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Energy-efficient wireless sensor networks: models, algorithms, applications

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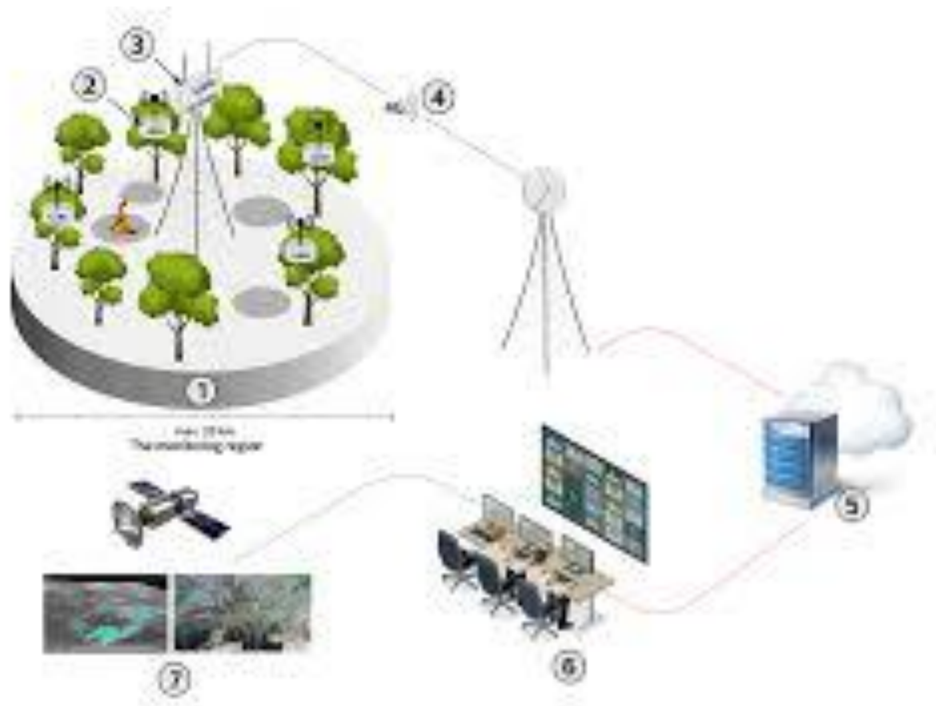
Wireless ad hoc network

Ad hoc network: A network with a decentralized structure formed by heterogeneous devices that autonomously organize themselves into a network

No external network infrastructure is required to transmit data, devices within radio range communicate with each other

Wireless Sensor Network (WSN): A network of spatially dispersed numerous static, quasi-static, or mobile smart sensing devices that monitor the environment, record, and transmit data

WSN often relay on spontaneous network formation



Self-organization

The process by which a complex system's shape, spatial structure, or behavior emerges due to the interactions between its components

1971: ALOHAnet, the first public demonstration of a wireless packet data network connecting 7 computers located on 4 Island (University of Hawaii project)

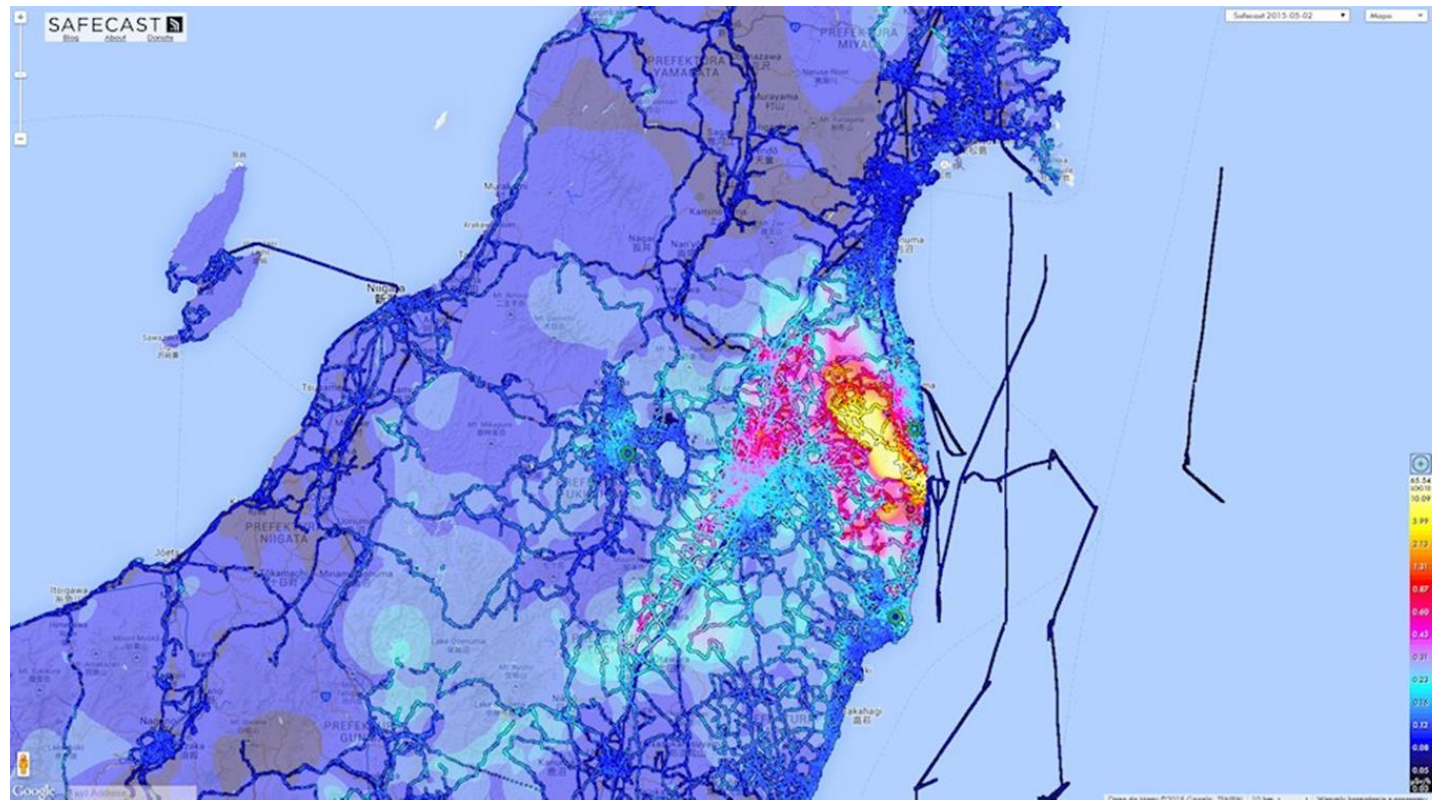
1997: IEEE 802.11 (WiFi)

1999: IEEE 802.15.1 (Bluethooth)

2004: IEEE 802.15,4 and ZigBee

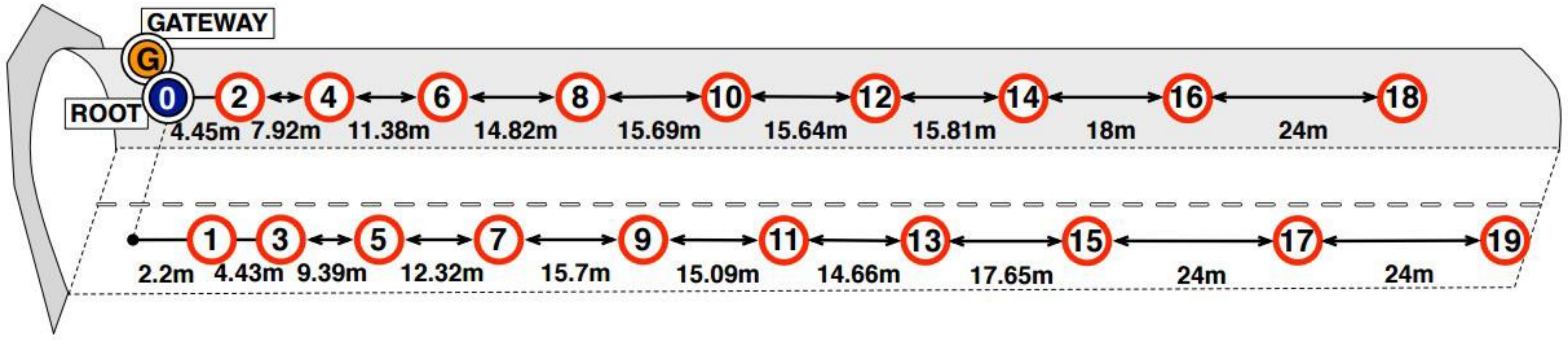
Bult K. et al., *Low Power Systems for Wireless Microsensors*, ISLPED, 1996

WSN applications

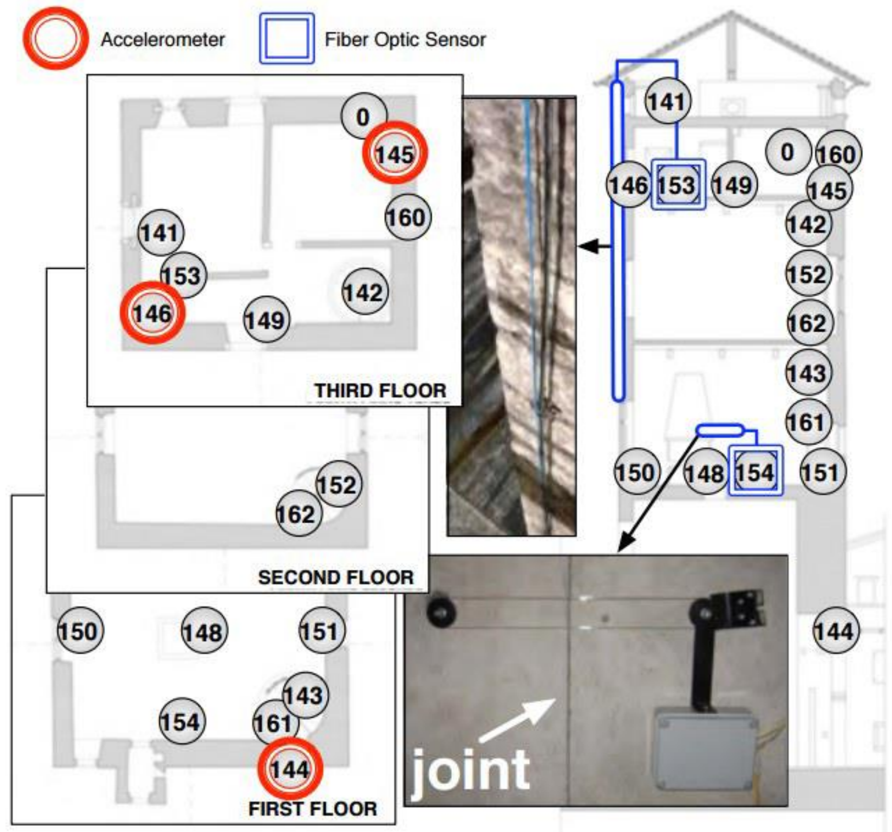


https://map.safecast.org/

Fukushima nuclear power plant disaster

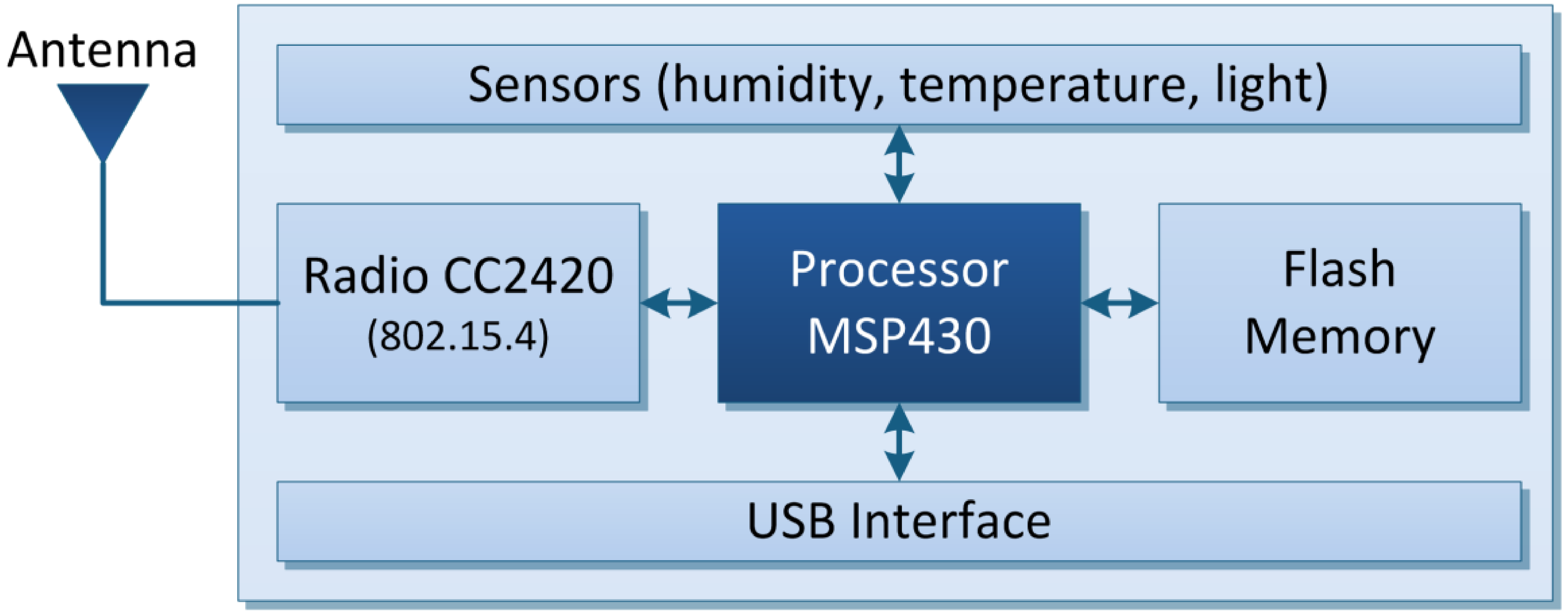


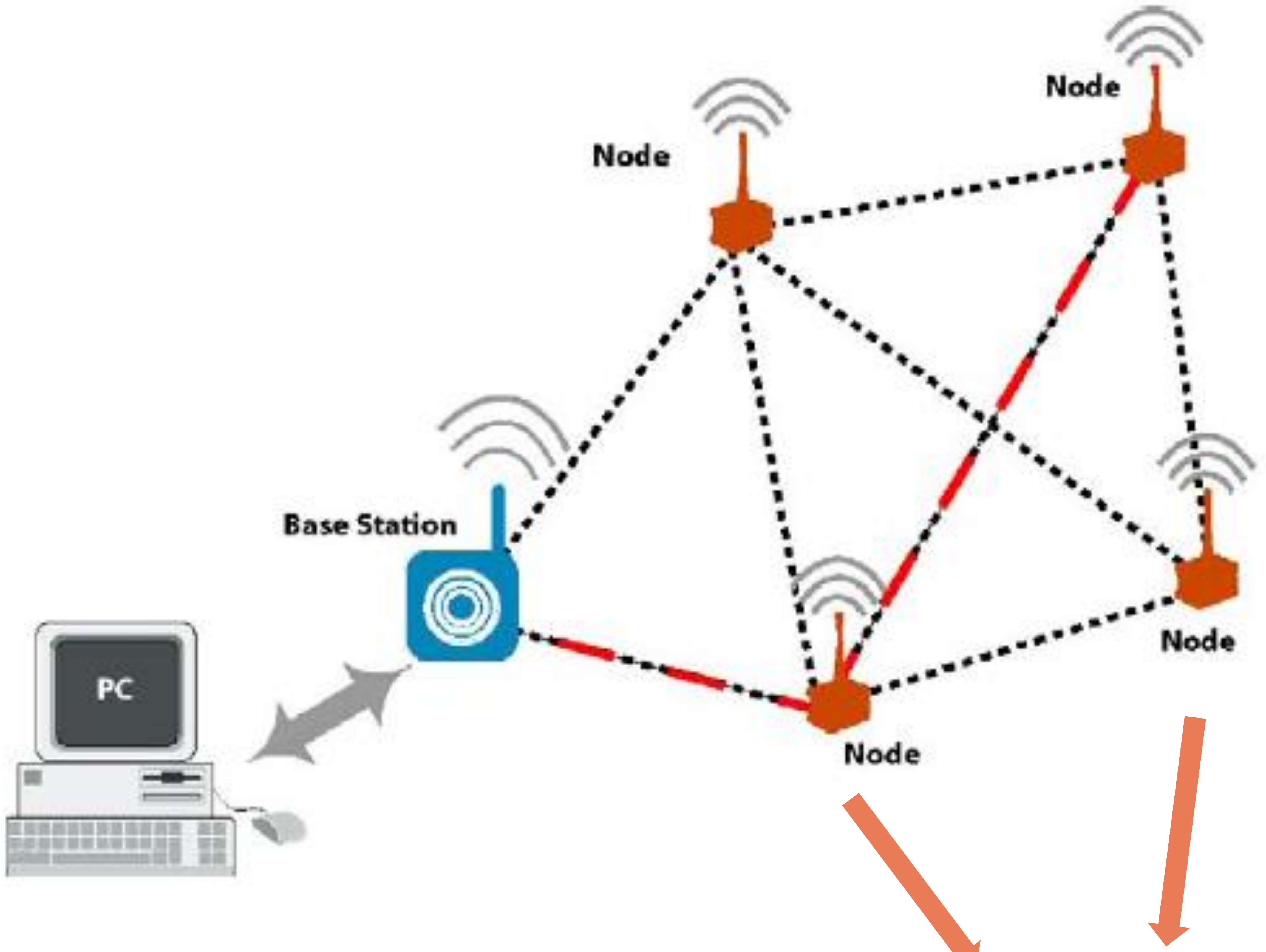
Tunell S.Viglio monitoring



Torre Aquila (Trento) monitoring

Wireless Sensor Network (WSN





Problems:

