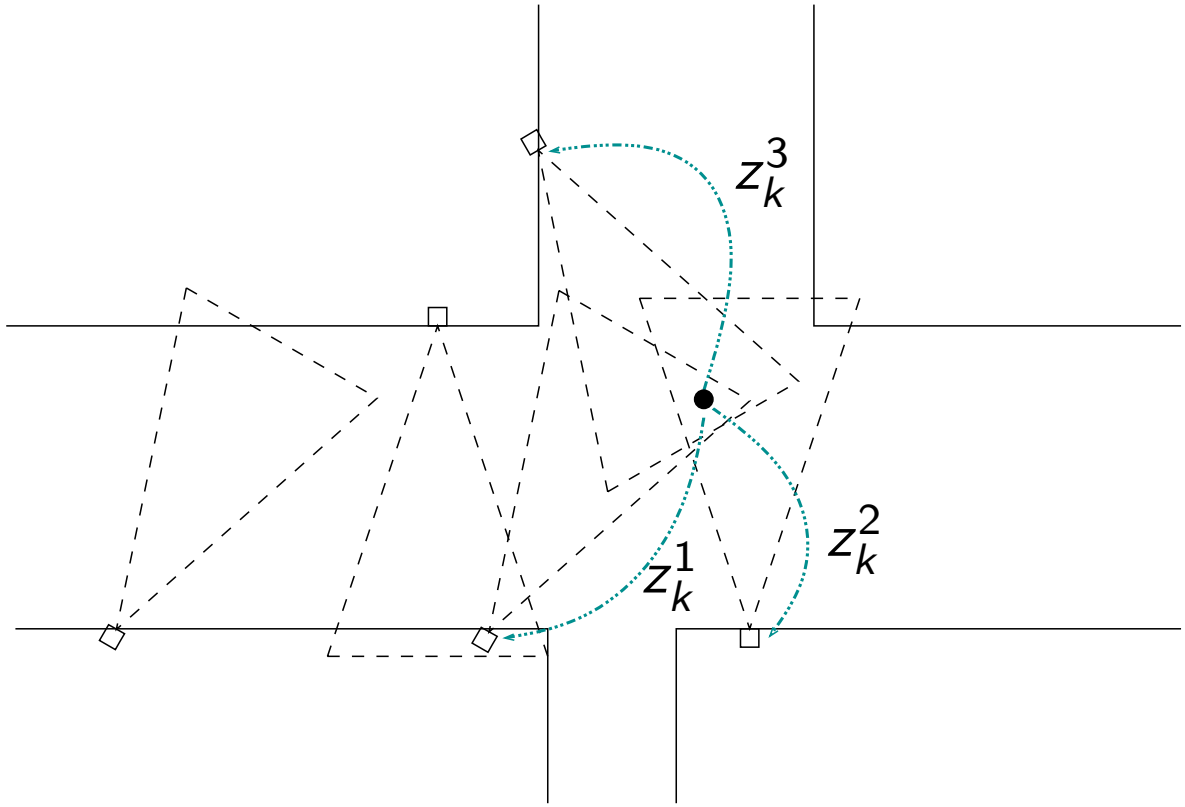

Measurement Vector: $z_k = \{z_k^1, z_k^2, z_k^3\}$

Bayesian Filtering

State Transition:

$$x_k = F_k(x_{k-1}, v_{k-1})$$

$F_k(\cdot)$	State transition function
x_{k-1}	Previous state of the target
v_{k-1}	Sequence of process noise generally non-Gaussian

Measurement:

$$z_k = H_k(x_k, n_k)$$

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Bayesian formulation: using Probability Density Functions

- $F_k \mapsto p(x_k|x_{k-1})$ Transition PDF
- $H_k \mapsto p(z_k|x_k)$ Likelihood PDF

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Aim: estimation of the *posterior* PDF $p(x_k|z_{1:k})$

Bayesian Filtering

Prediction:

$$p(x_k|z_{1:k-1}) = \int p(x_k|x_{k-1})p(x_{k-1}|z_{1:k-1})dx_{k-1}$$

Update (filtering):

$$p(x_k|z_{1:k}) = \frac{p(z_k|x_k)p(x_{k-1}|z_{1:k-1})}{p(z_k|z_{1:k-1})}$$

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Notice: the Bayesian recursion is a general conceptual solution

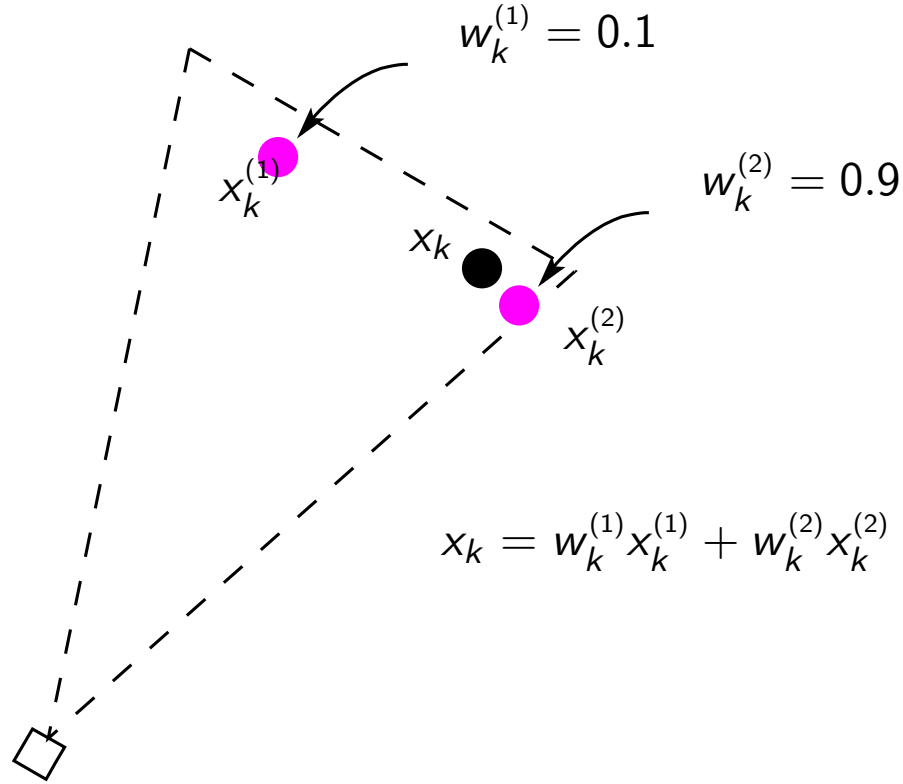
- Optimal solutions: available under linearity and Gaussianity assumption (i.e. Kalman Filter)
- Approximations: among the others, **Particle Filter**

Particle Filter

Idea: approximate a PDF with a set of samples extracted from it (Sequential Monte Carlo Method)

$x_k^{(i)}$ Particle: possible state of the target;

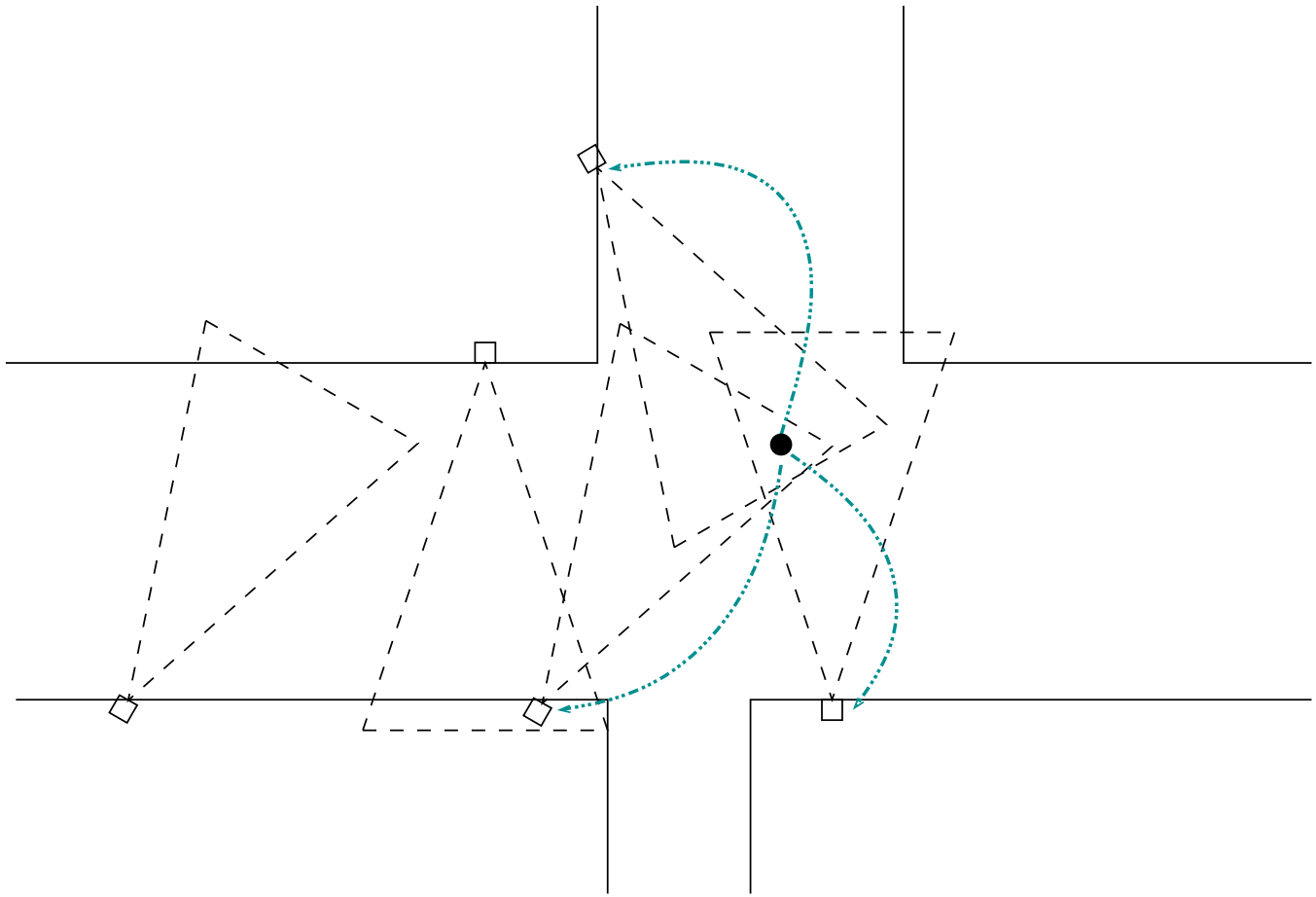
$w_k^{(i)}$ Weight: plausibility of the particle