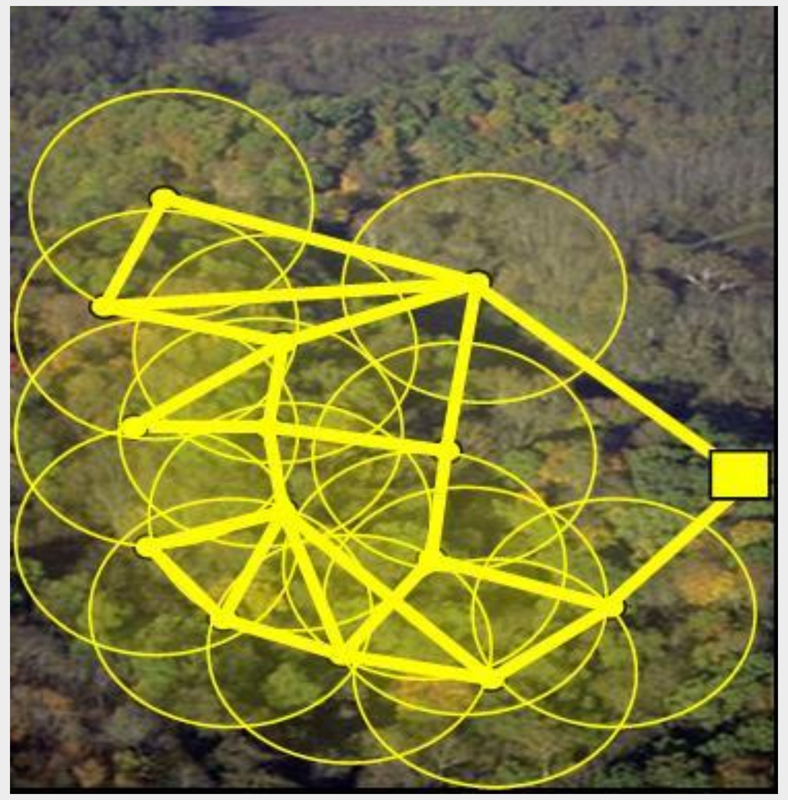
- Limited energy resources: nodes - small battery-fed devices
- Wireless communication: poor quality of connection, limited network throughput and communication range, security
- Limited data processing capabilities and memory
- Dynamic topology

WSN modeling

WSN – a network built with N static or mobile sensing devices D_i communicating wirelessly

WSN is an undirected graph $WSN=(V,E)$

- set of vertices: sensing devices, $V=S_D$
- set of edges: links available at time *t*, $E=S_L$



$$\boldsymbol{WSN = (S_D, S_L), S_D \neq \emptyset, S_L \neq \emptyset}$$

where

$S_D = \{D_i, i = 1, \ldots, N\}$

$S_L = \{(D_i, D_j): D_i \in S_D, D_j \in S_D, \|\mathbf{c}_i - \mathbf{c}_j\| \leq r_{t_i}, i, j = 1, \ldots N, i \neq j\}$

$\mathbf{c}_i = [x_i, y_i, z_i]$ - D_i location in the workspace (transmitting antenna coordinates), r_{t_i} - D_i radio transceiver range

Workspace: a set of possible sensors locations

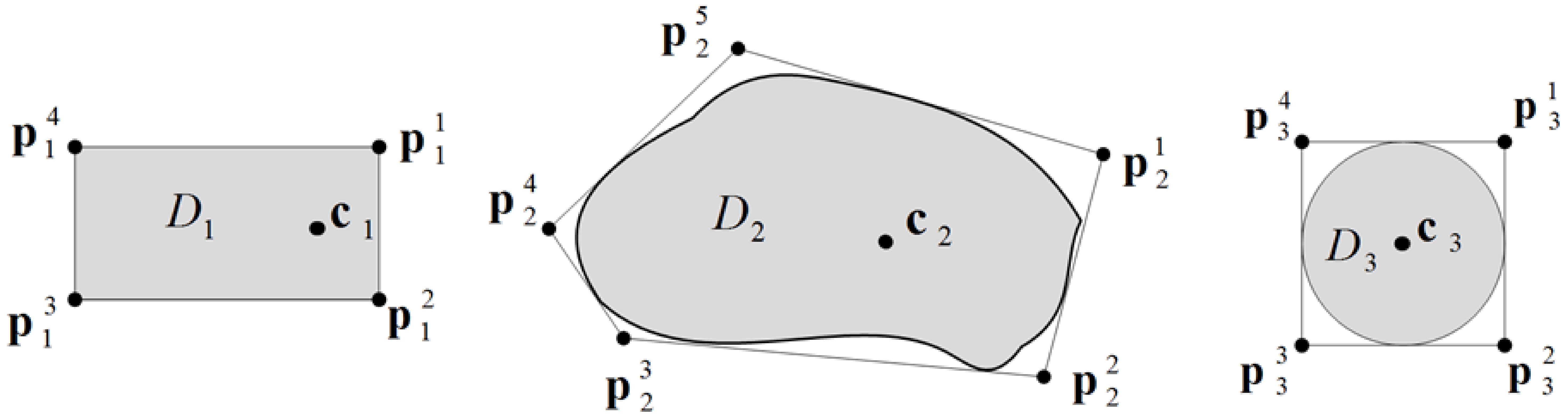
$$W = \{(\mathbf{o}_j : \mathbf{o}_j \in \mathbb{R}^3, \mathbf{o}_j = [x_j, y_j, z_j], j = 1, \ldots, J\}$$

Set of obstacles in the workspace (S_O^s, S_O^m): S_O^s - a set of static obstacles, S_O^m - a set of mobile obstacles

WSN node model - position

The network node D_i is a rigid solid of arbitrary shape

- D_i is inscribed in a polyhedron Env_i (envelope) with vertices $\mathbf{p}_i^j \in \mathbb{R}^3, j = 1, \dots, |P_i|$
- Reference point $\mathbf{c}_i$ – the location of D_i transmitting antenna



Each obstacle is inscribed in a polyhedron:

Env_l – an envelope of l static obstacle, Env_m – an envelope of m mobile obstacle

WSN node model – energy and memory

Limited computing power, memory, and energy resources

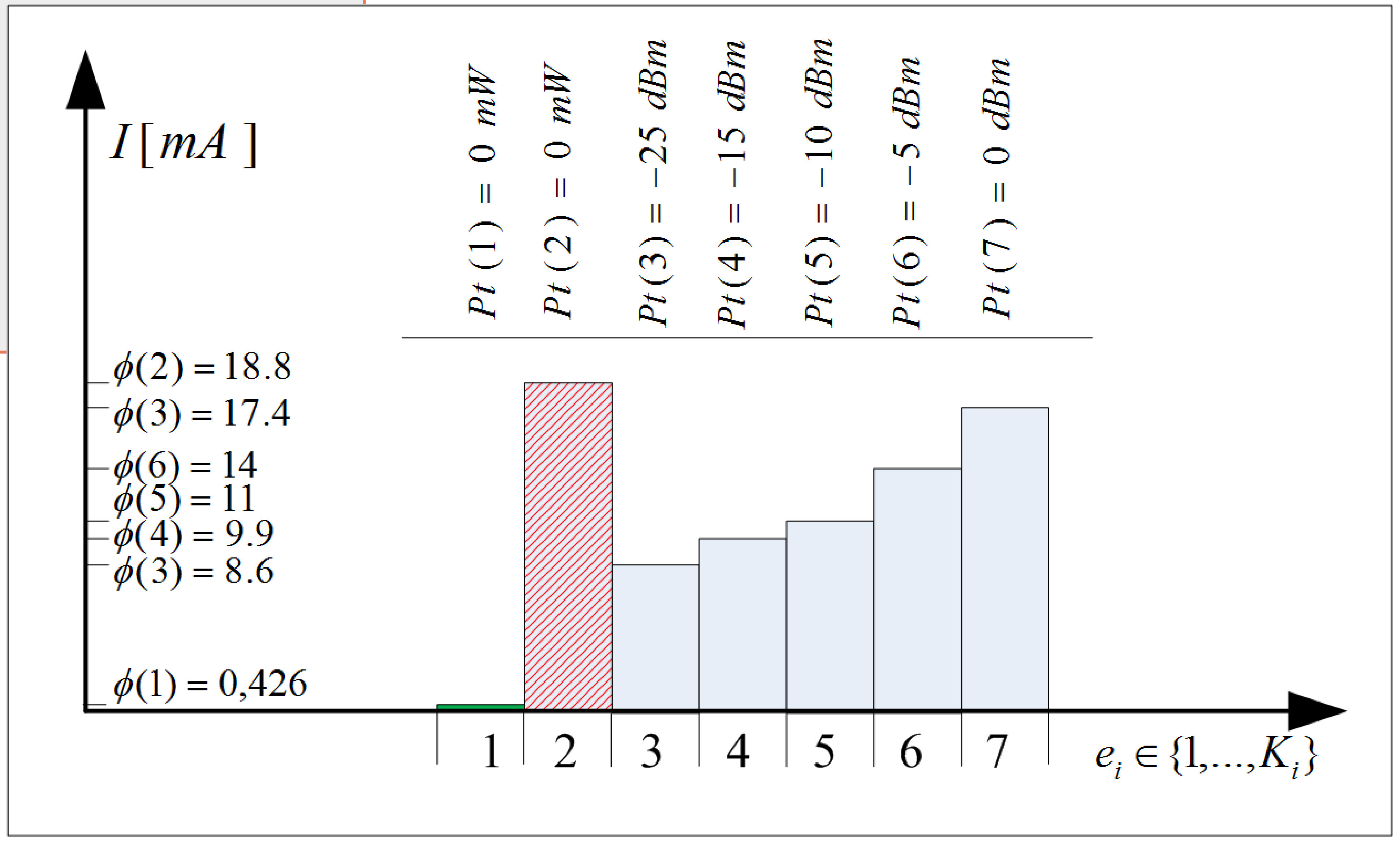
$$\xi_i(t_{k+1}) = \xi_i(t_k) - \underbrace{\int_{t_k}^{t_{k+1}} \phi_i(e_i,t)dt}_{\textit{radio}} - \underbrace{\sum_1^M s_i^m \int_{t_k}^{t_{k+1}} \psi_i^m(t)dt}_{\textit{sensors/detectors}} - \underbrace{\int_{t_k}^{t_{k+1}} \Theta(t)dt}_{\textit{battery discharge}}$$

$\xi_i(t)$ - energy state (battery level) of D_i at time t

$\phi_i(e_i,t)$ - energy consumed by radio module at time t, and energy mode e_i, $i=1,\dots,K$

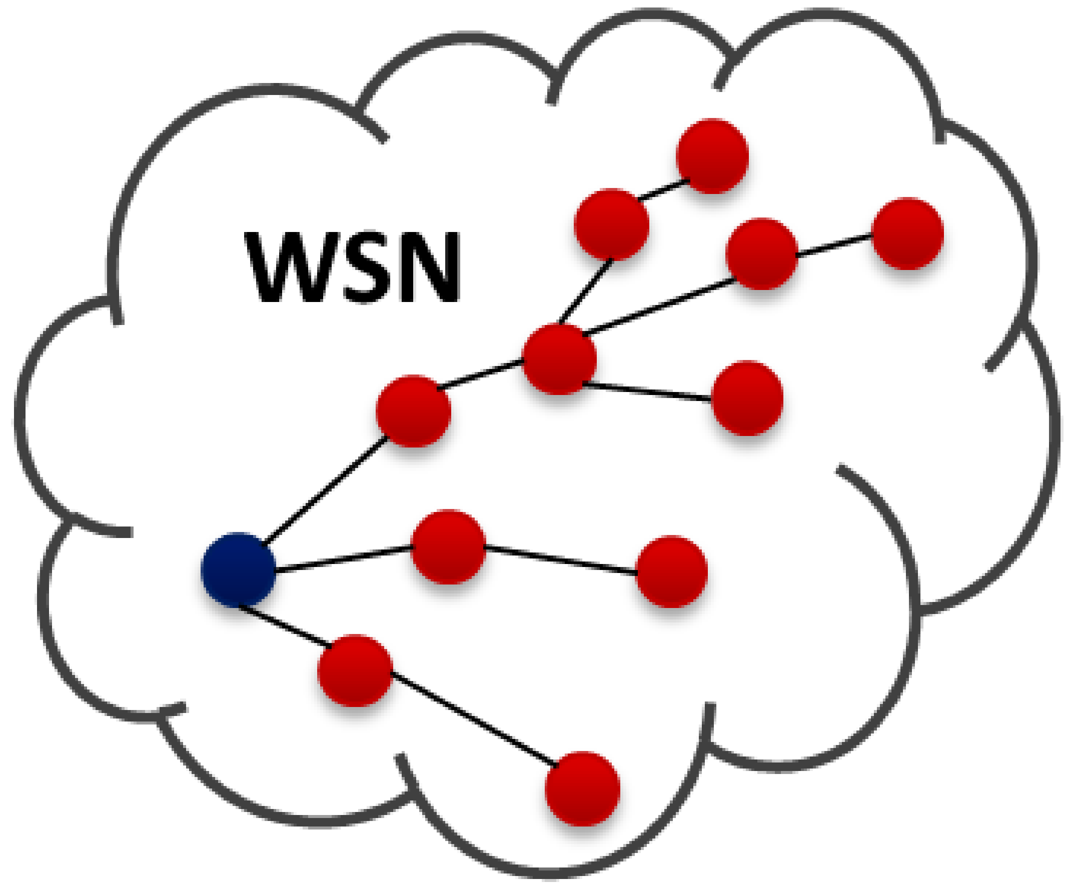
$\psi_i^m(t)$ - energy consumed by m-th sensor at time t, $s_i^m \in \{0,1\}$

$\Theta(t)$ - battery discharge process



$$\underbrace{b_i(t_{k+1})}_{\textit{buffer state}} = b_i(t_k) + \underbrace{\gamma_i^c(t_k)}_{\textit{new data}} - \underbrace{\gamma_i^d(t_k)}_{\textit{removed data}}$$

WSN model – the wireless channel



The average signal degradation (path loss) with a distance of d

$$Pl[\mathrm{dB}] = P^t[\mathrm{dBW}] - P^r[\mathrm{dBW}]$$

Analitycal-empirical models of the path loss

- The long-distance path model

$$Pl(d)[\mathrm{dB}] = Pl(d_0)[\mathrm{dB}] + 10n\log\left(\frac{d}{d_0}\right)$$

- The long-normal shadowing model

$$Pl(d)[\mathrm{dB}] = Pl(d_0)[\mathrm{dB}] + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$$

The distance between nodes i and j estimation

$$d_{ij} = d_0 \cdot 10^{(P^t - Pl(d_0))/10n} \cdot 10^{-P^r_{ij}/10n}$$

d_0 - close-in reference distance

n - „distance gradient”

X_σ - zero-mean Gaussian distributed random variable

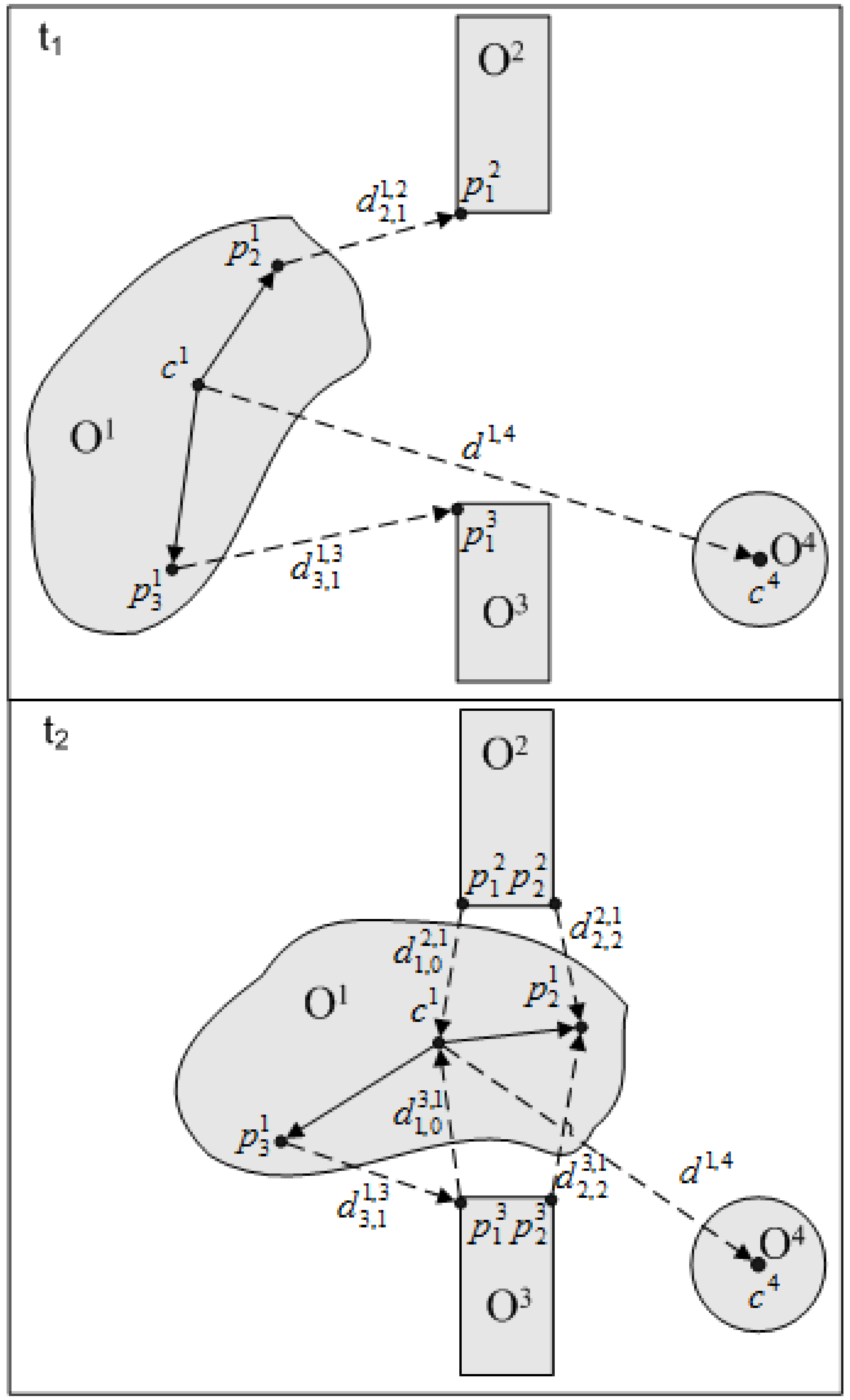
WSN node model - motion

- Network node D_i: the set of points $\left\{\mathbf{c}_i, \mathbf{p}_i^1, \dots, \mathbf{p}_i^{P_i}\right\}$
- Each obstacle O_j: the set of points $\{\mathbf{p}_j^1, \dots, \mathbf{p}_j^{P_j}\}$
- D_i can move avoiding obstacles, $v_i \in [v_{min}, v_{max}]$, $\omega_i \in [\omega_{min}, \omega_{max}]$

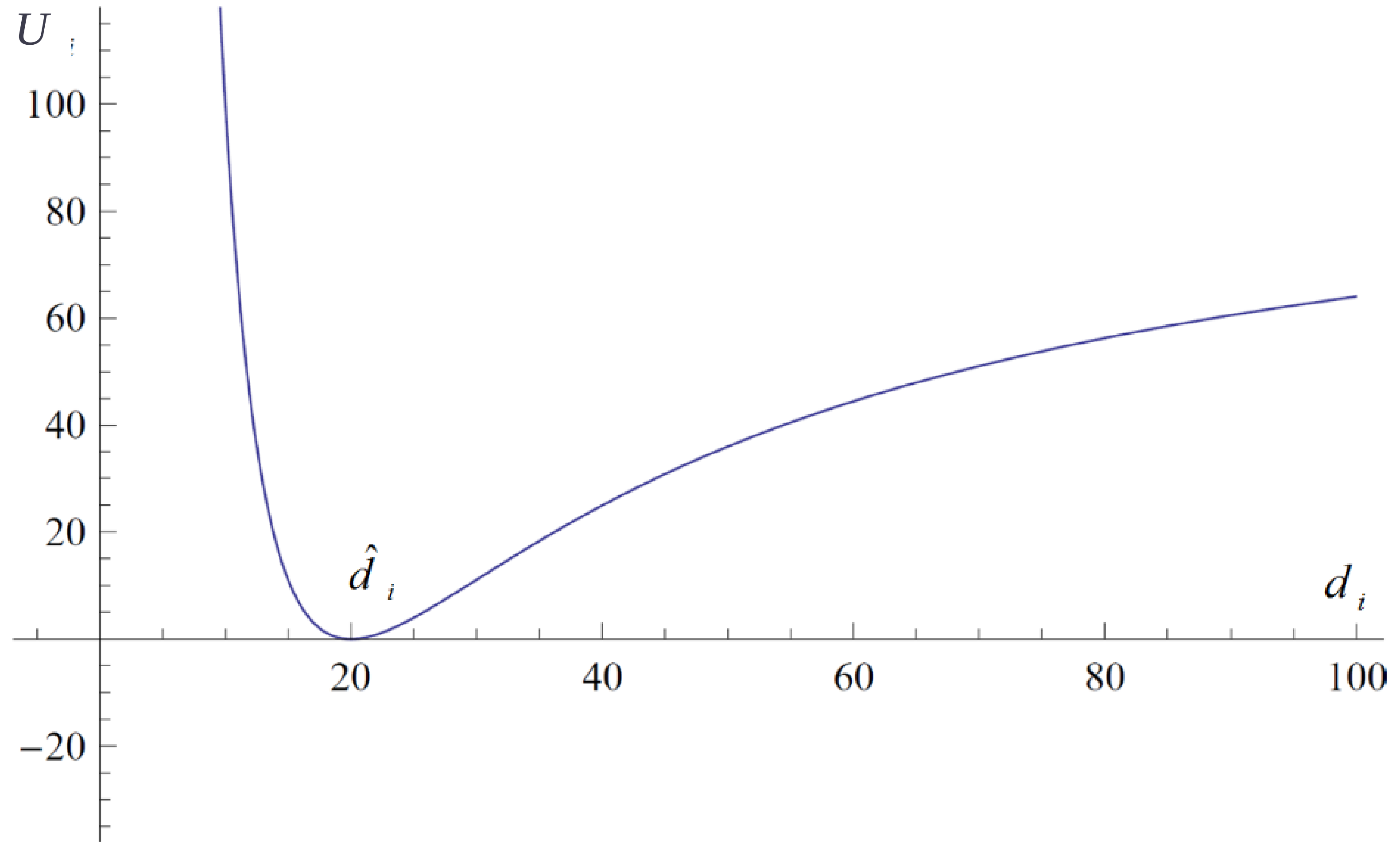
$$\bar{v}_i = \frac{\mathbf{c}_i(t_{k+1}) - \mathbf{c}_i(t_k)}{\Delta t}, \qquad k \geq 1$$

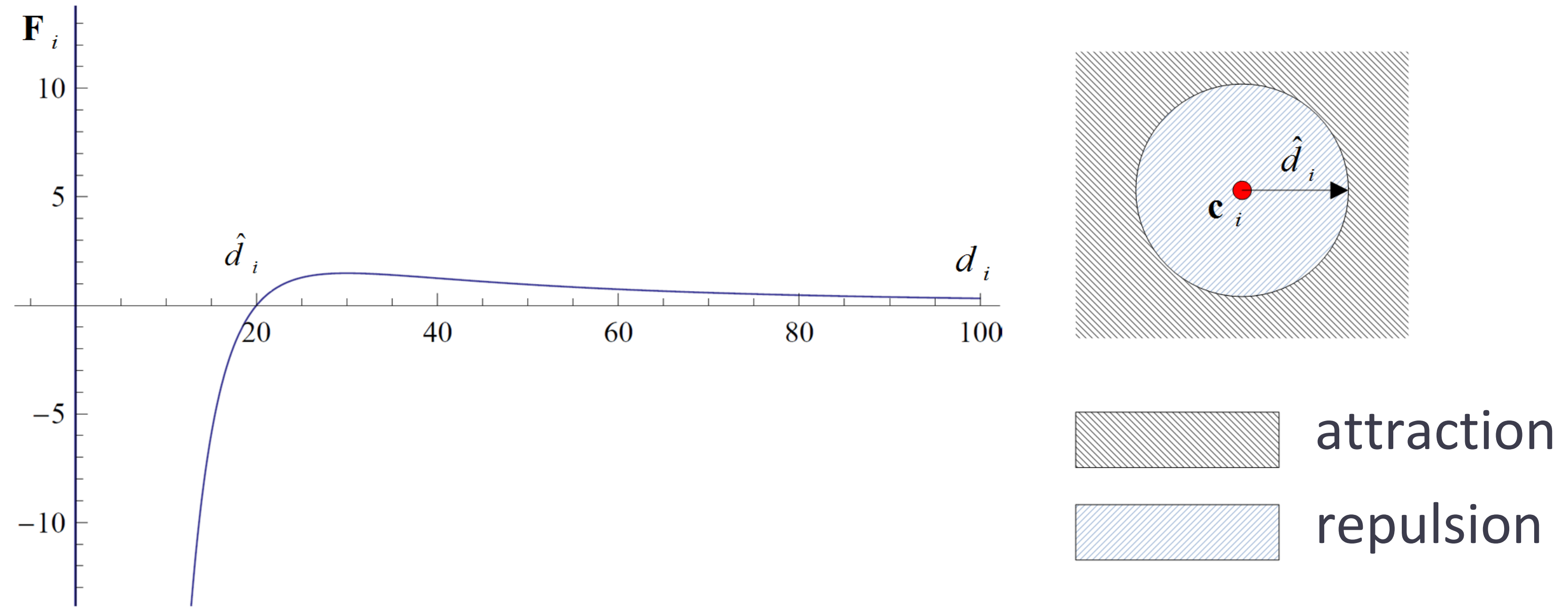
$$Vol(Env_i) \cap Vol(Env_k^m) \cap Vol(Env_l^s) = \emptyset$$

- Mapping the shape of objects with any degree of accuracy
- Ease of motion modeling and collision avoidance
- Ability to pass through narrow passages



Self-organised WSN - motion trajectory calculation





The inspiration - classical mechanics and liquid crystals

The interactions between a pair of molecules are commonly modeled using the Lennard-Jones potential function

The function with characteristics similar to Lennard-Jones

$$U_i(d_i) = \left(\frac{\hat{d}_i}{d_i} - 1\right)^2$$

$$\mathbf{F}_i(d_i) = -\nabla U_i(d_i)$$

d_i - measured distance
$\hat{d}_i$ - reference distance
U_i - potential

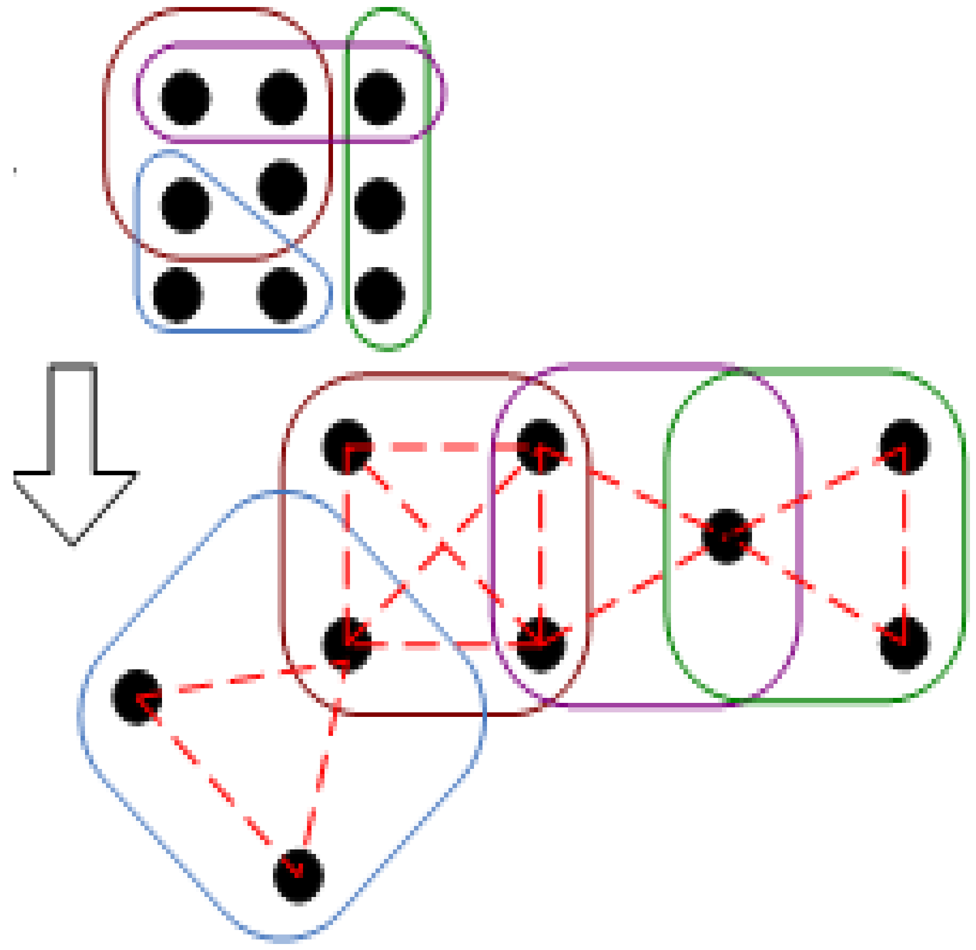
Self-organised WSN – motion trajectory calculation

1. Base station: initial conditions, network clustering, coordination
2. WSN node: displacement calculation solving the optimization problem

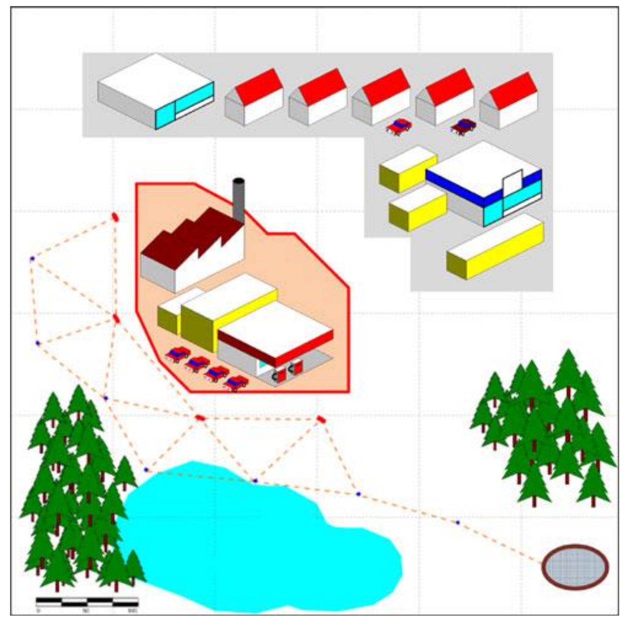
$$\min_{c_i, p_i^1 \dots p_i^L} \left[\sum_{SN_i} \epsilon_{ij} \left(\frac{\hat{d}_{ij}}{d_{ij}} - 1 \right)^2 + \sum_{S_O^s} \epsilon_{il} \left(\frac{\hat{d}_{il}}{d_{il}} - 1 \right)^2 + \sum_{S_O^m} \epsilon_{ik} \left(\frac{\hat{d}_{ik}}{d_{ik}} - 1 \right)^2 + \epsilon_{ig} \left(\frac{\hat{d}_{ig}}{d_{ig}} - 1 \right)^2 \right]$$