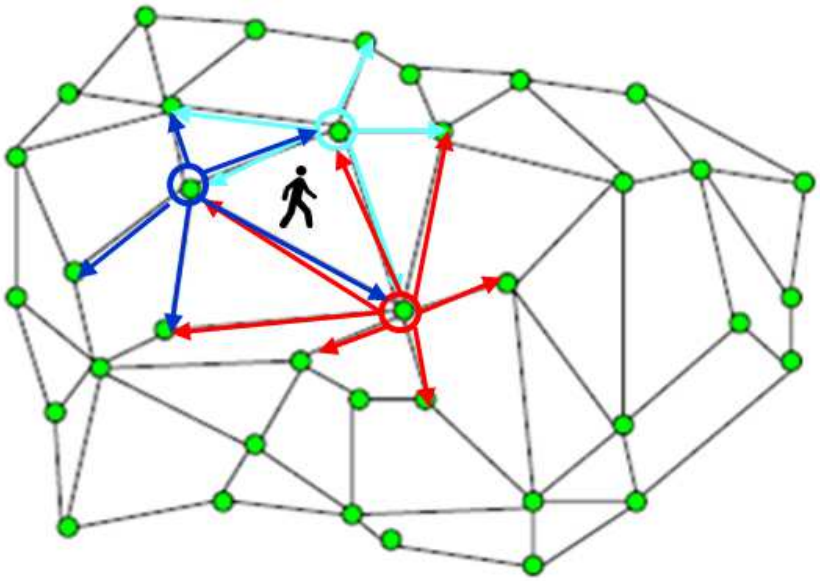
$$p(x_k|z_{1:k}) \approx \sum_{i=1}^{P} w_k^{(i)} \delta(x_k - x_k^{(i)})$$

Distributed Particle Filtering

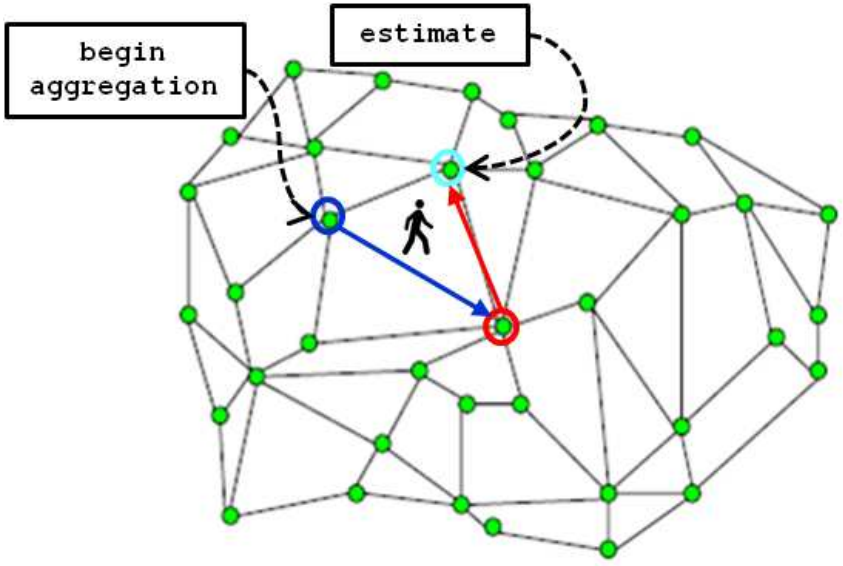
Our Focus: Distributed Tracking



Approaches for DPF



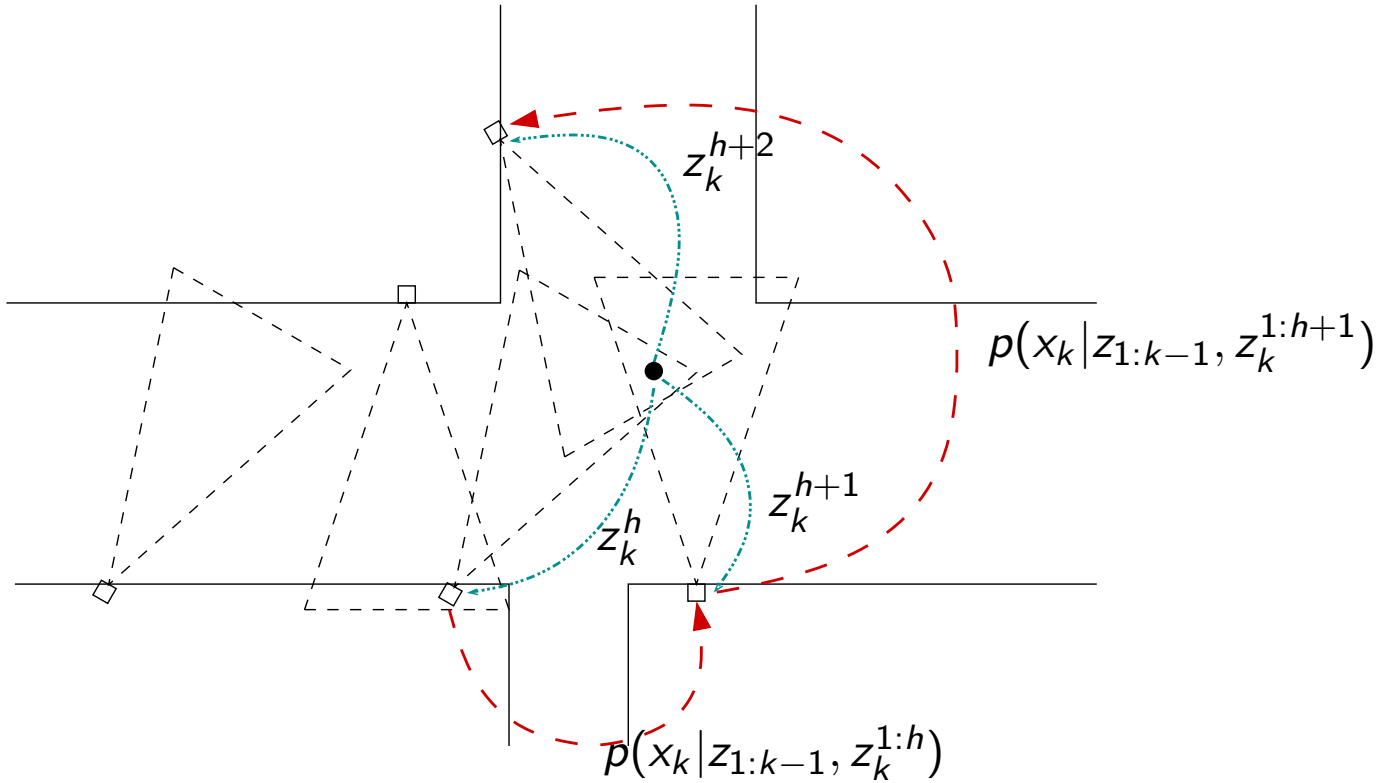
Consensus-based



Aggregation-based

Proposed solution

Sequential (spatially) refinement of the posterior PDF: *Partial Posterior* (PP);



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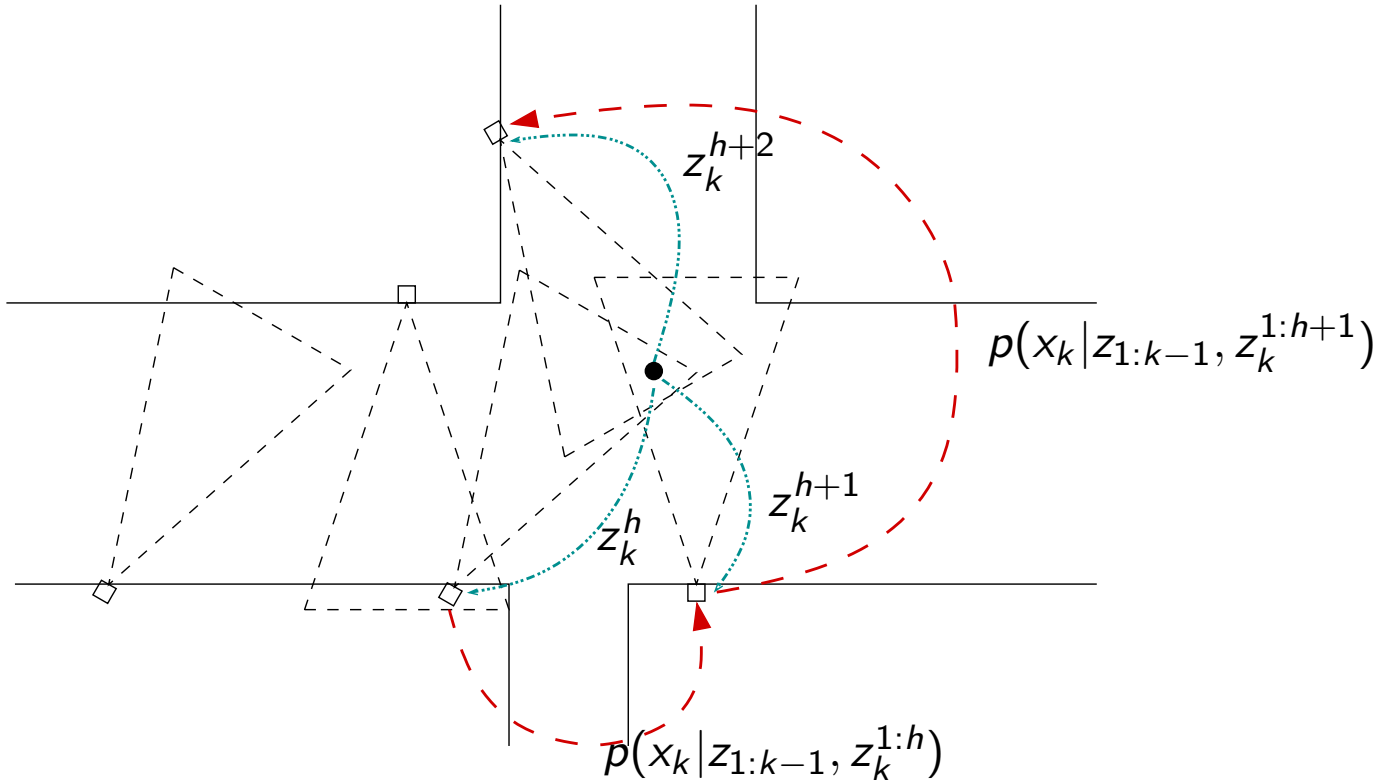
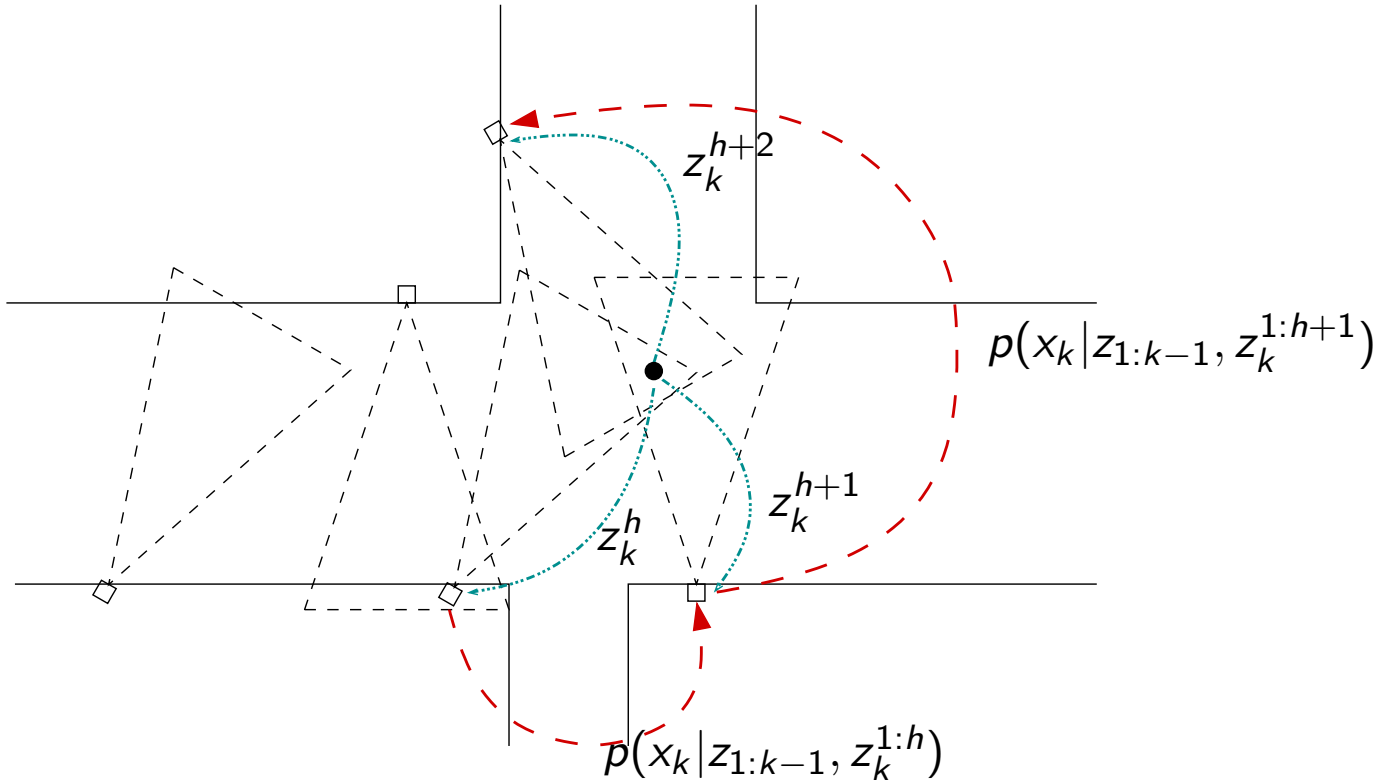


- Problem: Particle dissemination

Proposed solution

Sequential (spatially) refinement of the posterior PDF: *Partial Posterior* (PP);



- Problem: Particle dissemination
- Solution: Guassian Mixture Model to approximate PP

Proposed solution

Realistic conditions in camera-based WMSNs

Problems addressed:

- mechanisms to be defined for aggregation chain: first-node and next-hop selection
- need adaptation for limited Field-Of-View sensors (cameras):
  - detection miss
  - target hand-over
  - target loss
- network-simulator environment is required
- simplistic model for target
  - detection algorithm neglected (target as bounding box)
  - different type of motion (e.g. linear, random)

Simulation setup

Simulations

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

Network

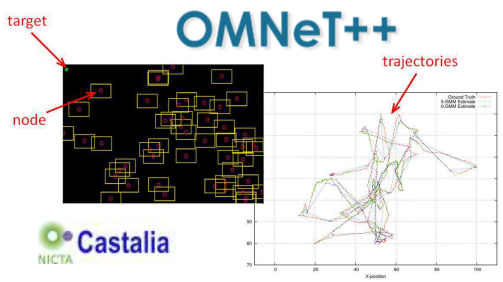
- T-MAC protocol, BW = 250 kbps
- request-to-send/clear-to-send mechanism
- acknowledged-transmission mechanism
- number of retransmissions: 10