neighbours — *static obstacles* — *mobile obstacle* — *goal*

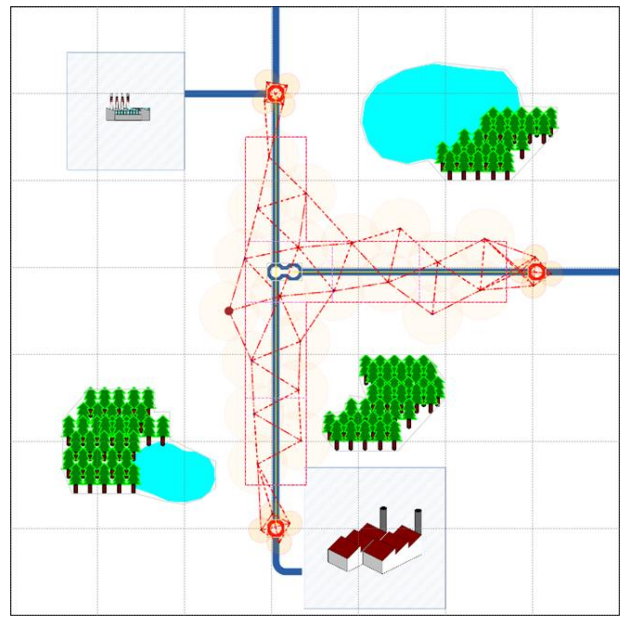
ϵ_i - weighting factor



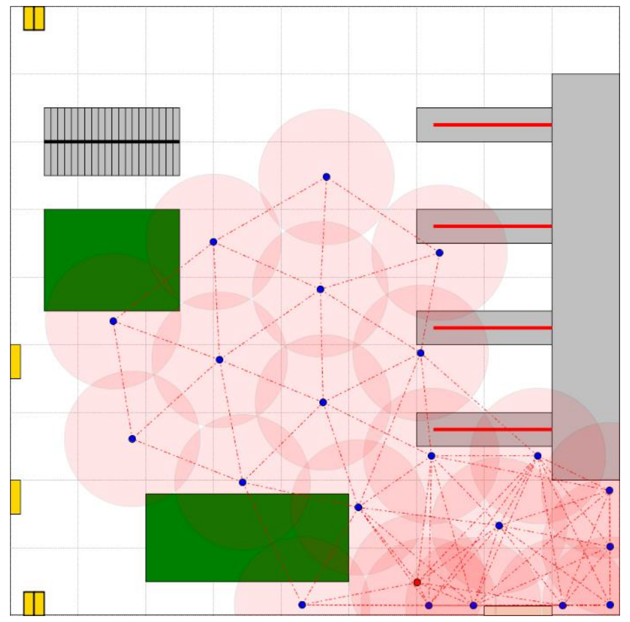
Temporary communication network



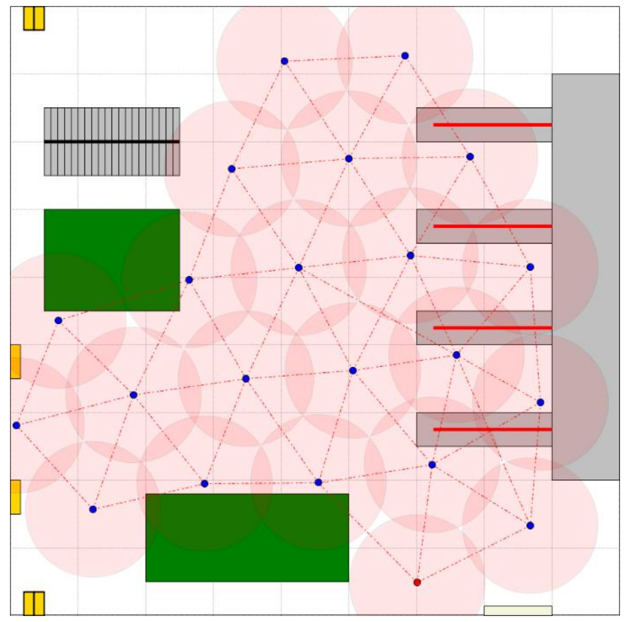
Instalation monitoring



Workspace covering



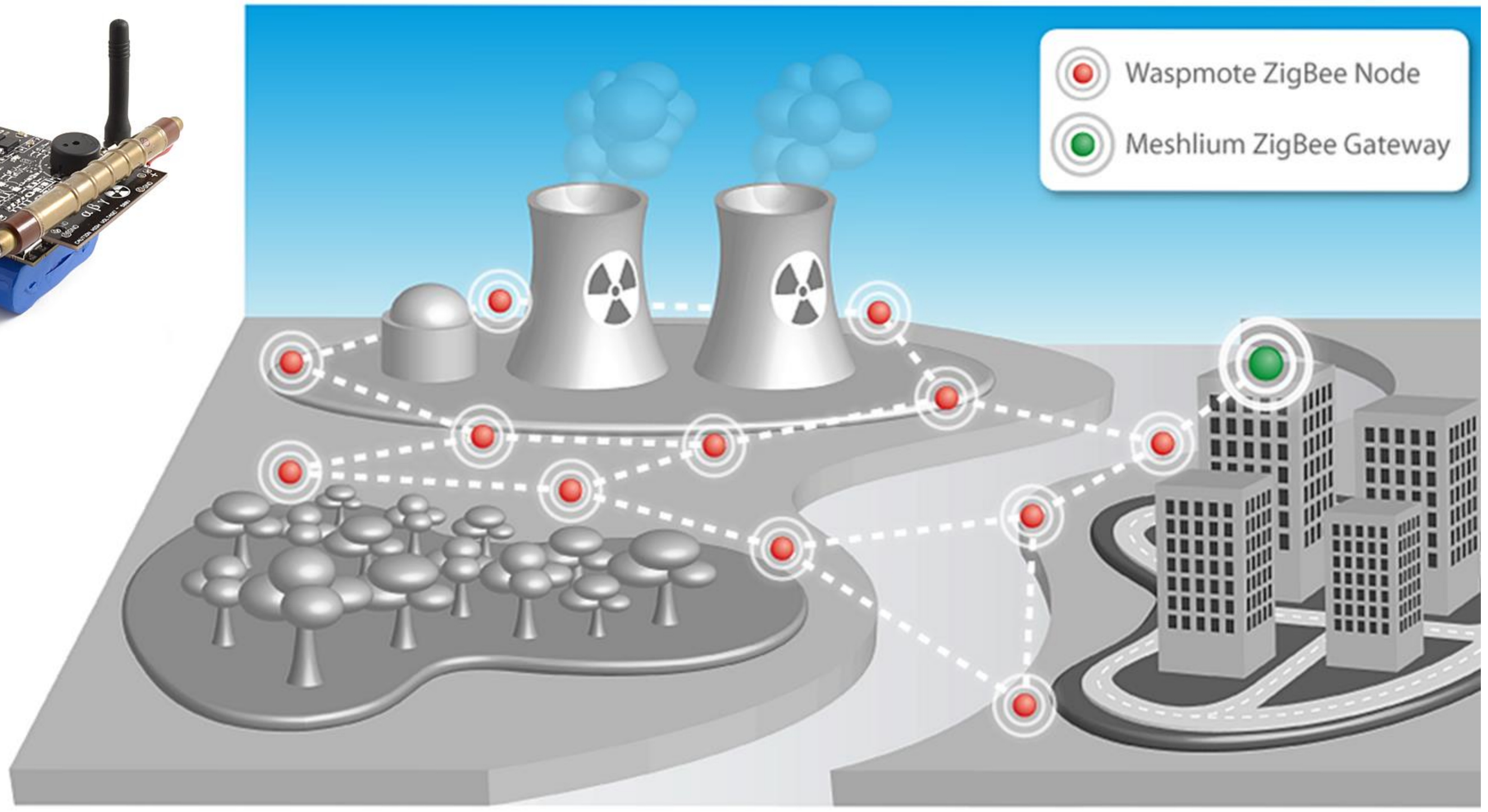
unknow obstacles



known obstacles

dist

WSN node model – summary



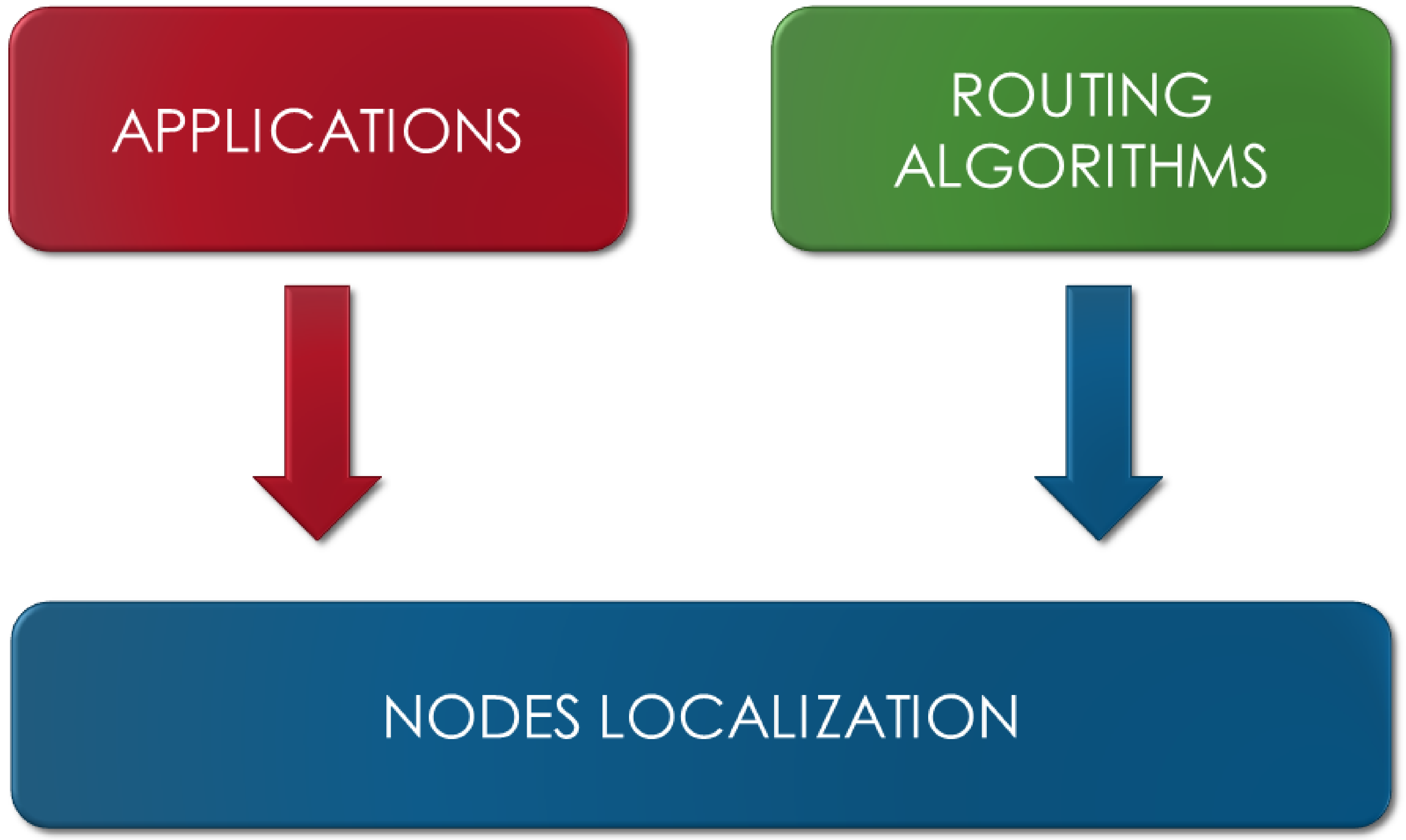
$$\mathbf{x}_i = [\underbrace{P_i, \mathbf{c}_i,}_{\textit{position}} \underbrace{\xi_i,}_{\textit{energy}} \underbrace{b_i}_{\textit{memory}}]$$

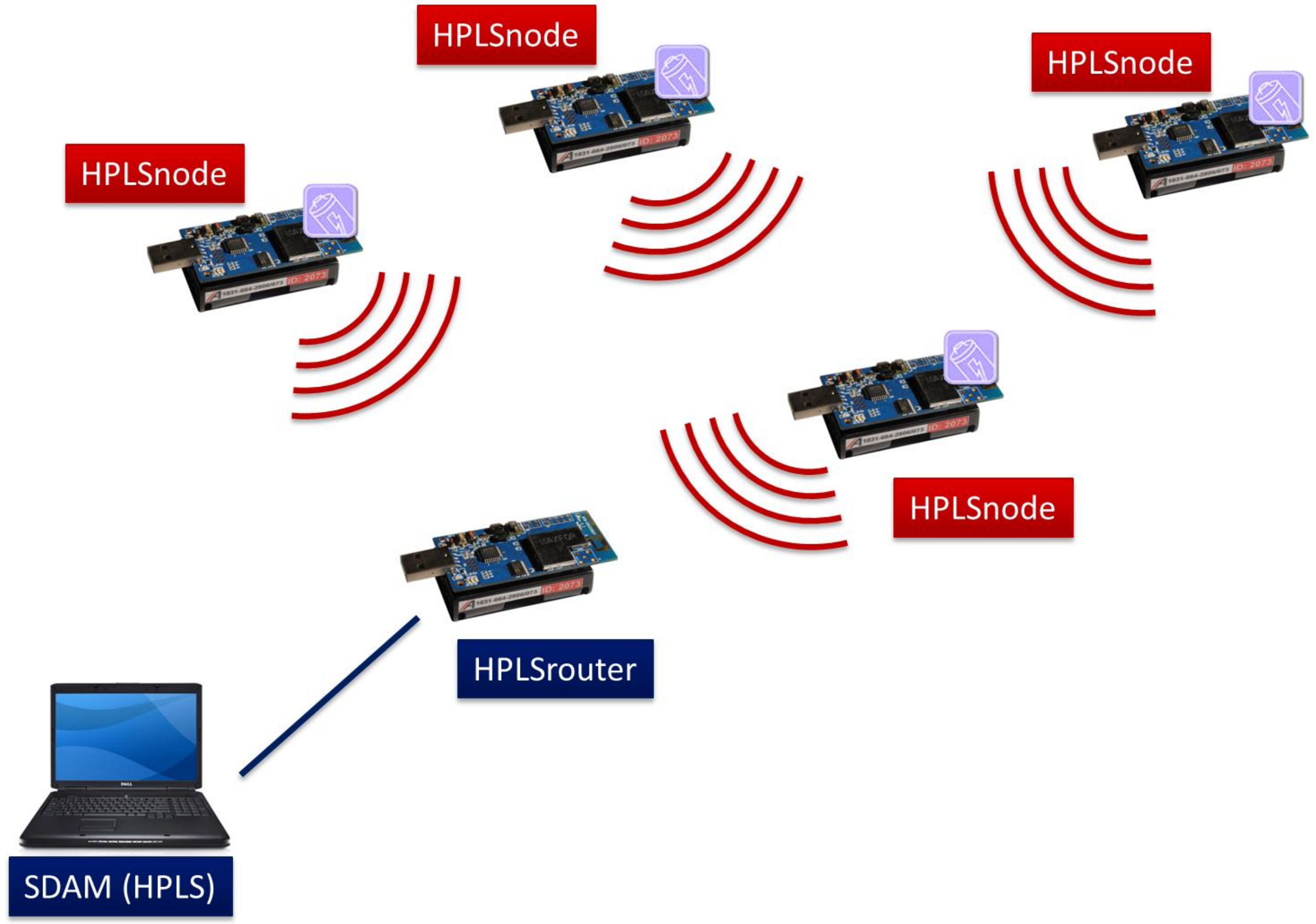
$$\boldsymbol{u}_i = [\underbrace{\omega_i, \mathbf{v}_i,}_{\textit{position}} \underbrace{e_i, s_i^1, \dots, s_i^M,}_{\textit{energy}} \underbrace{\gamma_i^c, \gamma_i^d}_{\textit{memory}}]$$

Problem 1: network nodes localization

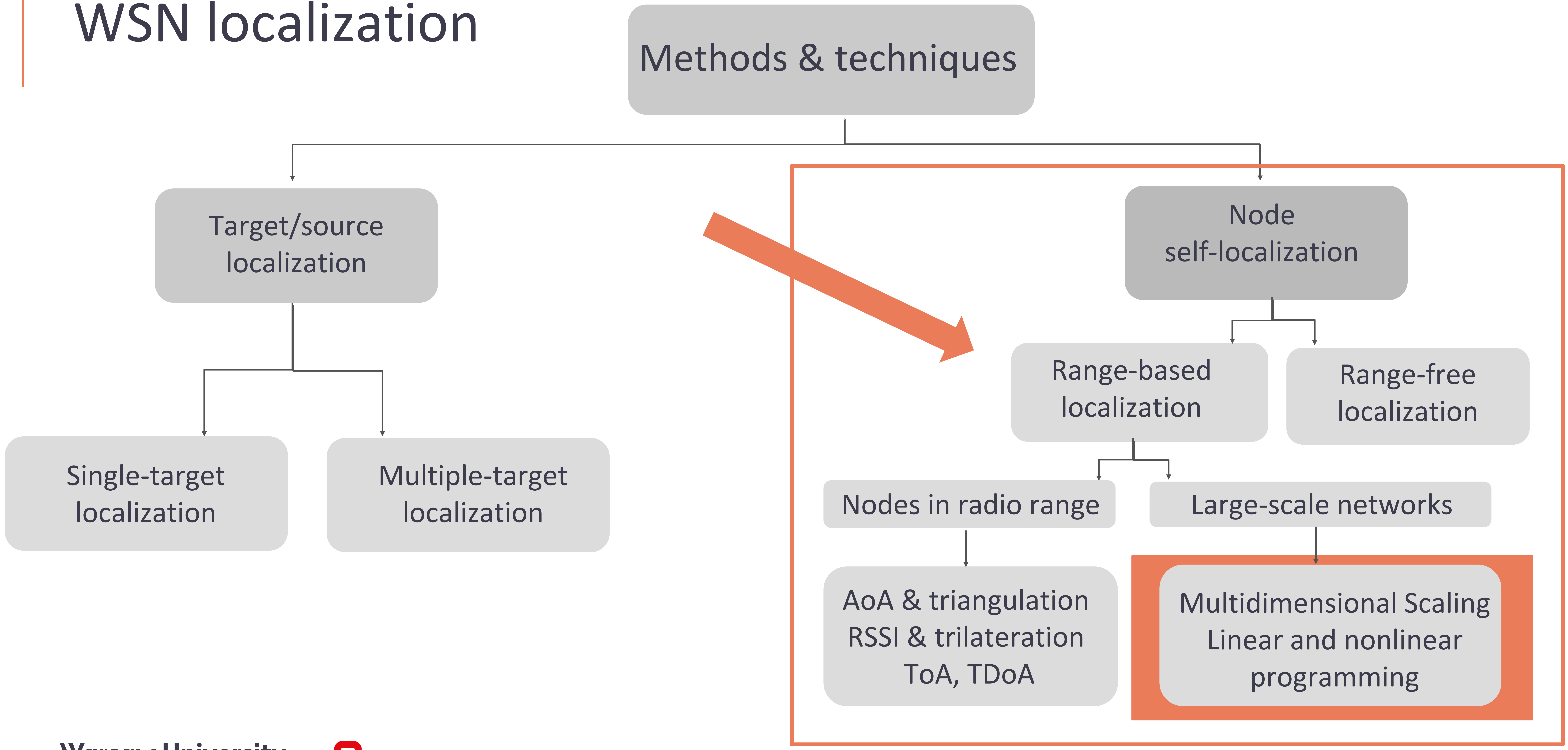
A self-organized ad hoc network can consist of sensors with initially unknown positions in the workspace