Different GMM configurations

- No GMM approximation: DPF-0
- Variable number of GMM components: DPF-1, DPF-5

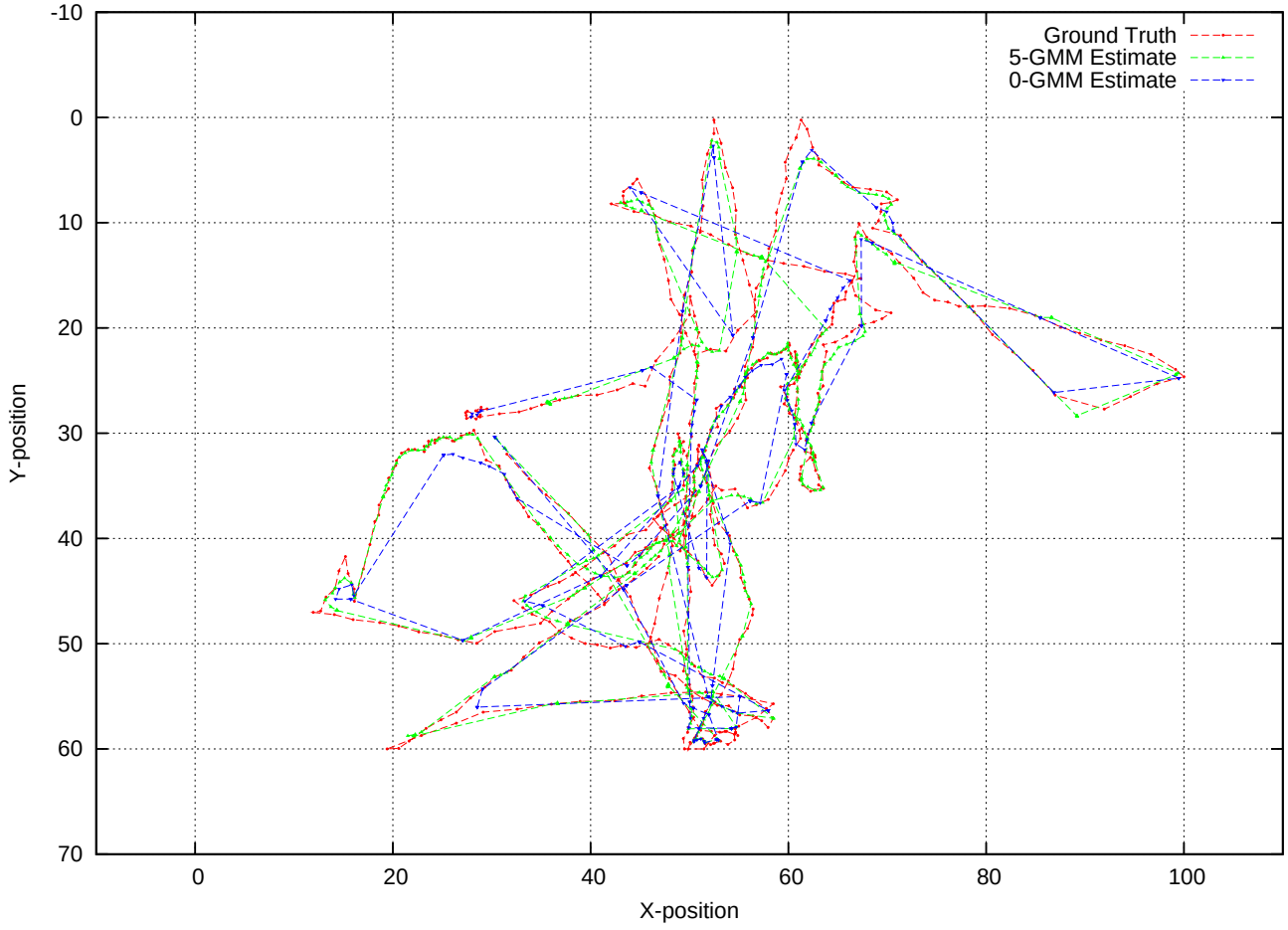
Cameras

- Covering 6000 sqm (random uniform distribution)
- Top-down facing cameras: 6m from the ground plane (FOV is 10m X 6m)
- Frame rate = 1fps



Results

Example of simulation run



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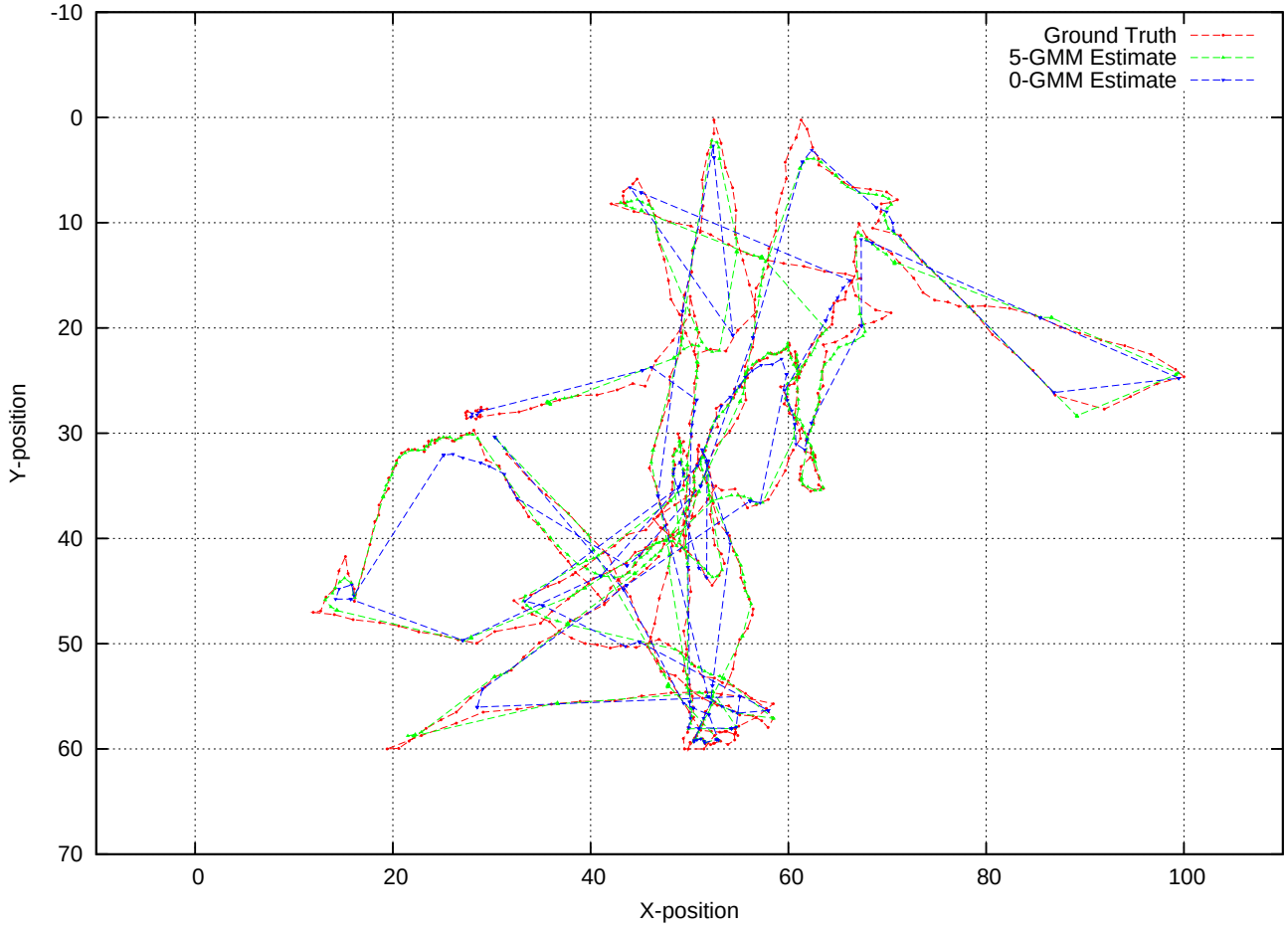
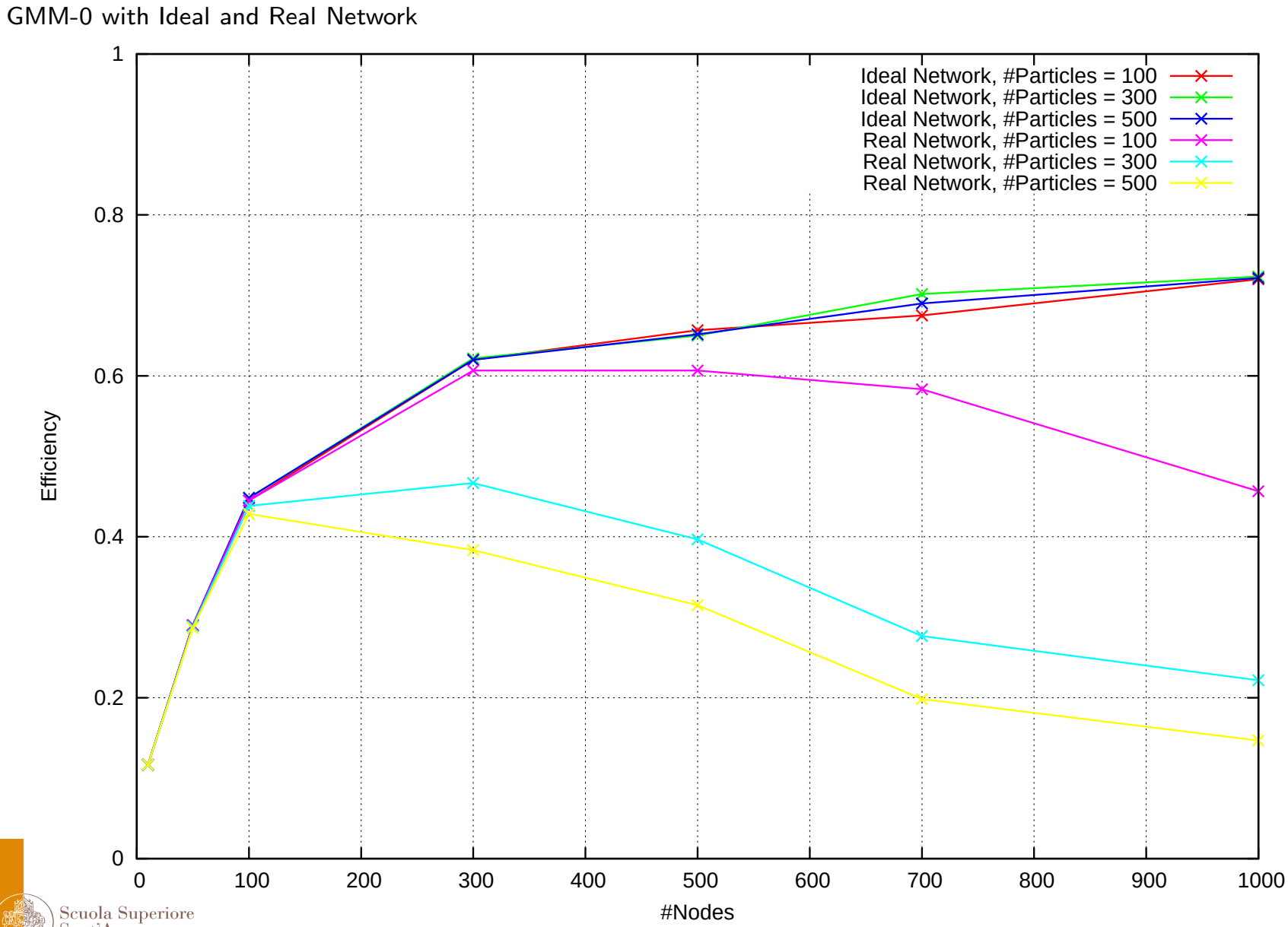
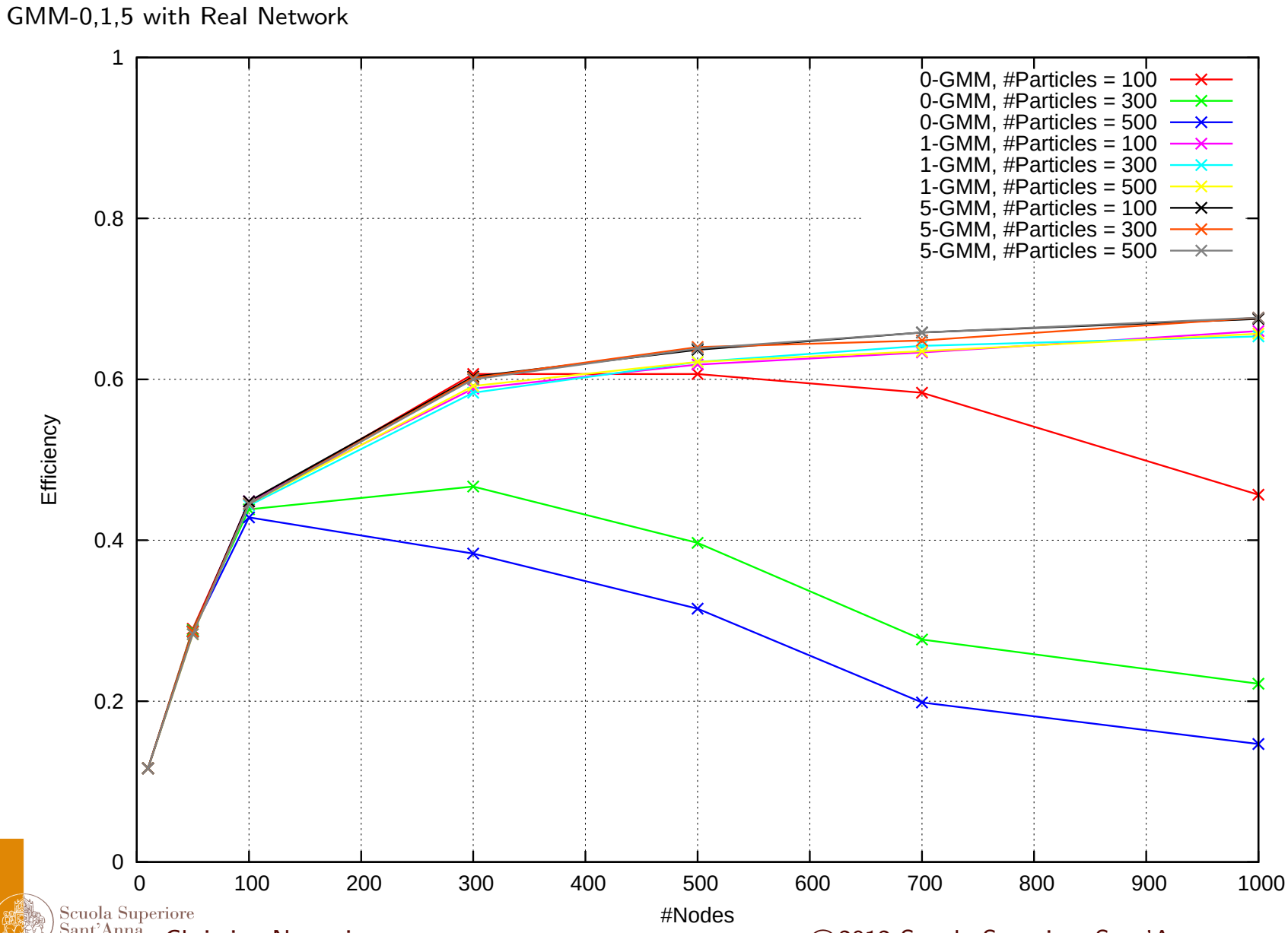