Localization task: sensing devices positions estimation

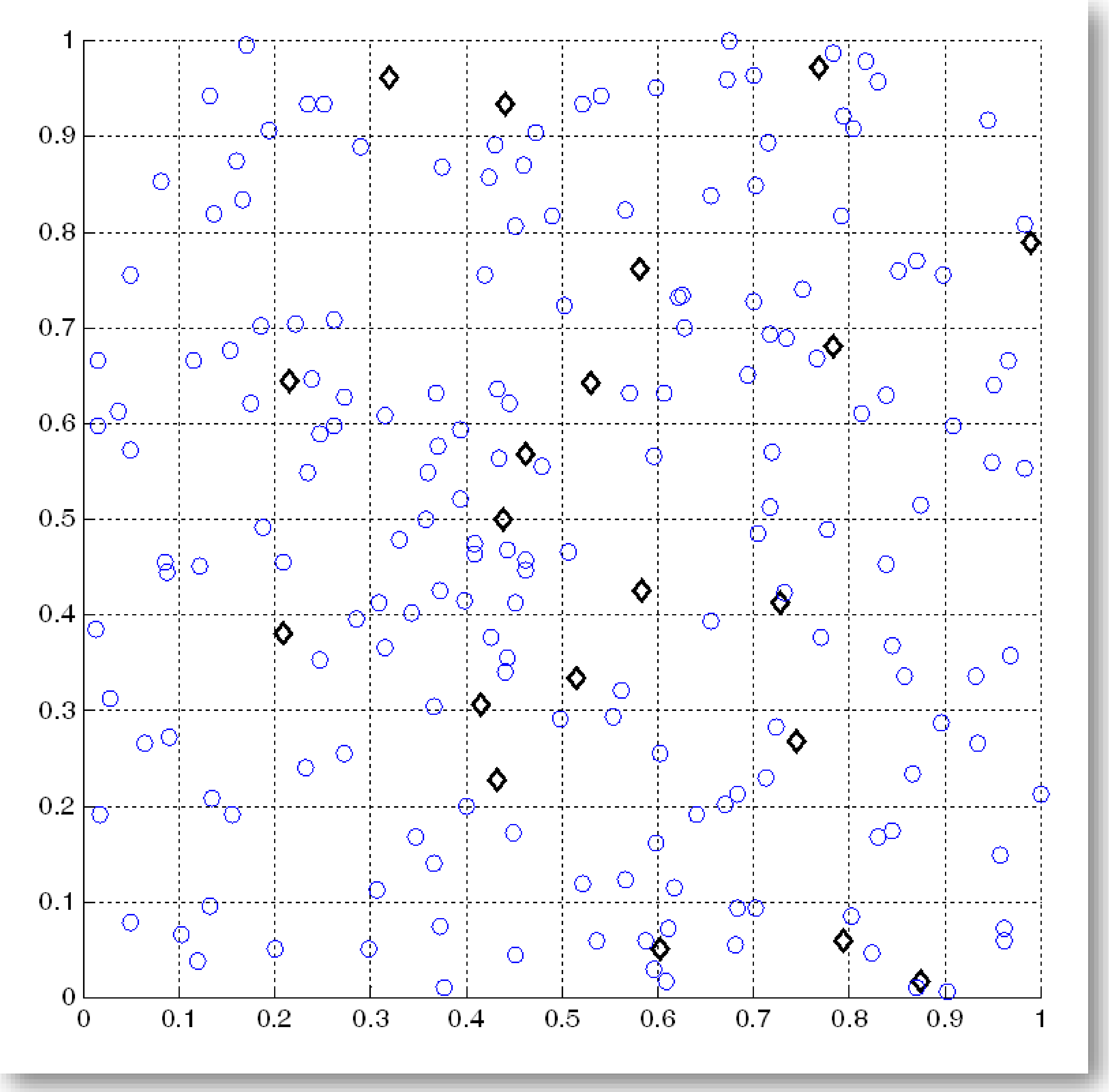




WSN localization



Localization problem: distance-based method



Let us consider the network

K – total number of anchor nodes

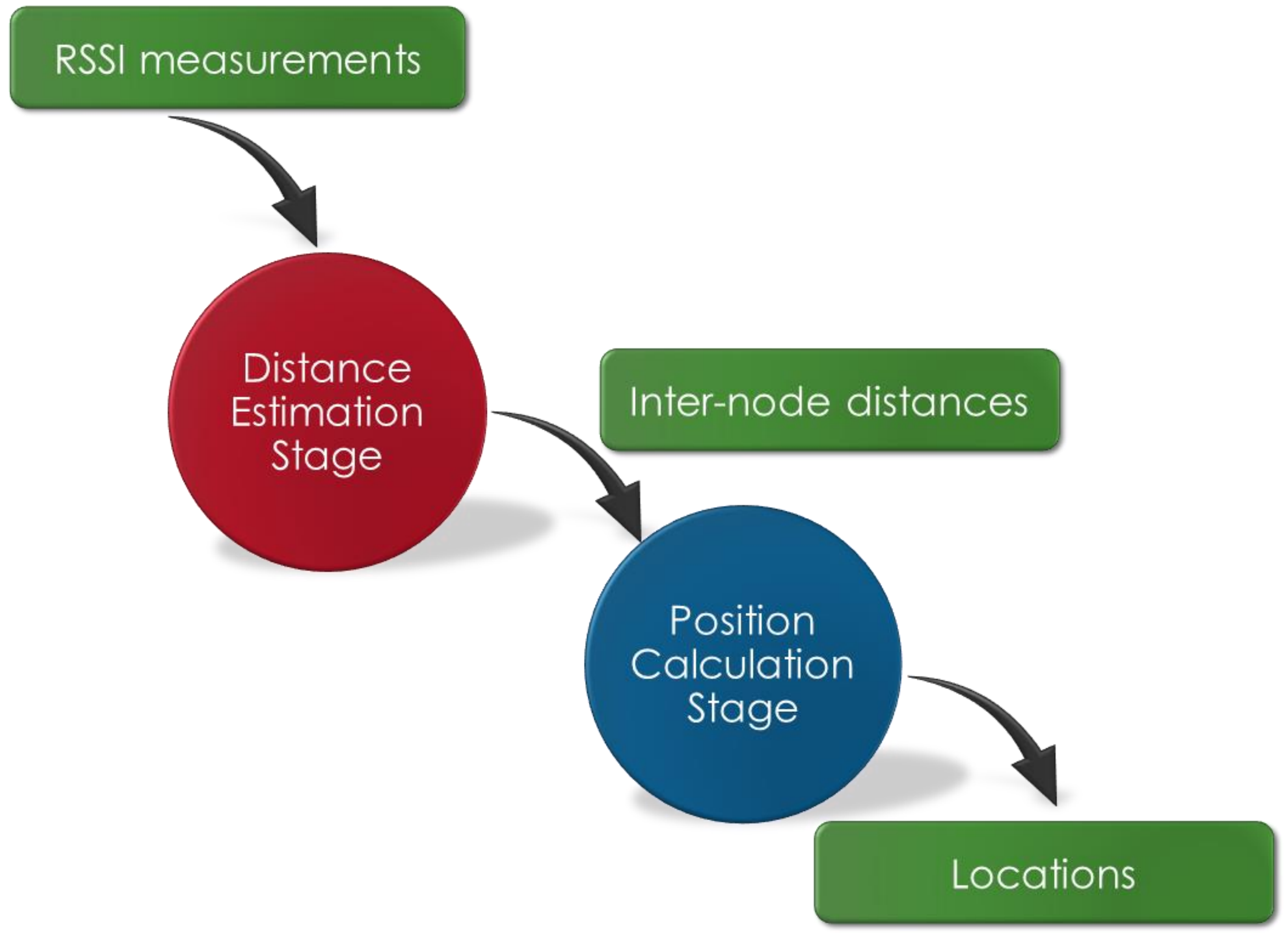
M – total number of non-anchor nodes

The goal

find the location of non-anchor nodes

◇ - **anchor nodes**

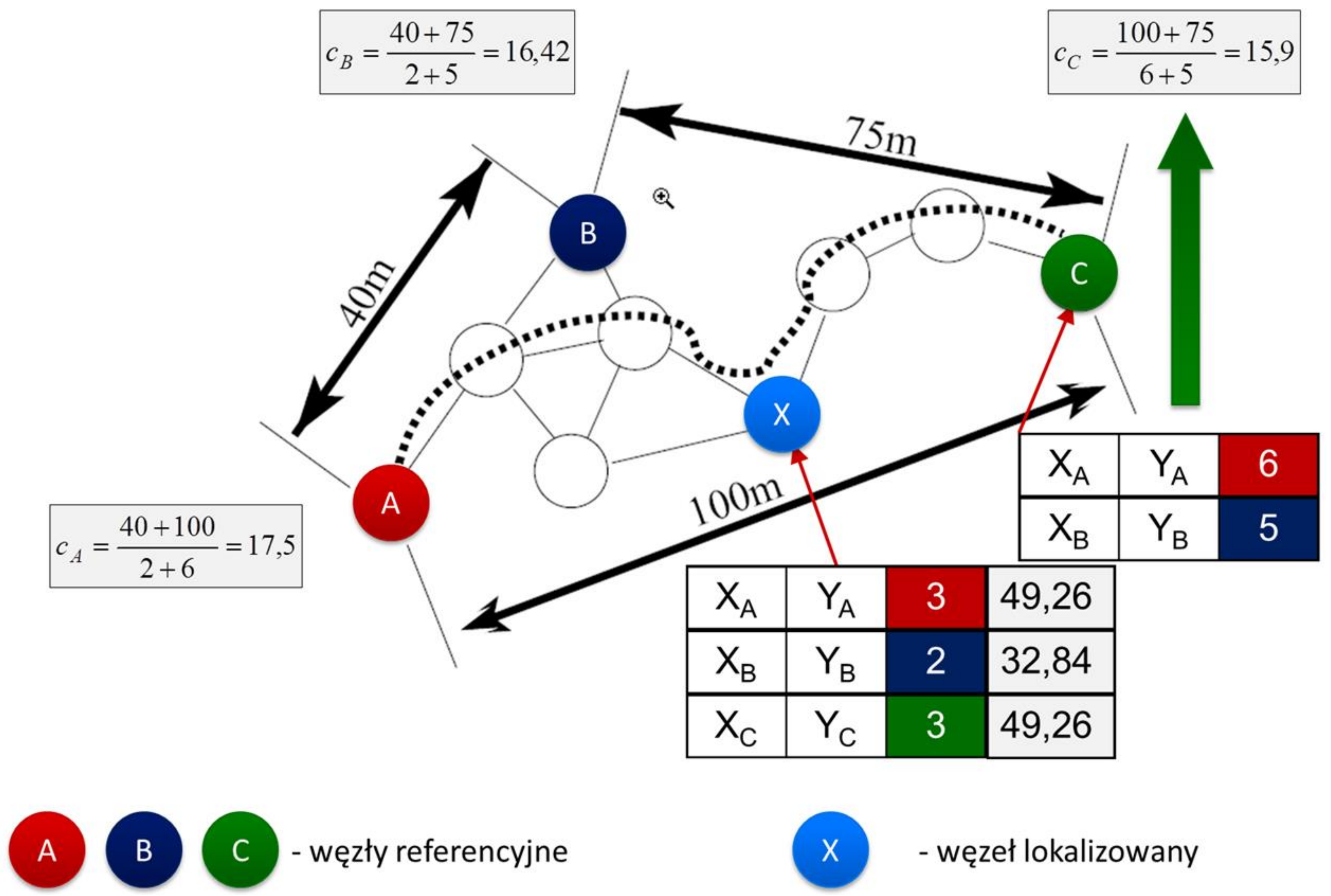
○ - **non-anchor nodes**



Range-based vs range-free localisation

Connectivity-based (range-free) localization algorithms

- APS - Ad Hoc Positioning System [D. Niculescu and B. Nath]
- SDP - Convex position estimation in wireless sensor networks [L. Doherty, K. Pister, L. El Ghaoui]
- MDS - Localization from Connectivity in Sensor Networks [Y.Shang, W. Ruml, Y. Zhang]

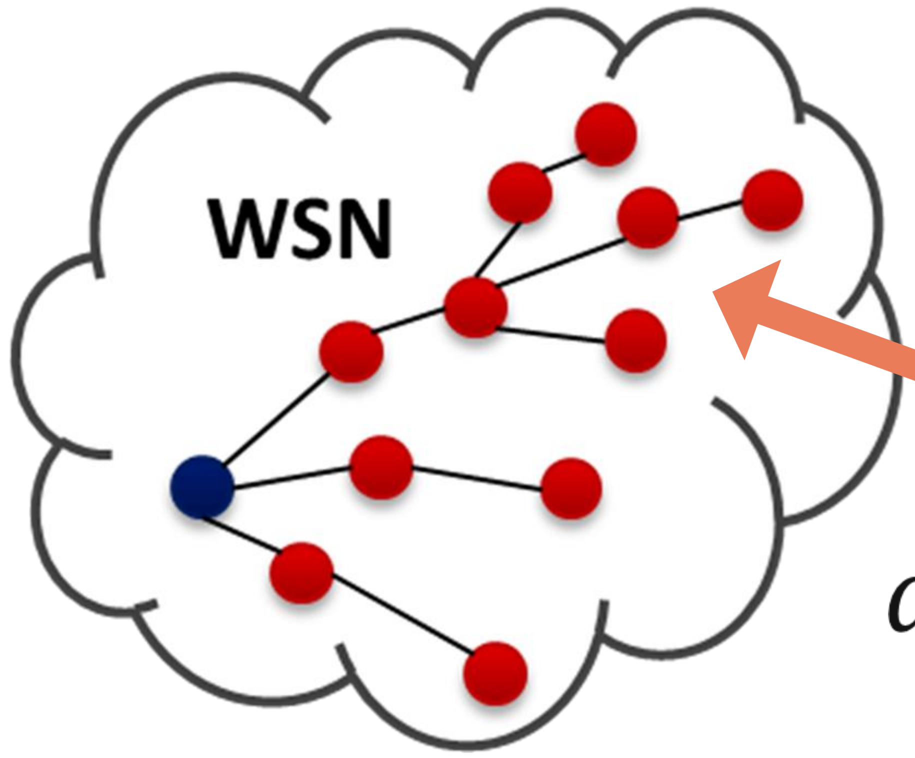


Distance-based (range-based) localization algorithms

- Semidefinite programming for ad hoc wireless sensor network localization [P. Biswas and Y. Ye]
- Simulated Annealing-based localization in Wireless Sensor Networks [A. Kannan, G. Mao, B. Vucetic]
- Two-phase Stochastic Optimization to Sensor Network Localization [M. Marks, E. Niewiadomska-Szynkiewicz]

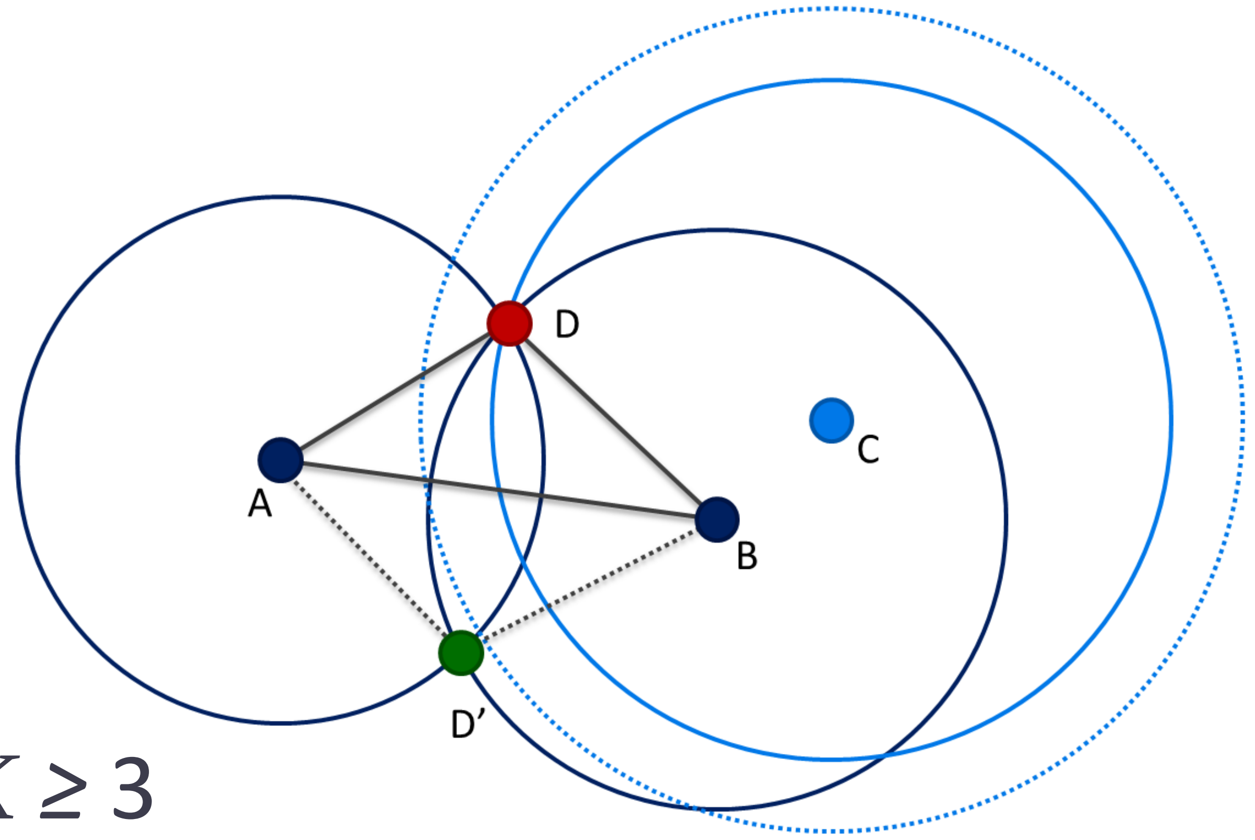
Inter-node distances estimation

- RSSI (received signal strength indicator)
- Wireless channel model



$$d_{ij} = d_0 \cdot 10^{(P^t - Pl(d_0))/10n} \cdot 10^{-P^r_{ij}/10n}$$

Two-stage method with correction



Phase I

The auxiliary solution (initial localization) is produced

Phase II

The solution of the first phase is modified by applying simulated annealing

Trilateration

Calculate $\mathbf{c} = [x,y,z]$ for $k=1,\ldots,K$, $K \geq 3$

$$d_k = \left\| \mathbf{c} - \mathbf{c}_k^r \right\|_2$$

Nonlinear optimization

Solve the optimization problem with estimated distances between all neighbors from sets SN_k and SN_i

$$\min_{c_i, i=1,\ldots,M} \left\{ J = \sum_{k=1}^{K} \sum_{j \in SN_k} \left(\left\| c_k^r - c_j \right\| - \tilde{d}_{kj} \right)^2 + \sum_{i=1}^{M} \sum_{j \in SN_i} \left(\left\| c_i - c_j \right\| - \tilde{d}_{ij} \right)^2 \right\}$$

Anchor nodes (known position)

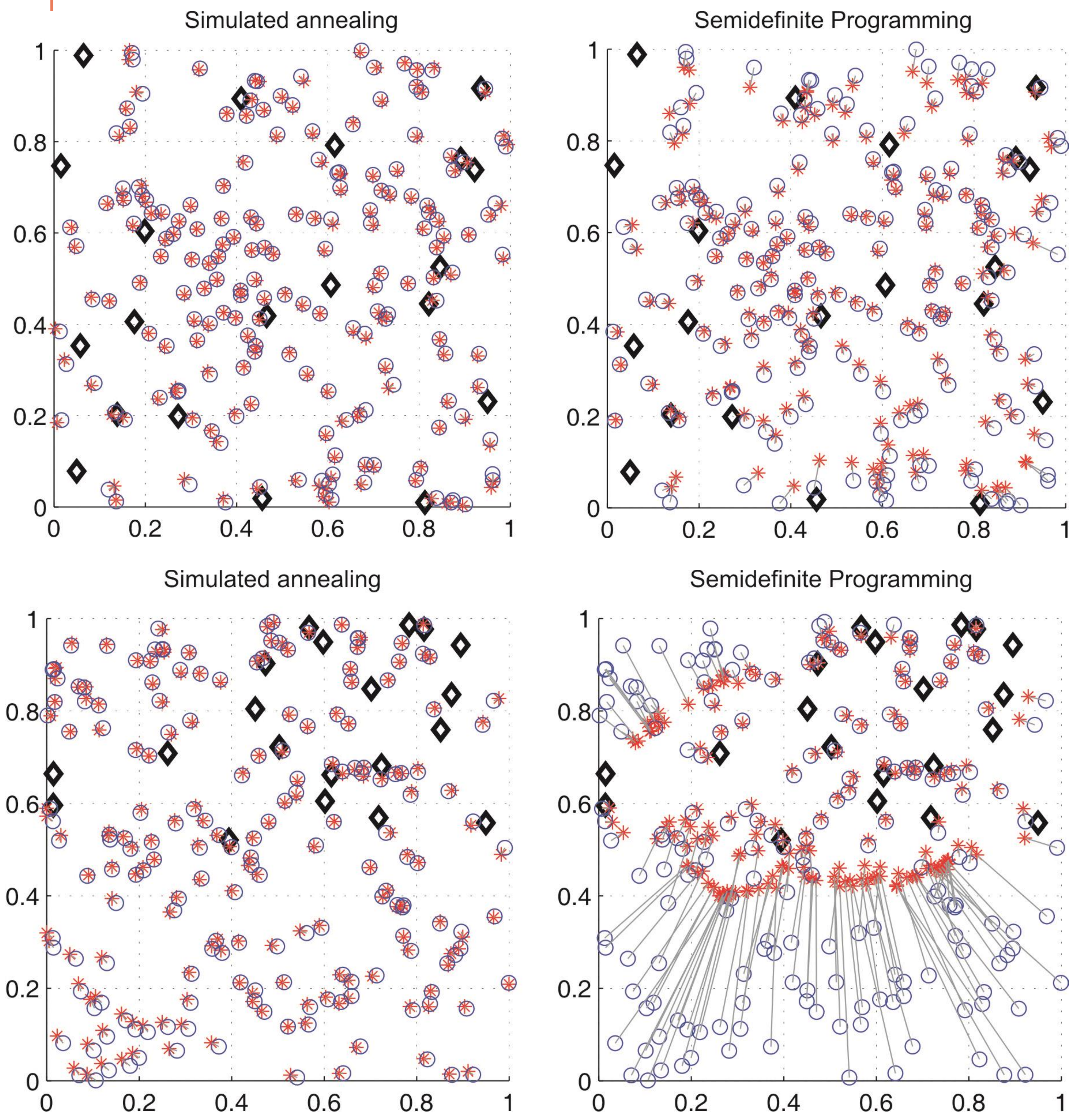
Distance (neighbors)

Localized nodes (unknown position)