- Estimation Efficiency: $\#Estimations/\#Observations$
- Average Estimation Delay

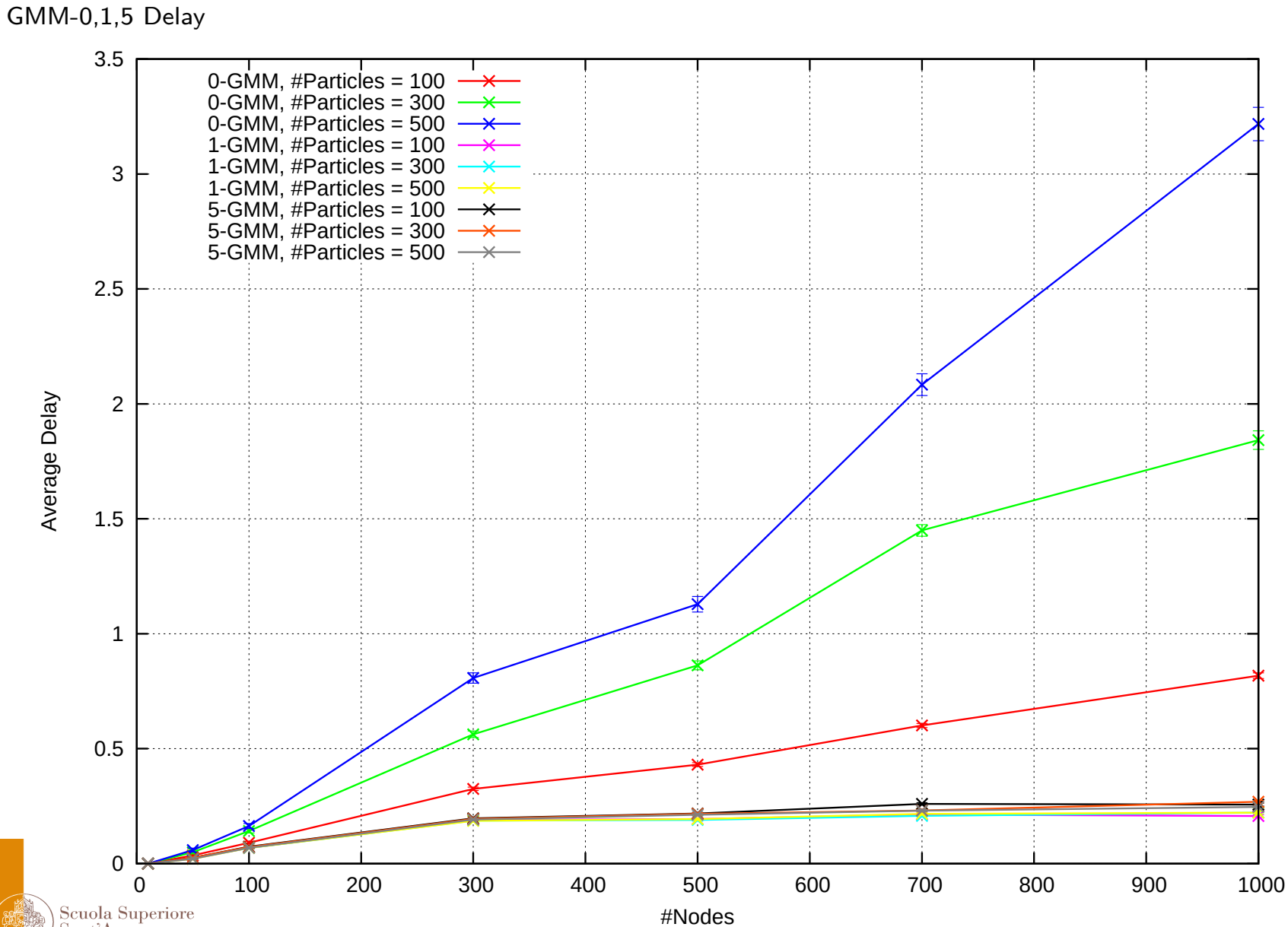
Results



Results



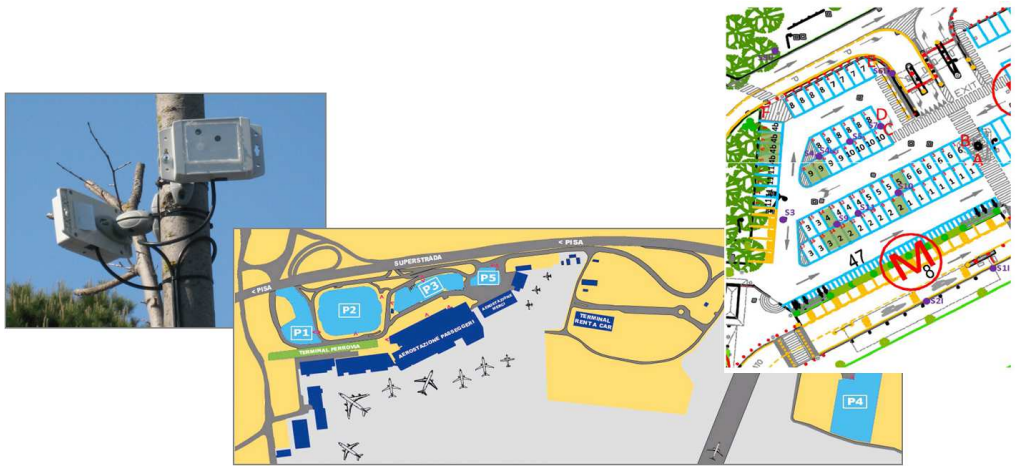
Results



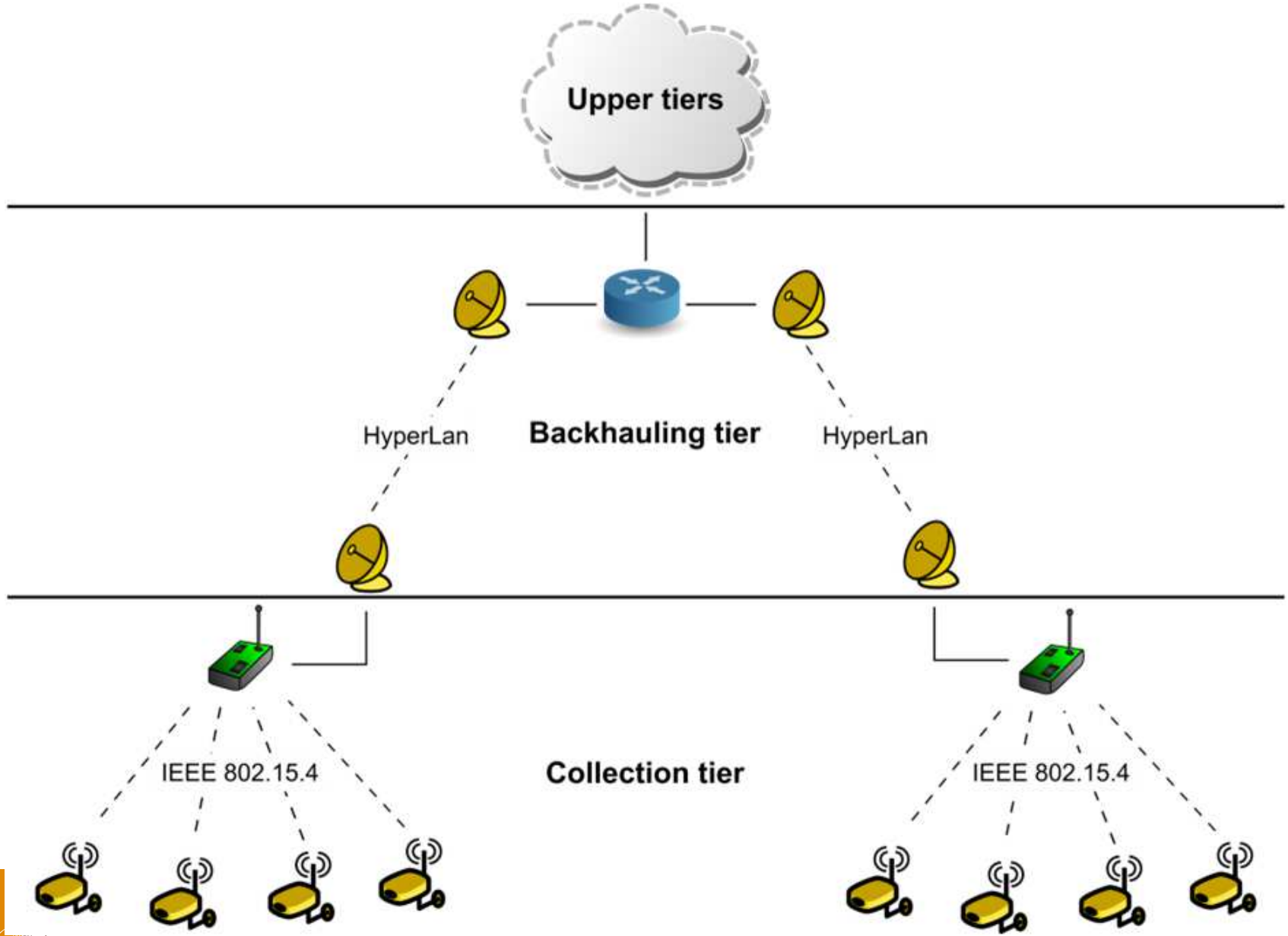
Outline

IPERMOB

- IPERMOB: Regional project (3.3 MEur total cost, 670 KEur SSSA)
- Aim: building an infrastructure to control Urban Mobility in Real-Time
- The testbed at the Pisa International Airport:
  - Parking lots occupancy;
  - Traffic flow measurement.



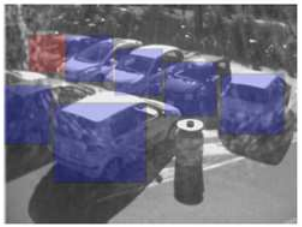
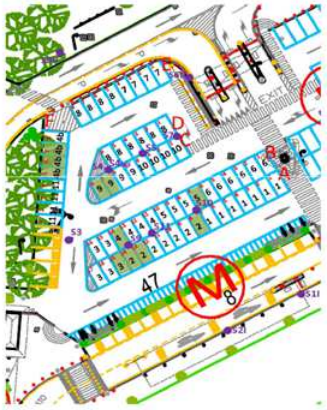
Multi-tier Architecture



The deployment

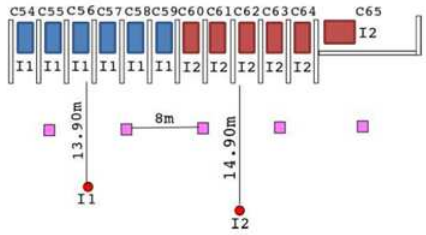
Outdoor Parking Lot

- Monitored Slots: 63
- Installed Sensors: 12
- $\frac{\#Slots}{\#Sensors} = 5.25$

Indoor Parking Lot

- Monitored Slots: 12
- Installed Sensor: 2
- $\frac{\#Slots}{\#Sensors} = 6$



Vehicle flows

- Installed Sensor: 5



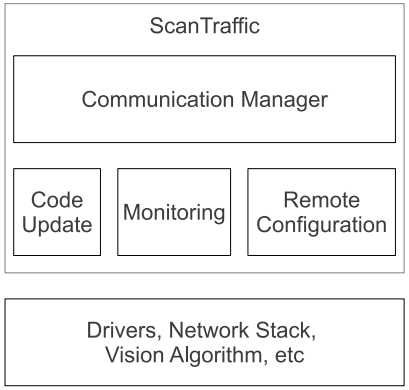
Personal Contribution

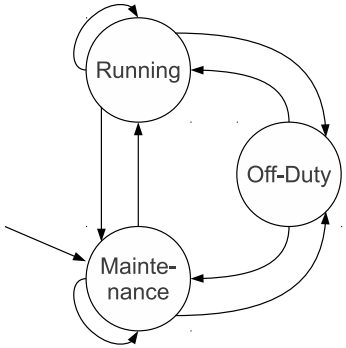
- HW/SW platform definition
  - Porting ERIKA RTOS to PIC32
  - Some device drivers: basic MCU support (Timers, SPI, UART, etc) and VGA camera
  - Support board prototyping (HW design)
- IEEE 802.15.4 compliant stack: *μWireless*
- Small Computer Vision library: *μCV*
- Definition of the computer vision algorithm

Node Communication Architecture

Collection-Tier: ScanTraffic [AAP+12]

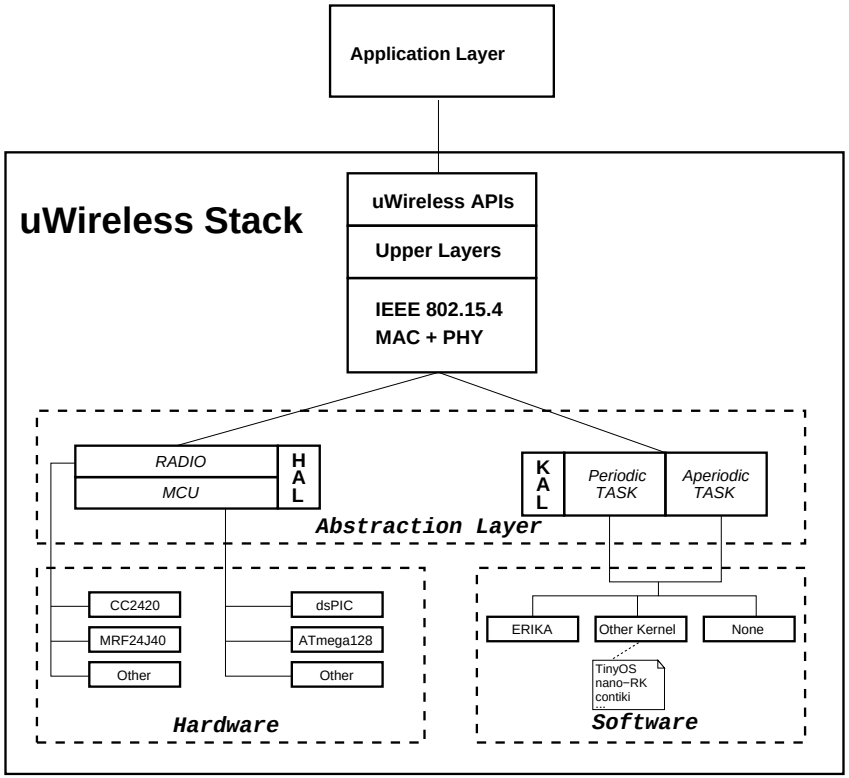
- Middleware for data collection
- Other services: code-update, remote configuration





Network stack: μWireless

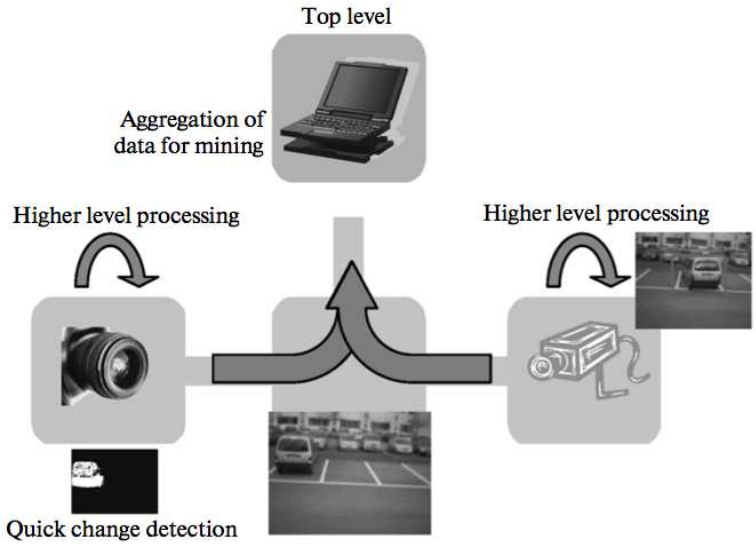
- Real-time traffic: Guaranteed Time Slot mechanism
- Hardware-independent (HAL)
- OS-independent (KAL)



Computer Vision

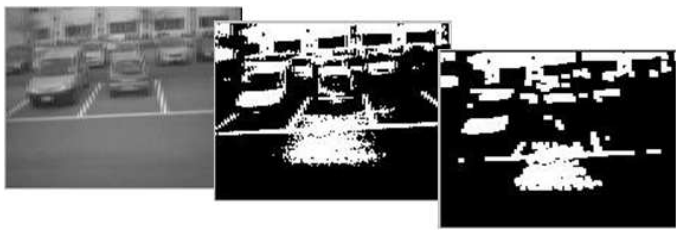
A multi-tier approach [MMN+11] (parking slot)

- Fast change detection algorithm (actually used)
- Cascade of classifiers (off-line)



μCV: Computer Vision library

- Optimized for microcontrollers
- Architecture-independent: pure C-code implementation
- Basic CV operations: binarization, mathematical morphology, differencing, etc.



Outline

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  - The *SeedEye* multimedia-sensor platform
- Real testbed:
  - The IPERMOB project [AAP+12]

thank you

c.nastasi@sssup.it

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Luca Santinelli, Mangesh Chitnis, Christian Nastasi, Fabio Checconi, Giuseppe Lipari, and Paolo Pagano.
A component-based architecture for adaptive bandwidth allocation in wireless sensor networks.
In *SIES*, pages 174–183, 2010.

Networking

Quality of Service and WSNs

WSNs are pervasive networks designed for application specific purposes.

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In such kind of networks Quality of Service **MUST** meet the application requirements (application-driven).

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- Monitoring
- Event Detection
- Remote Control

Non-Functional Aspects

- Timeliness
- Energy Consumption
- Cost effectiveness
- Pervasiveness

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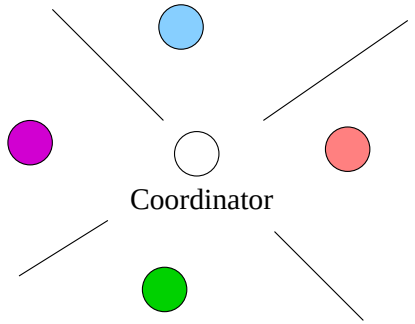
Considered scenario

To reconstruct an event it is necessary to aggregate the readings of the nodes looking at the same event from complementary perspectives (*observables*).



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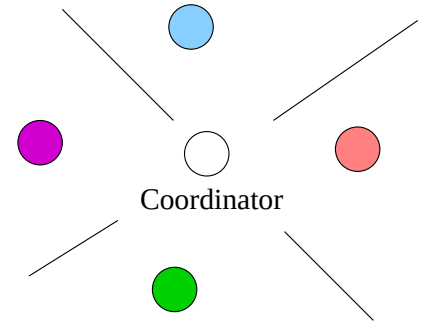
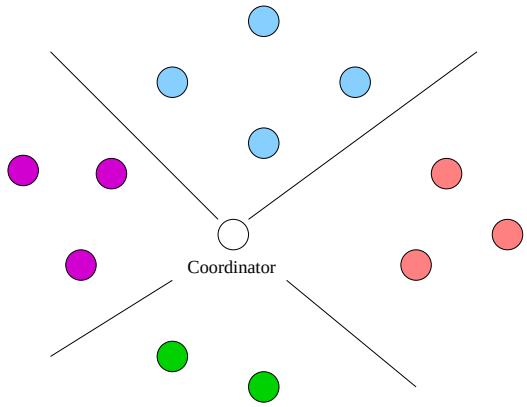


To cope with the unreliability of low-cost sensor nodes, each observable can be monitored by more than one node.



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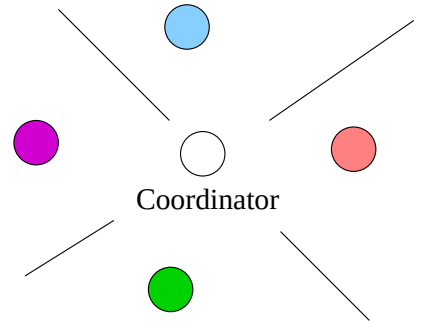

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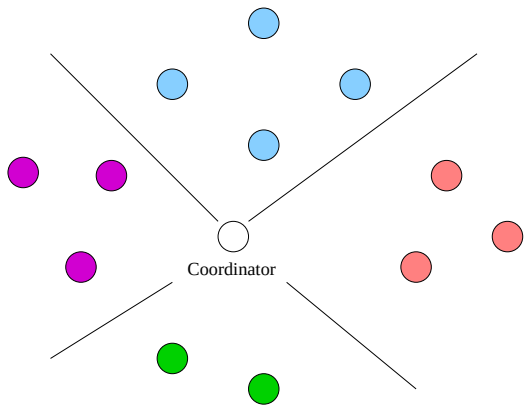


The redundancy increases

- availability of sensor data at the sink
- quality of the sensing measurements
- **number of nodes competing for the channel access (network overload)**

Goal

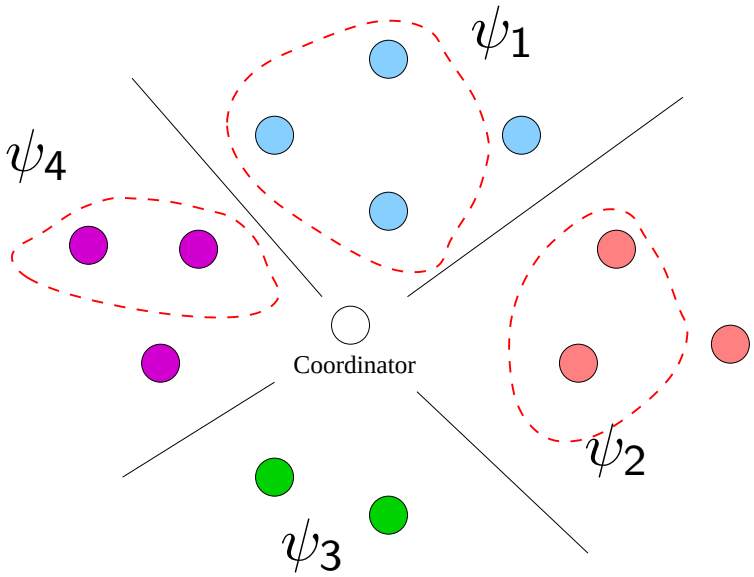
BACCARAT: *Bandwidth Allocation for Content-based Context-Aware Real-time ApplicaTions*

In particular we explicitely address:

- redundancy of information
- real-time communication on top of the IEEE 802.15.4 with Guaranteed Time Slots (GTSs)