TSA: Trilateration & Simulated Annealing

TGA: Trilateration & Genetic Algorithm

WSN localization – simulation results



S1

S3

Location error

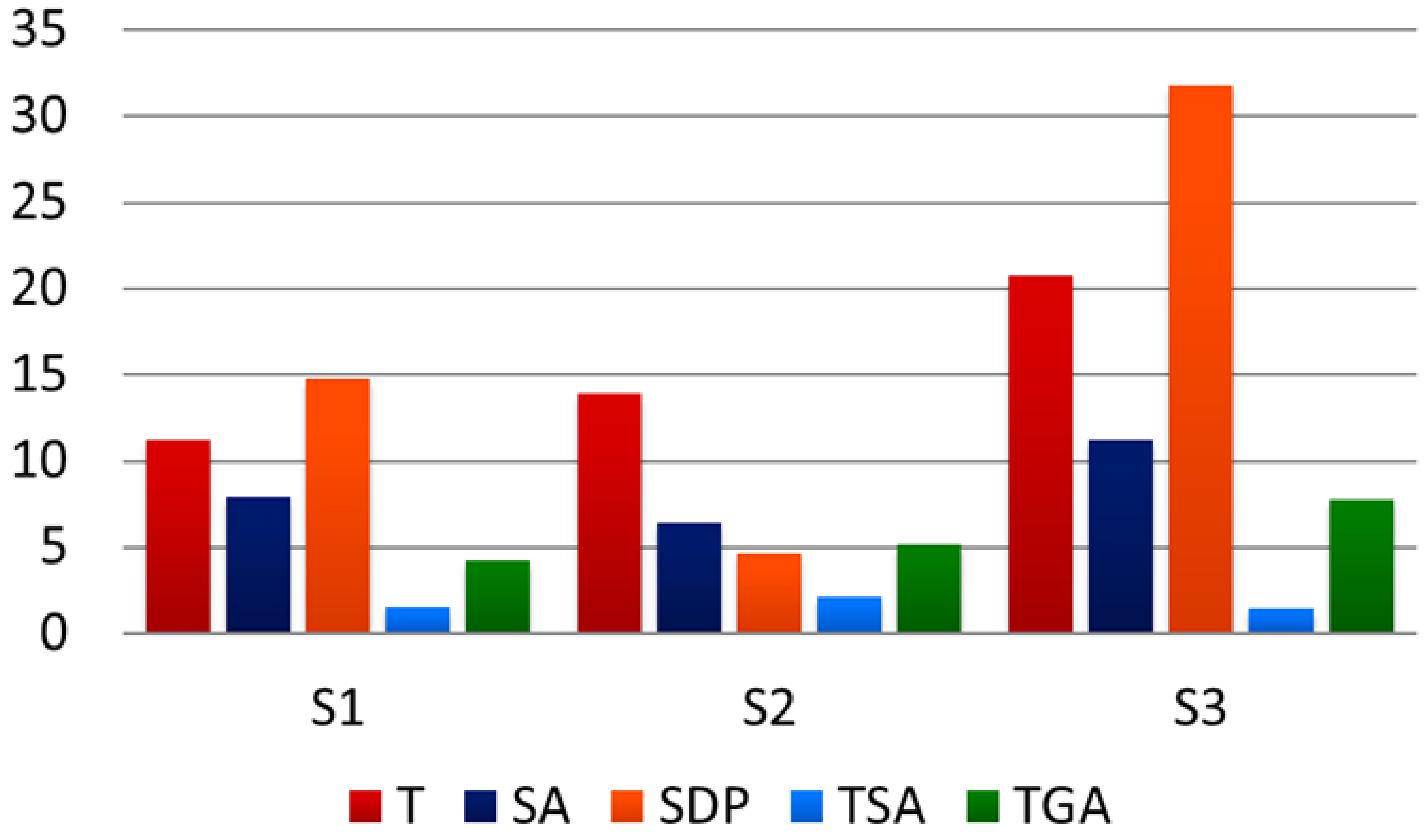
calculated position ↓   real position ↓

$$LE = \frac{1}{M}\sum_{i=1}^{M}\frac{\|\mathbf{c}_i - \bar{\mathbf{c}}_i\|_2^2}{r^2}100\%$$

anchor nodes - ◇

non-anchor nodes:

- real position ○
- calculated position ✳



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WSN localization: testbed networks

WSN inside the building

8 sensors + 1 base station

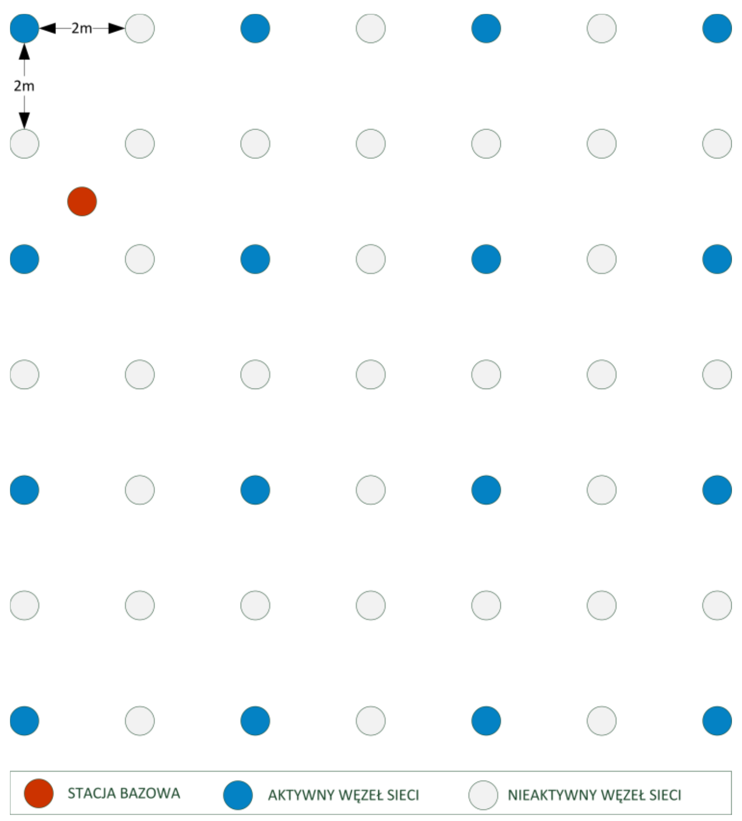
Methods: APS (DV-hop), APS (DV-distance)

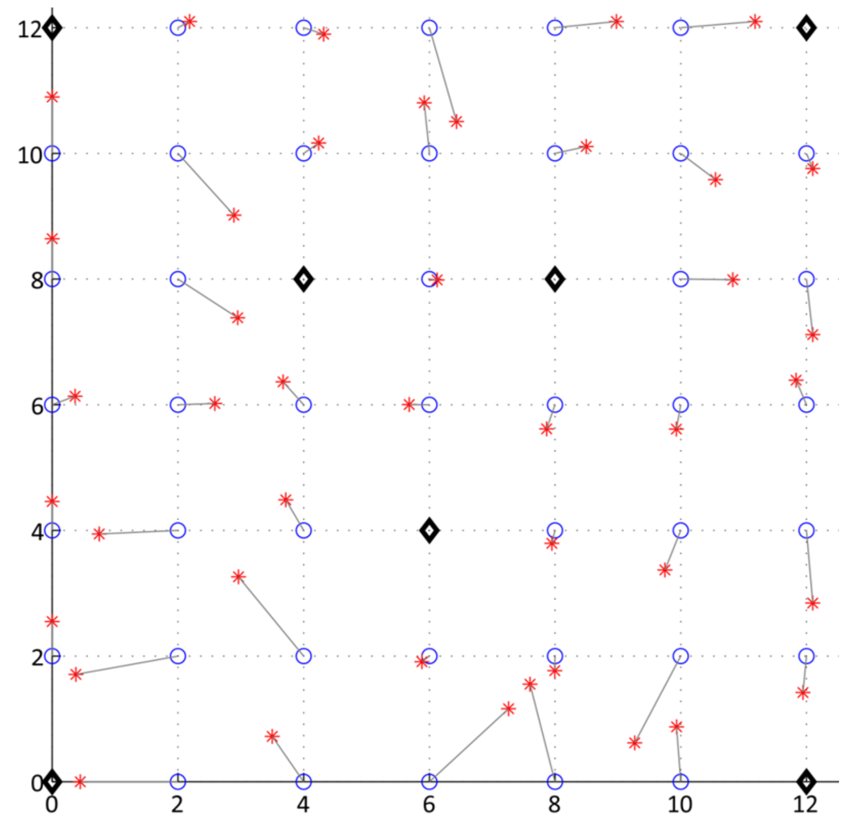
Method	LE: simulation	LE: testbed
DV-hop	55.34 %	**62.72 %**
DV-distance	16.67 %	**49.87 %**

WSN in the open space

49 sensors (7 anchor nodes)

Method: TSA



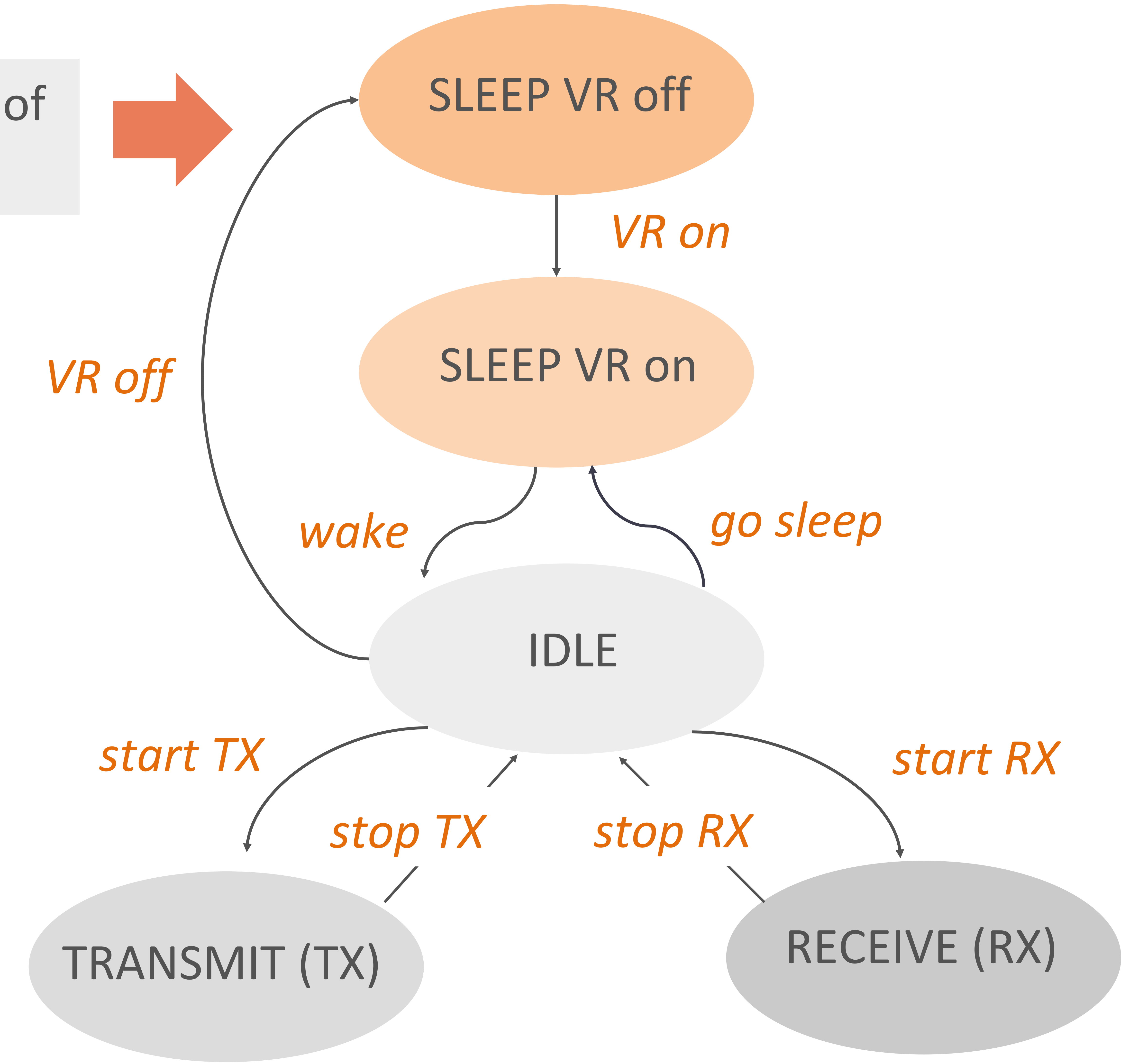


Method	LE: simulation	LE: testbed
TSA	0.18 %	**0,94 %**

Problem2: Energy-aware communication

Operating modes of the radio module

Radio mode	Signal strength [dmB]	CC2420 [2400MHz]	CC2500 [2400MHz]
SLEEP VR off [µA]		0.02	0.4
SLEEP VR on [mA]		0.02	0.16
IDLE [mA]		0.426	1.5
RECEIVE [mA]		18.8	16.6
TRANSMIT [mA]	-25	8.5	10.1
	-20	9.0	10.1
	-15	9.9	10.8
	-10	11.2	12.2
	-5	13.9	15.6
	0	17.4	21.2

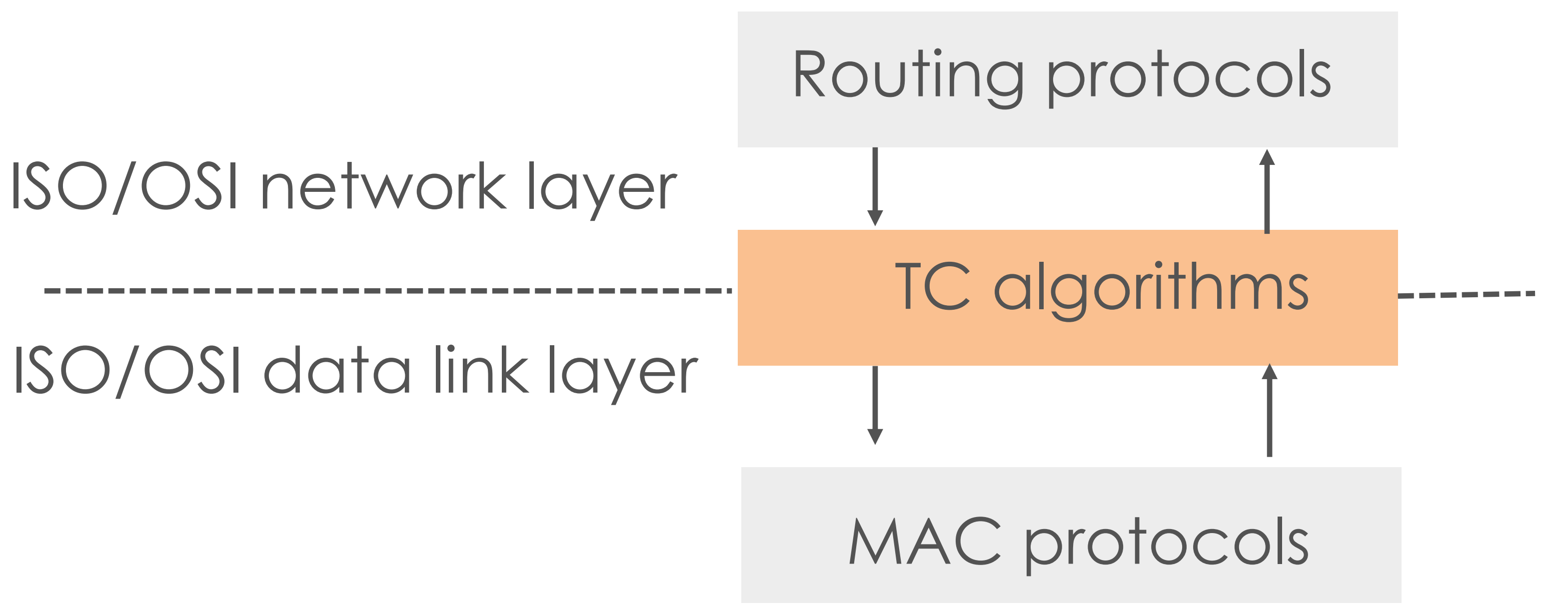


Energy-aware WSN: techniques

1. Topology control (TC)

Sensors deployment and transmission management guarantee:

- network integrity
- high transmission quality
- low energy costs

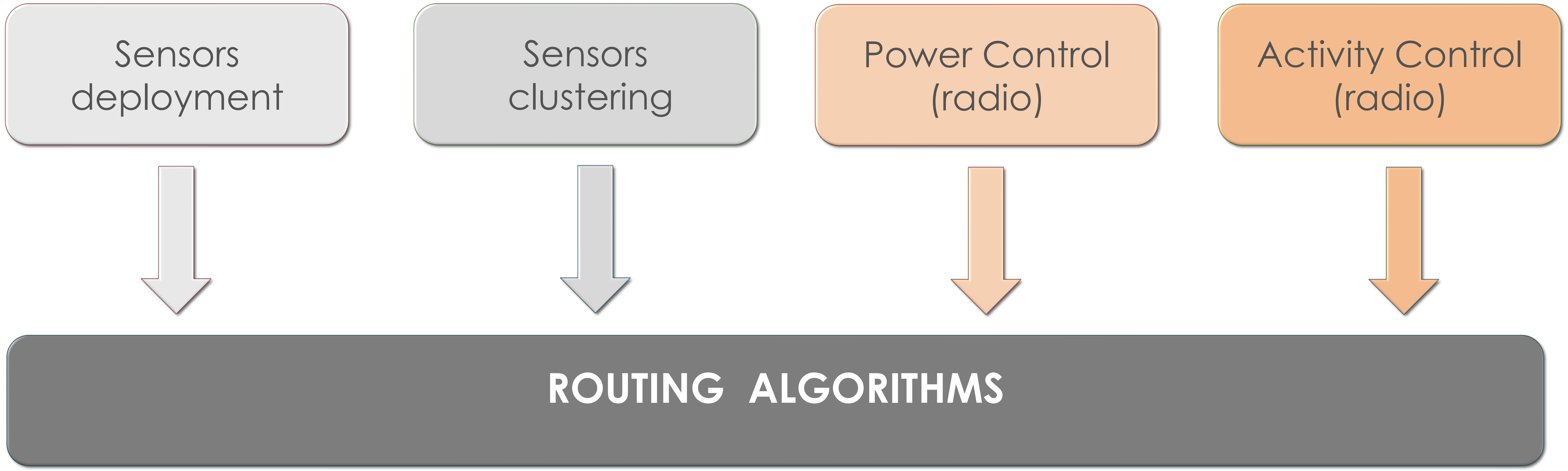


2. Media access control

Energy-aware MAC protocols

3. Routing

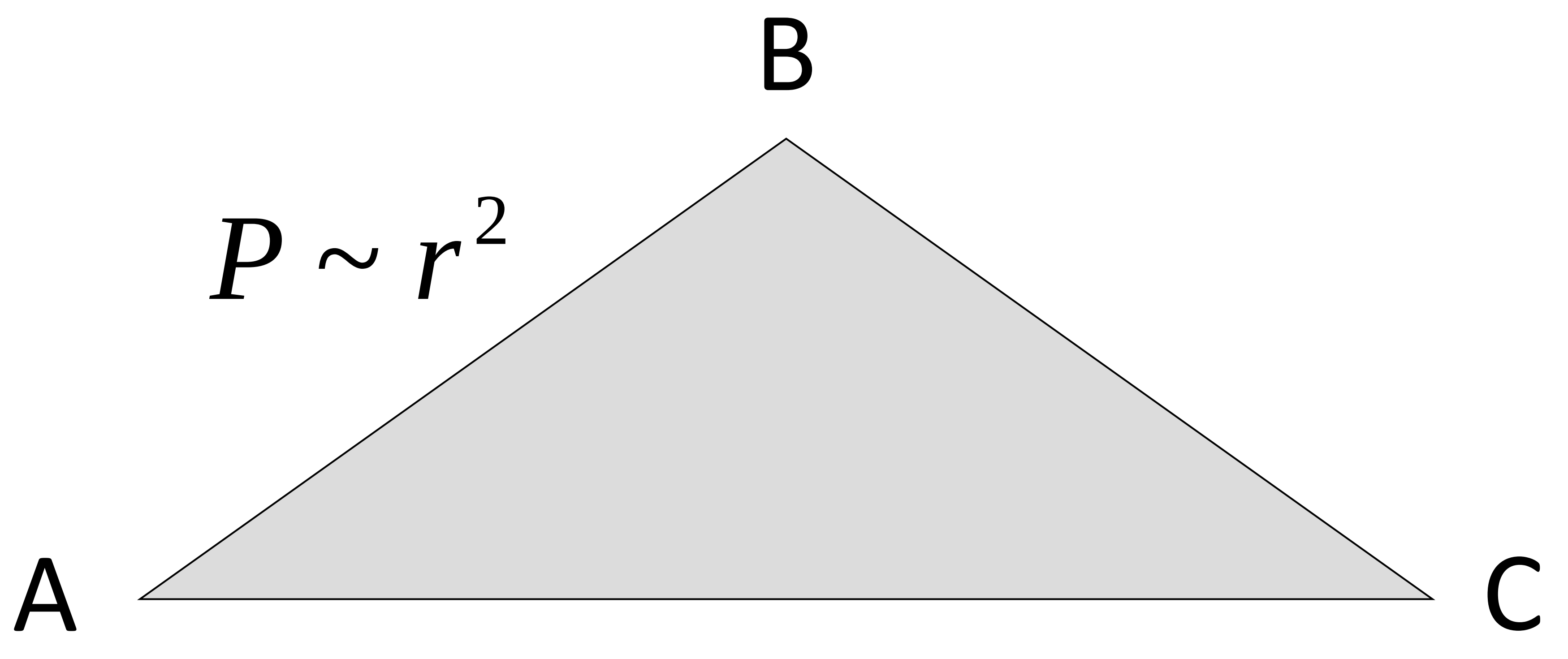
Energy-efficient routing protocols



Power control algorithms

Short transmissions

- involve smaller power consumption
- cause less interference and latency



$$|AC|^2 = |AB|^2 + |BC|^2 - 2|AB||BC|\cos(ABC)$$

Location-based topology control

- **R&M**: Minimum Energy mobile wireless networks [V. Rodoplu, T. Memg]
- **LMST**: Design and analysis of an mst-based topology control algorithm [N. Li, J. Hou, L. Sha]
- Comparative study of wireless sensor networks energy-efficient topologies and power save protocols [E. Niewiadomska-Szynkiewicz, P. Kwaśniewski, I. Windyga]
- Energy Aware Communication Protocols for Wireless Sensor Networks [E. Niewiadomska-Szynkiewicz]

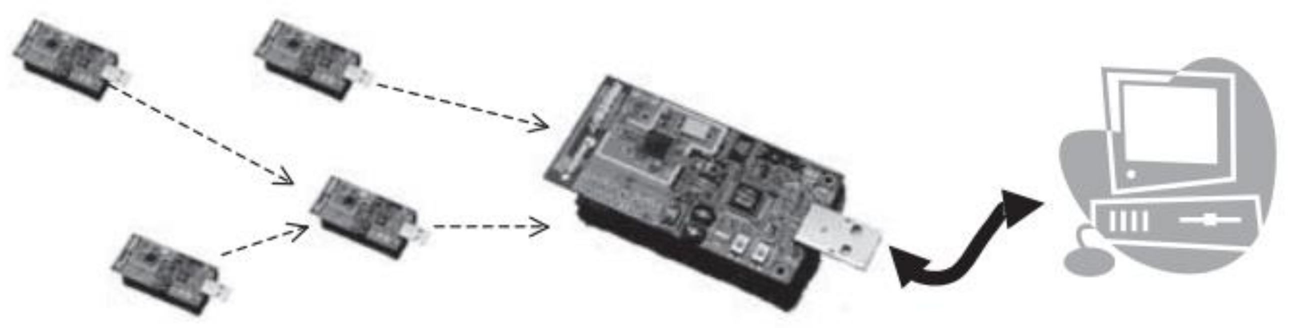
Neighbor-based topology control

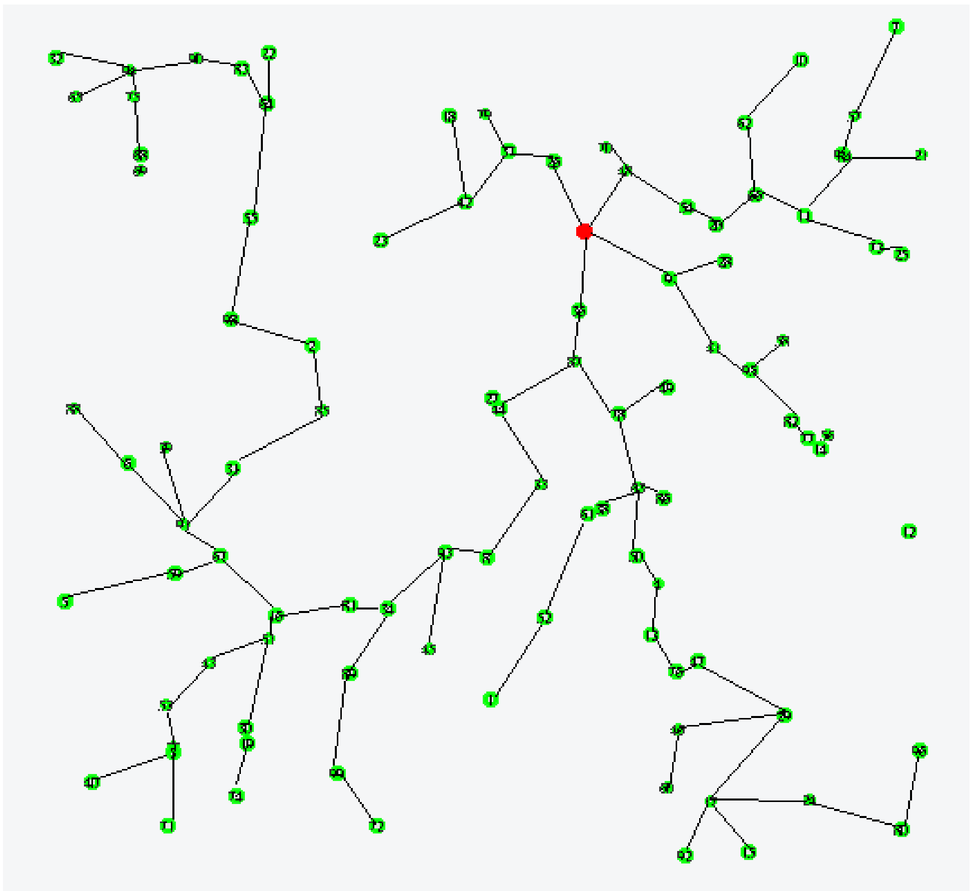
- **Kneigh**: The k-neighbors protocol for symmetric topology control in ad hoc networks [D. Blough, M. Leoncini, G. Resta, P. Santi]
- **XCT**: A practical topology control algorithm for ad hoc networks [R. Wattenhofer, A. Zollinger]

Direction-based topology control

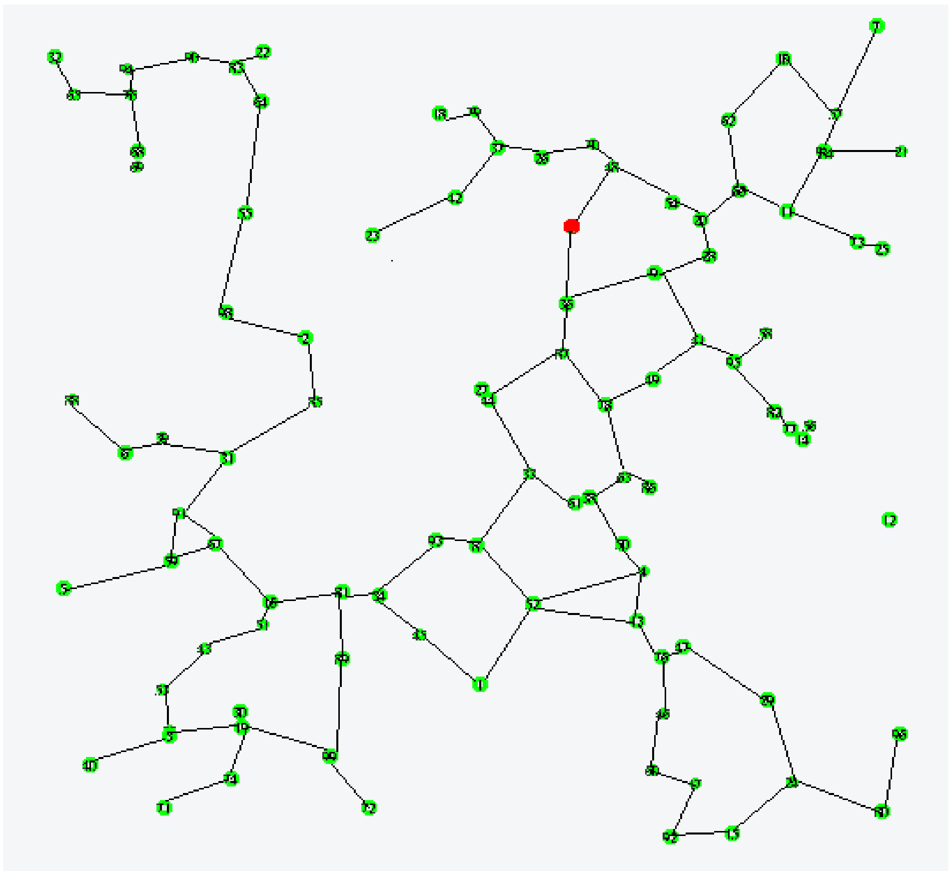
- **CBTB**: Distributed topology control for power efficient operation in multihop wireless ad hoc networks [R. Wattenhofer, L. Li, P. Bahl, Y. Wang]