Example

- The minimum requirement is one per observable: $w_k^G = 1$ for $i = 1, 2, 3, 4$
- Assuming all the flows have the same parameters
- Assuming to have bandwith for 7 flows



Event NOT reconstructed

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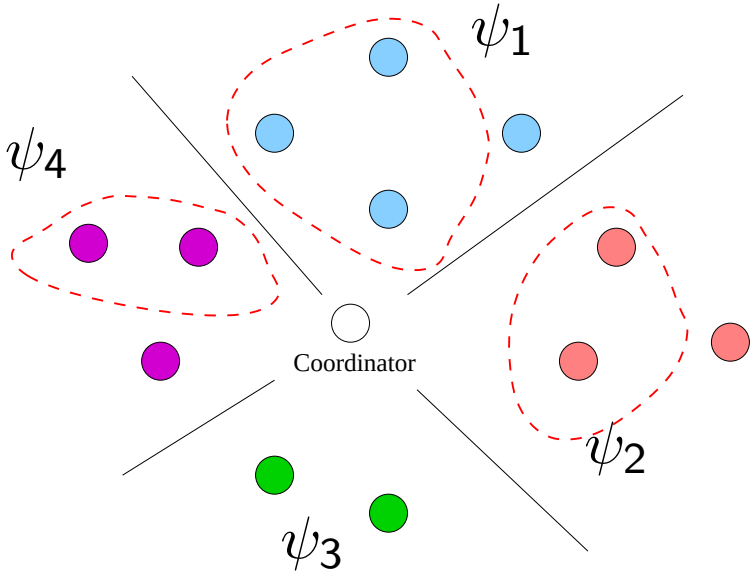
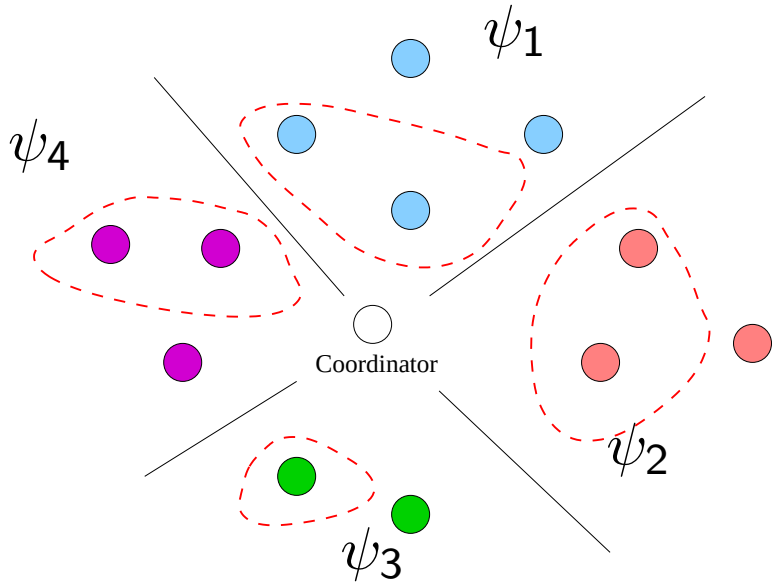


Event NOT reconstructed



Event reconstructed

Traffic differentiation and real-time guarantees

Idea

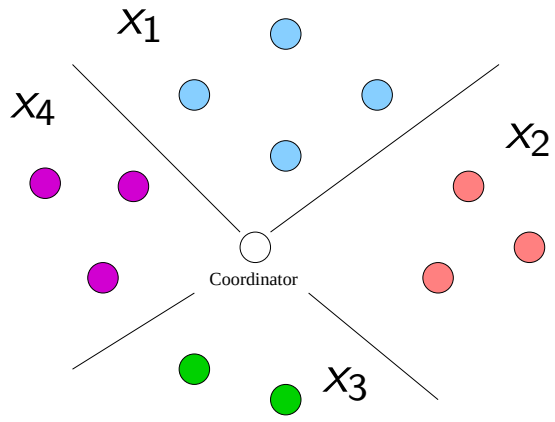
- Flows (and messages) are classified in two categories:
  - Guaranteed ones: those satisfying the minimum requirements (w_k^G)
  - Residual ones: the remaining ones
- Bandwidth allocated first to the guaranteed messages following an Earliest Deadline First (EDF) policy
- Remaining bandwidth allocated to the residual messages in order to enhance the confidence of the event recontruction

Two system phases

- Off-line: feasibility analisys to check if the minimum requirements can be satisfied
- On-line: bandwidth allocation based on the off-line study

Simulation Scenario

- Event-detection based on the measurement of 4 independent variables x_1, x_2, x_3, x_4



Test case:

- Message size constant for all node $\overline{C}_i = 300bytes$ (3 MAC data frames)
- Event arrival time with Gaussian distribution with $\mu = 1s$ and $\sigma = 4ms$
- We consider the minimum inter-arrival time $\overline{T}_i = \mu - 3\sigma$
- Message deadline $\overline{D}_i = 0.9\overline{T}_i$

Comparison:

- BACCARAT
- simple EDF
- FirstComeFirstServed (FCFS)

Metrics

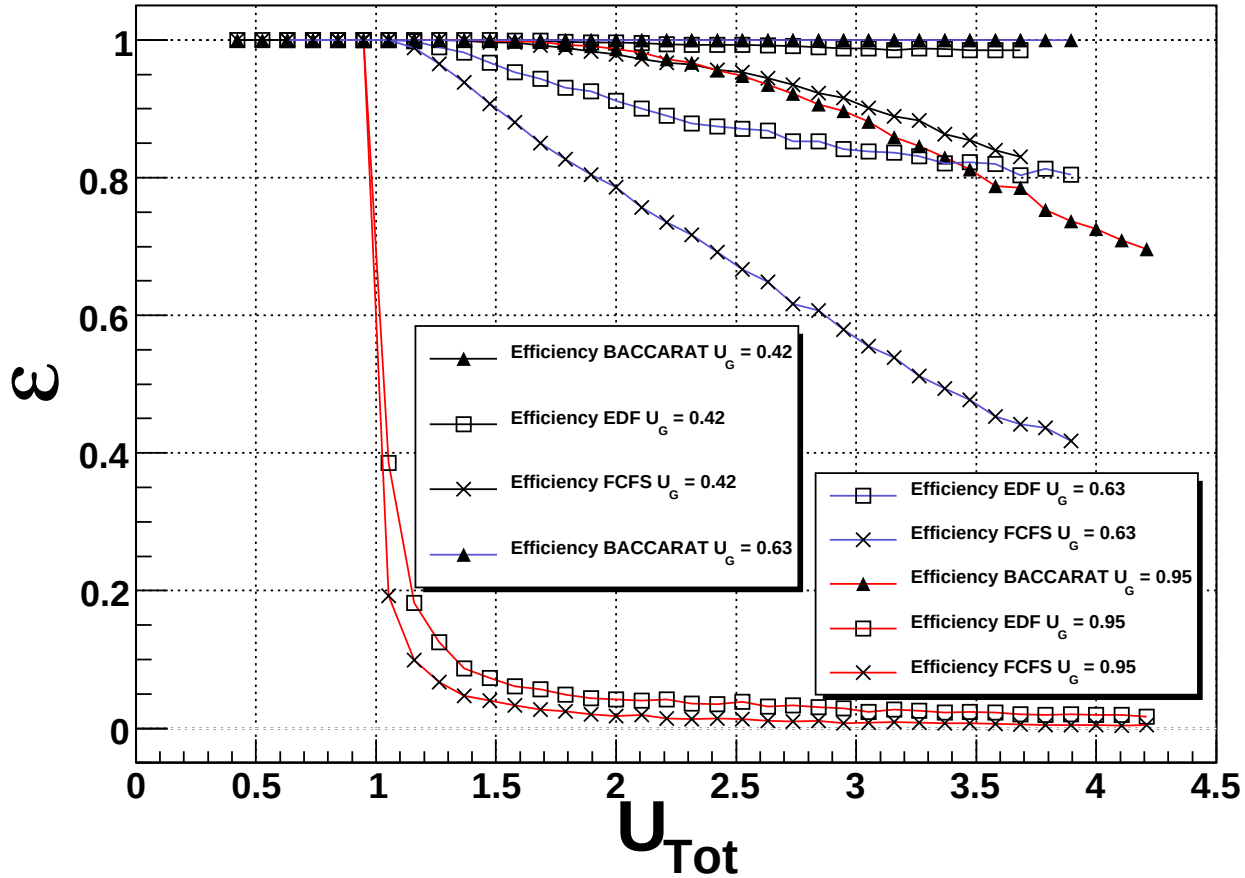
- An event is completely reconstructed if at least w_i^G messages are received for each variable ($i = 1, 2, 3, 4$)
  Event detection efficiency:

$$\varepsilon = \frac{\#Reconstructed\_Events}{\#Total\_Events}$$

- The accuracy of the measurement is related to the statistical uncertanty that affects the observed variables.
  Considering s^2 the uncertanty obtained with the received messages and considering s_M^2 the maximum uncertanty (obtained with the guaranteed messages), we define a quality index as:

$$Q = \varepsilon \frac{s_M^2}{< s^2 >}$$

Efficiency



U_{Tot} is proportional to the number of nodes (redundancy)

Quality Index