Power control algorithms

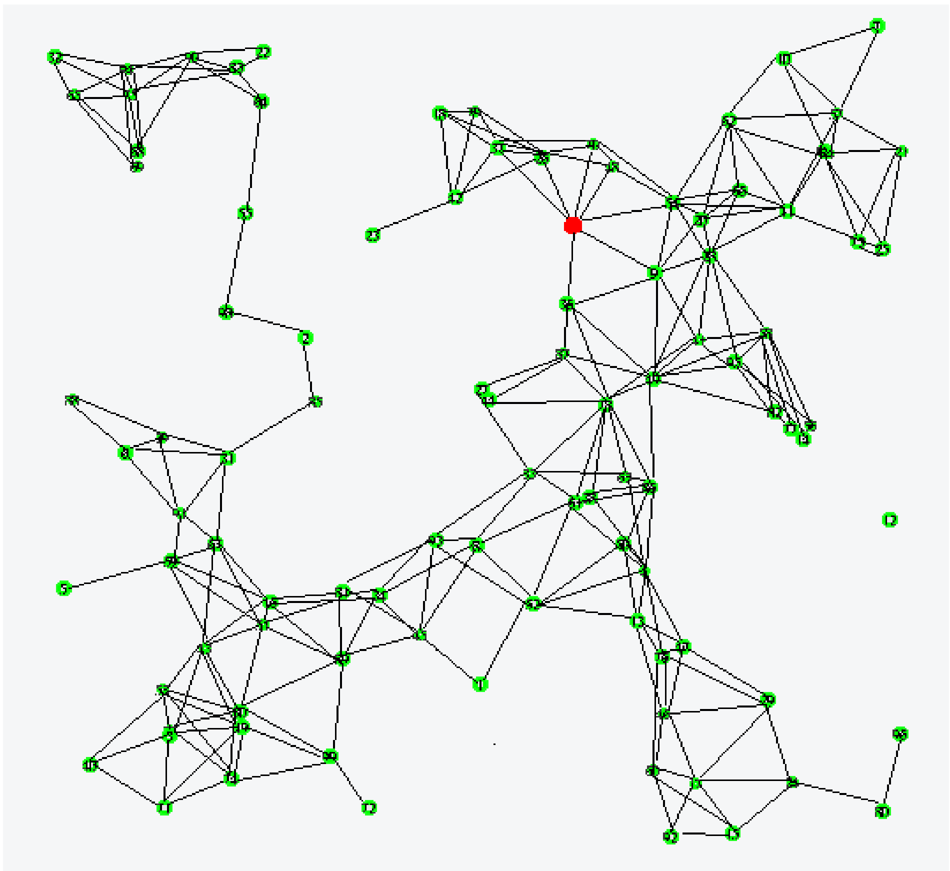




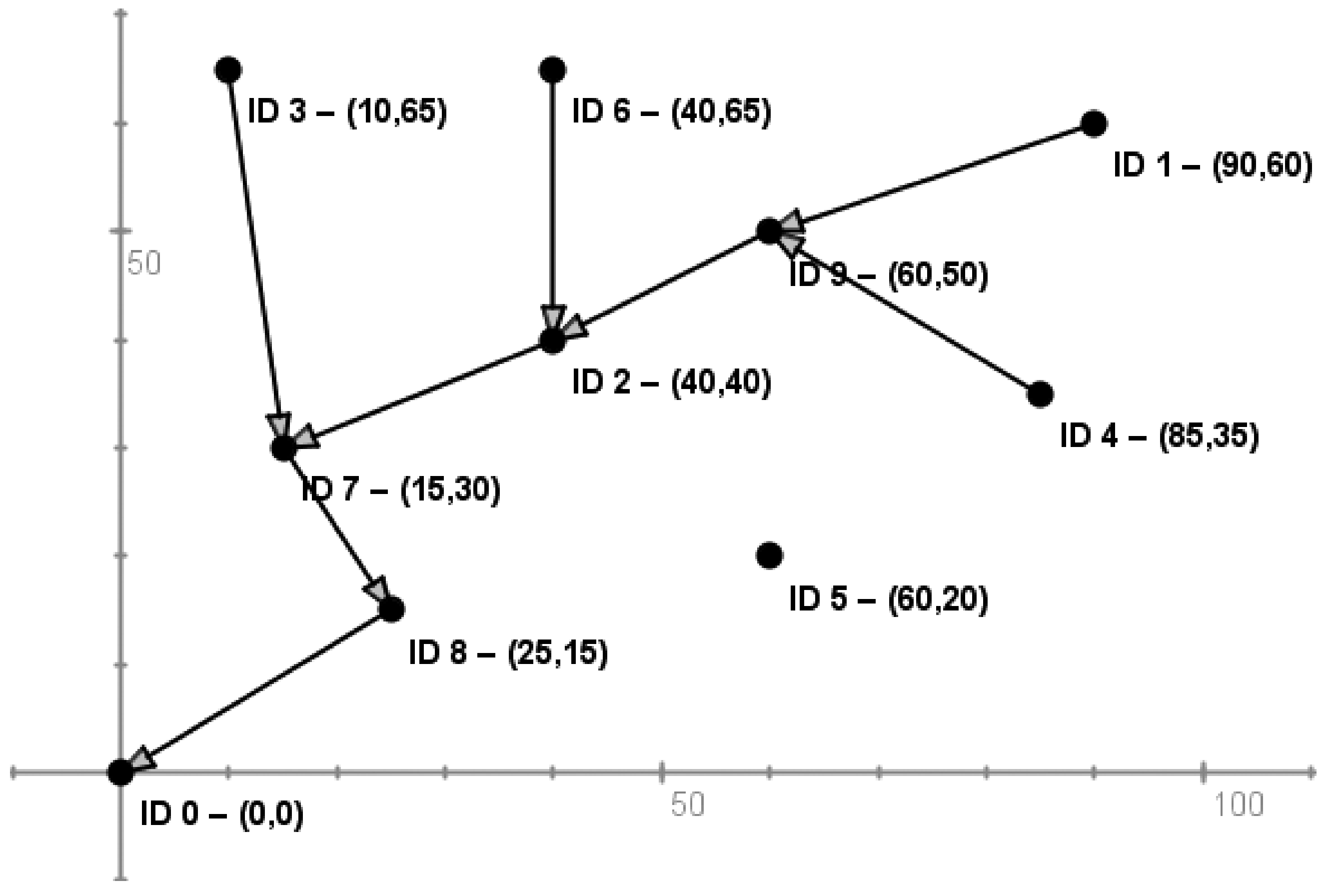
R&M protocol

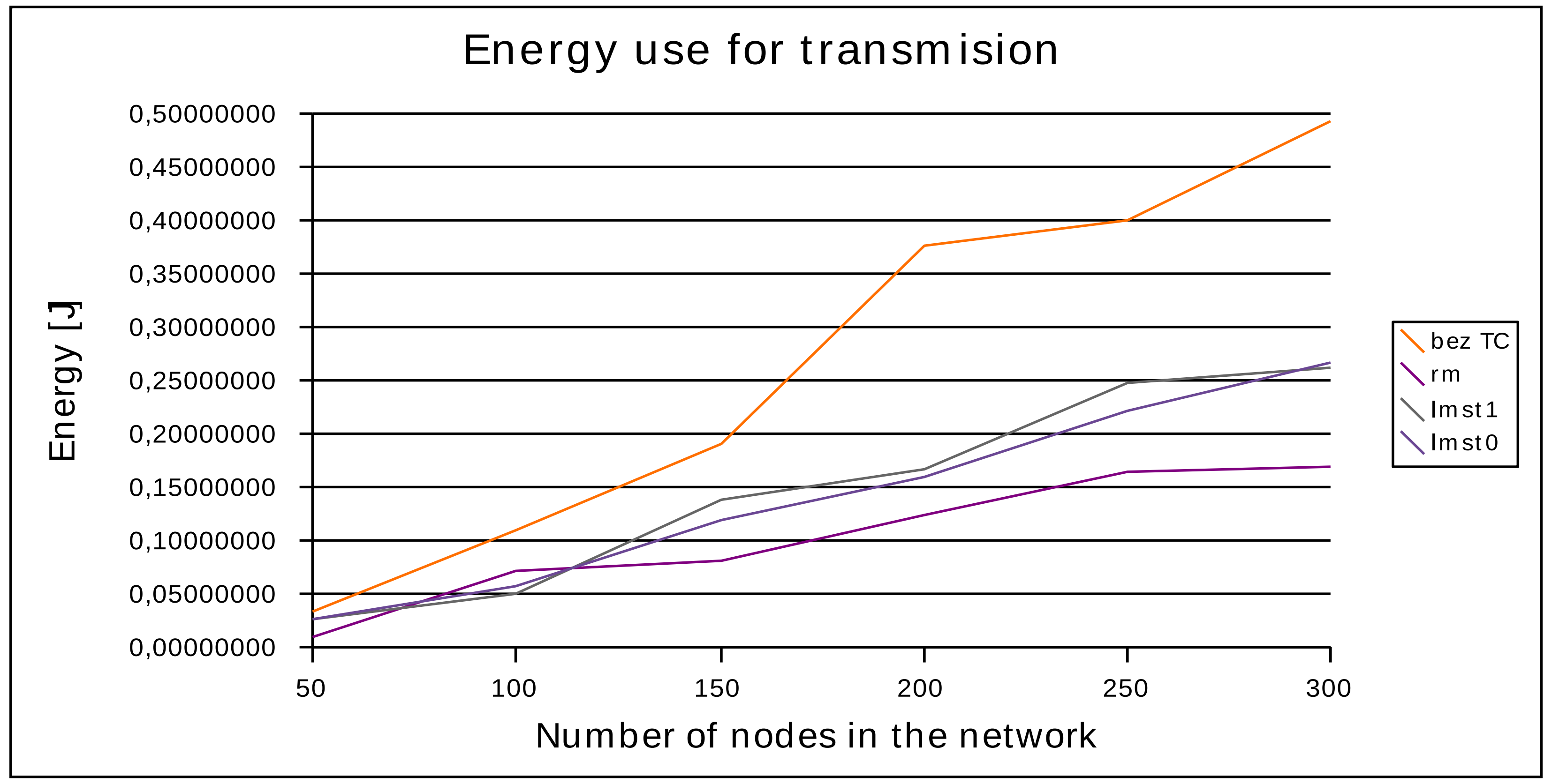


LMST protocol



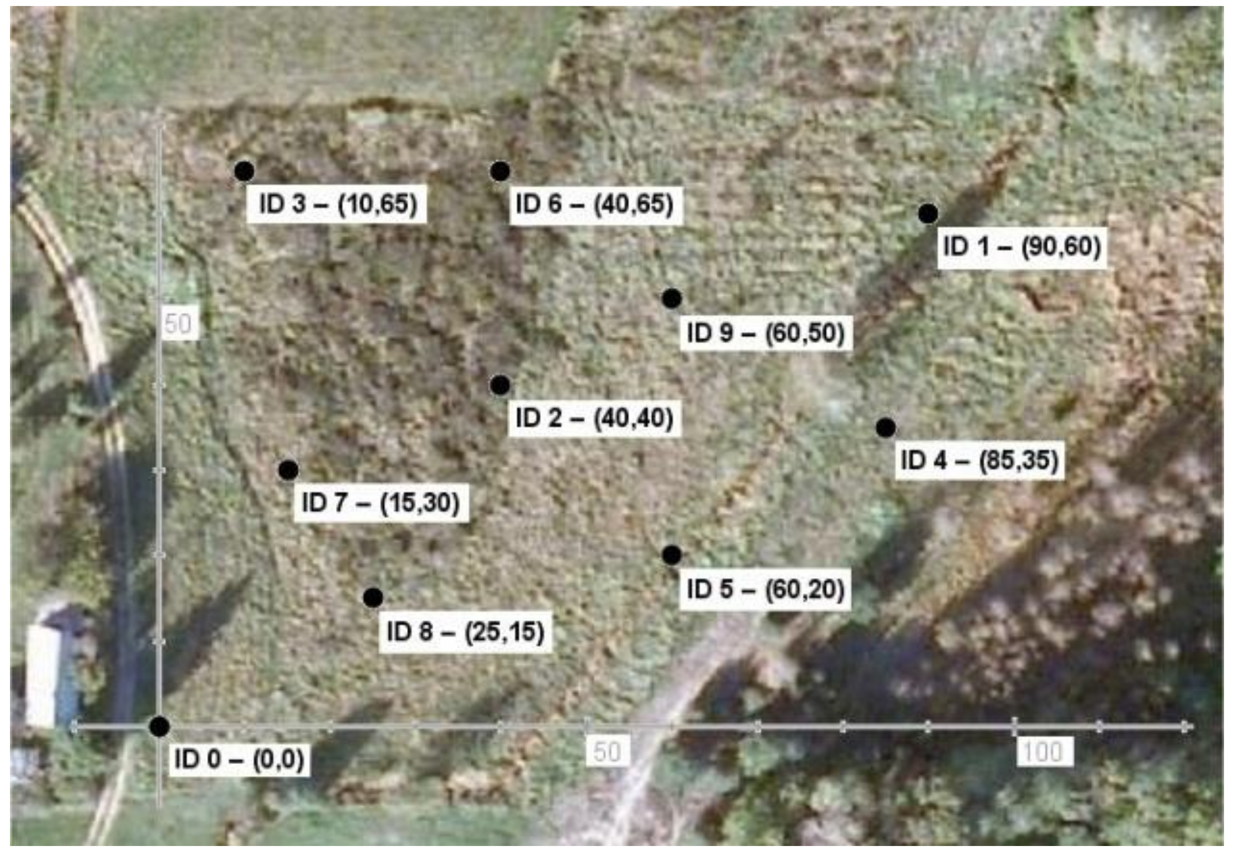
without PC protocols





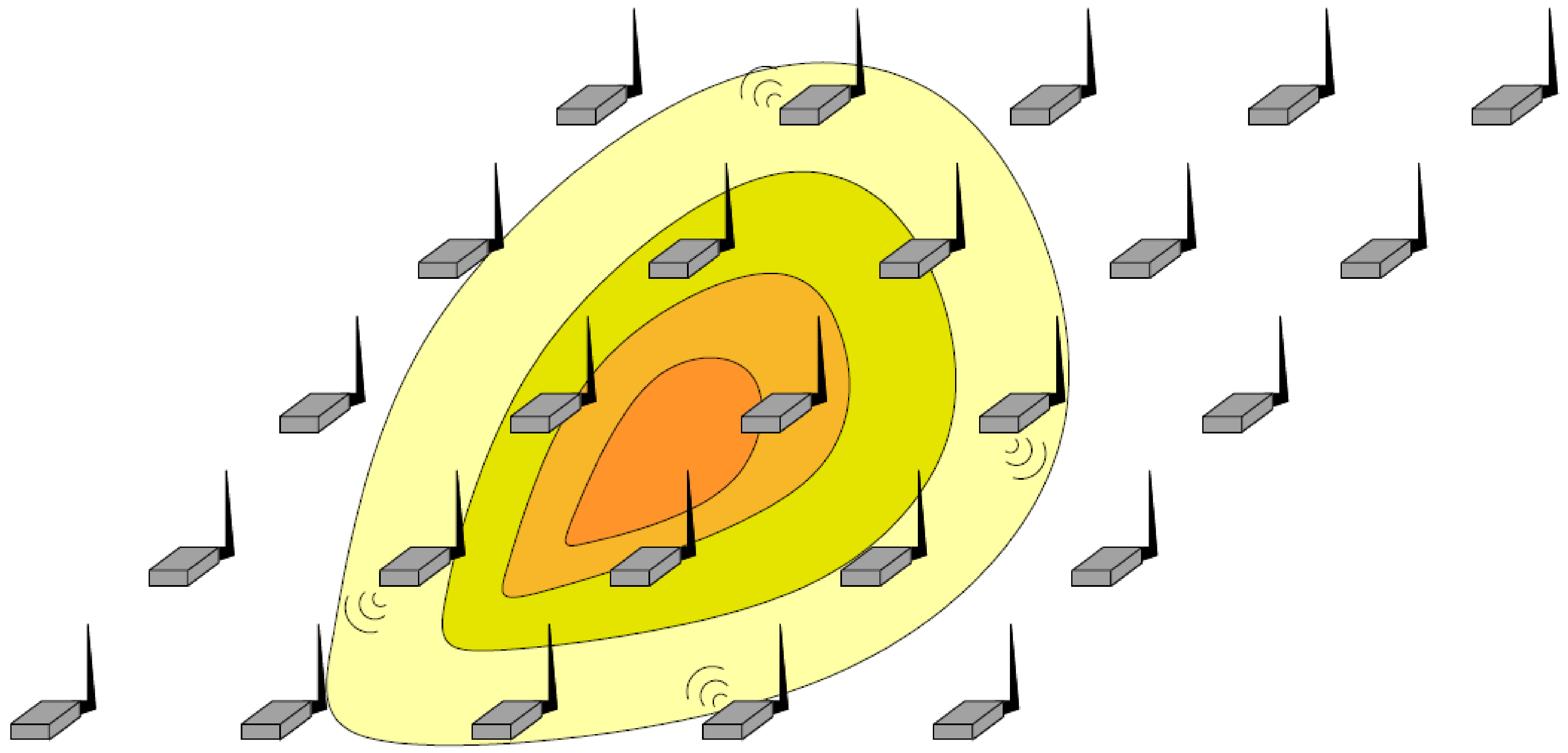
PC location-based protocols

- **R&M** [Rodoplu and Meng]
- **LMST** [Li, Wang, Song]



Activity control algorithms

Due to nodes redundancy and multiple paths selected nodes can be turned off while still guaranteeing full connectivity and maximum link utilization



Clustering-based activity control

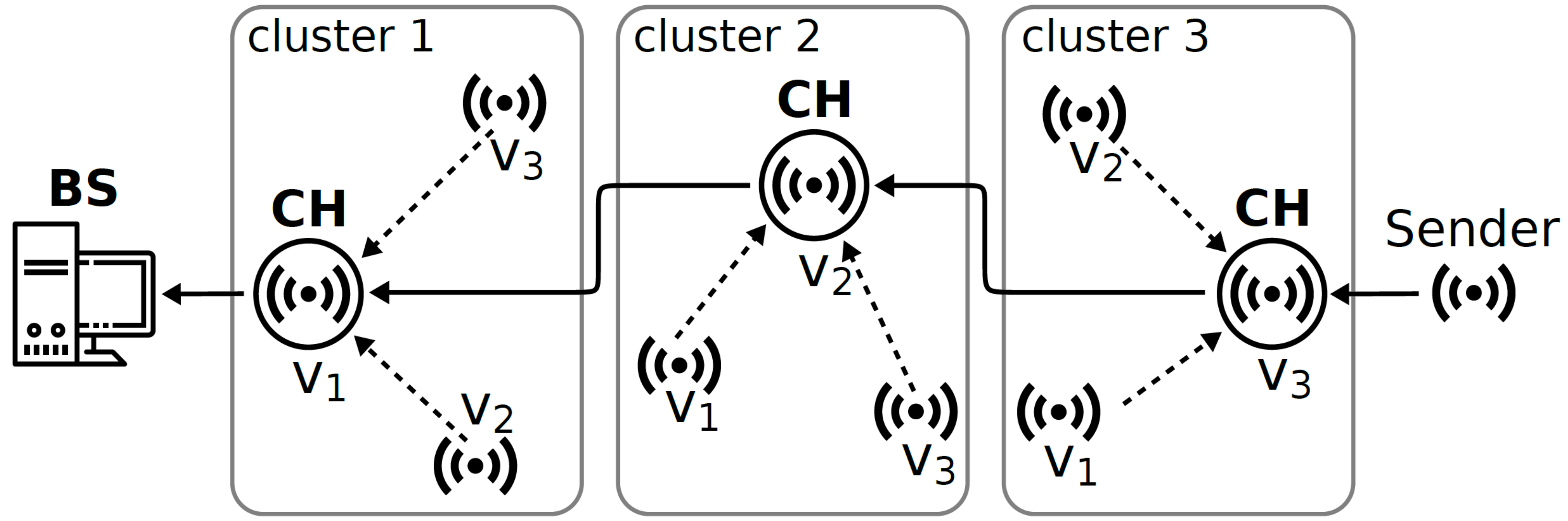
- **LEACH**: Energy-efficient communication protocol for wireless sensor networks [W. Heinzelman, A. Chandrakasan, H. Balakrishnan]
- **LEACH-AODV**: Secure low energy aodv protocol for wireless sensor networks [E. Niewiadomska-Szynkiewicz, F. Nabrdalik]
- **HEED**: Distributed clustering in ad-hoc sensor networks: A hybrid, energy-efficient approach [O. Younis, S. Fahmy]
- **EECS**: An energy efficient clustering scheme in wireless sensor networks [Ye, M., Li, C., Chen, G., Wu, J. Eecs]
- **GAF**: Geography-informed energy conservation for ad hoc routing [Y. Xu, J. Heidemann, D. Estrin]

Other techniques

- **ASCENT**: Ascent: Adaptive self-configuring sensor networks topologies [A. Cerpa, D. Estrin]
- **Span**: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks [B. Chen, K. Jamieson, Hm Balakrishnan, R. Morris]

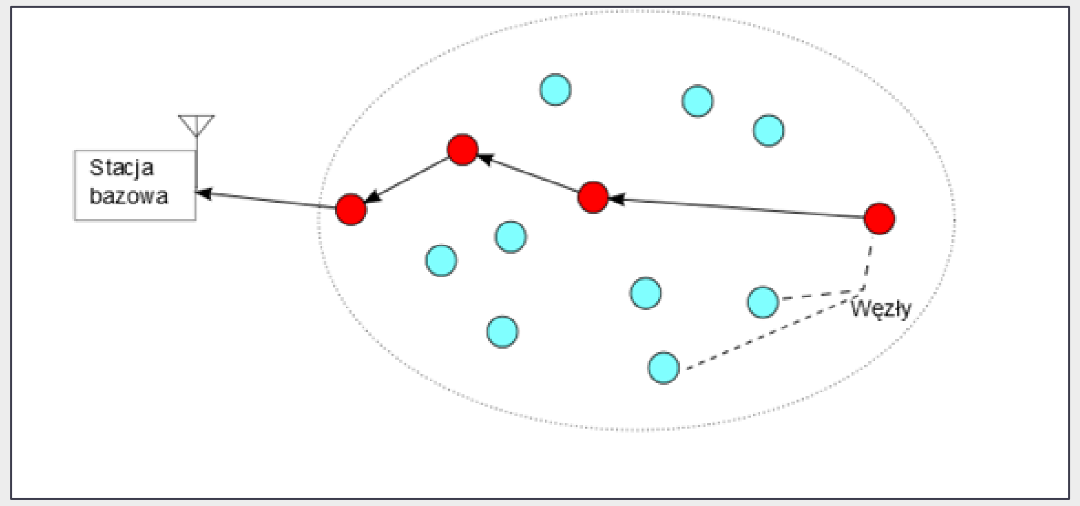
Activity control algorithms

Testbed: MTM-CM5000 motes, TinyOS, IEEE 802.15.4

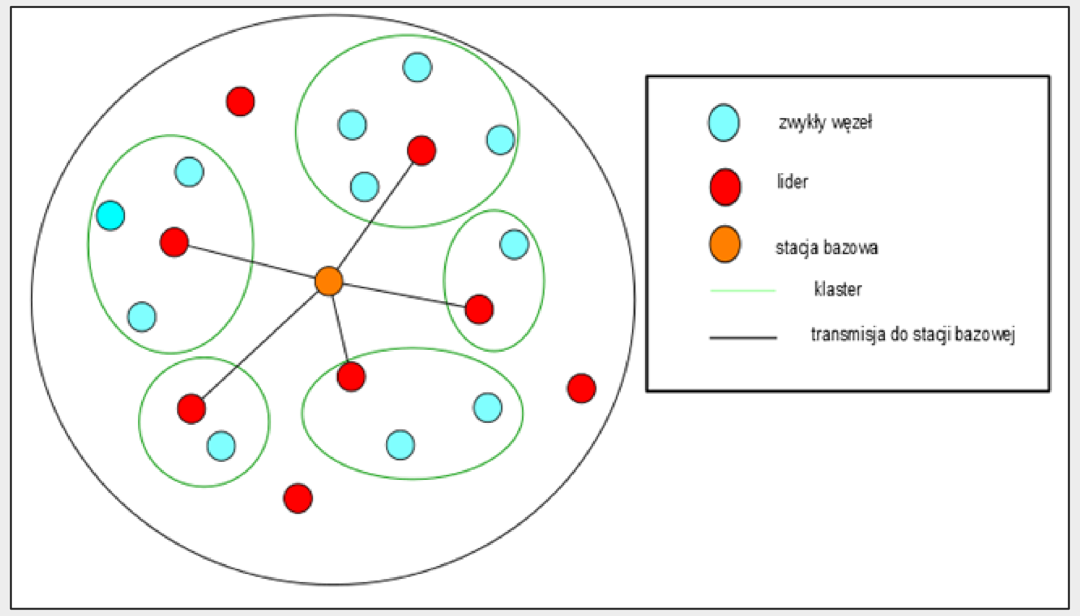


Method	Cluster 1			Cluster 2			Cluster 3		
	v1	v2	v3	v1	v2	v3	v1	v2	v3
AODV (without AC)	30	31	32	32	33	33	35	36	37
LEACH-AODV	41	43	48	46	50	52	48	53	55
GAF-AODV	66	79	82	82	83	84	83	84	85

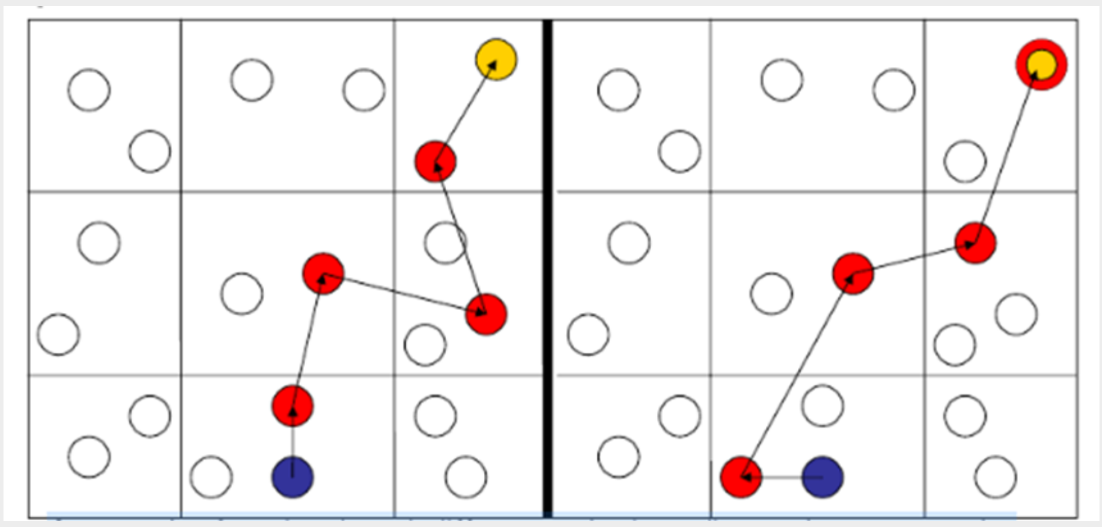
WSN nodes lifetimes in minutes



AODV: Ad-hoc On-demand Distance Vector



LEACH: Low-energy Adaptive Clustering Hierarchy



GAF: Geographic Adaptive Fidelity

Energy-aware: Mixed-Integer-Programming

Total energy consumption

$$\min_{b_i^t, e_i^{kt}} \left\{ J_{total} = \sum_{t=1}^{T} \sum_{i=1}^{N} \sum_{k=1}^{K} \phi_i^{kt} \, e_i^{kt} \right\}$$

$$e_{tk}^{i} = \begin{cases} 1, & \text{radio } i \text{ in energy mode } = k \\ 0, & \text{radio } i \text{ in energy state } \neq k \end{cases}$$

ϕ_i^{kt} - energy consumed at t, energy mode $k=1,\dots,K$

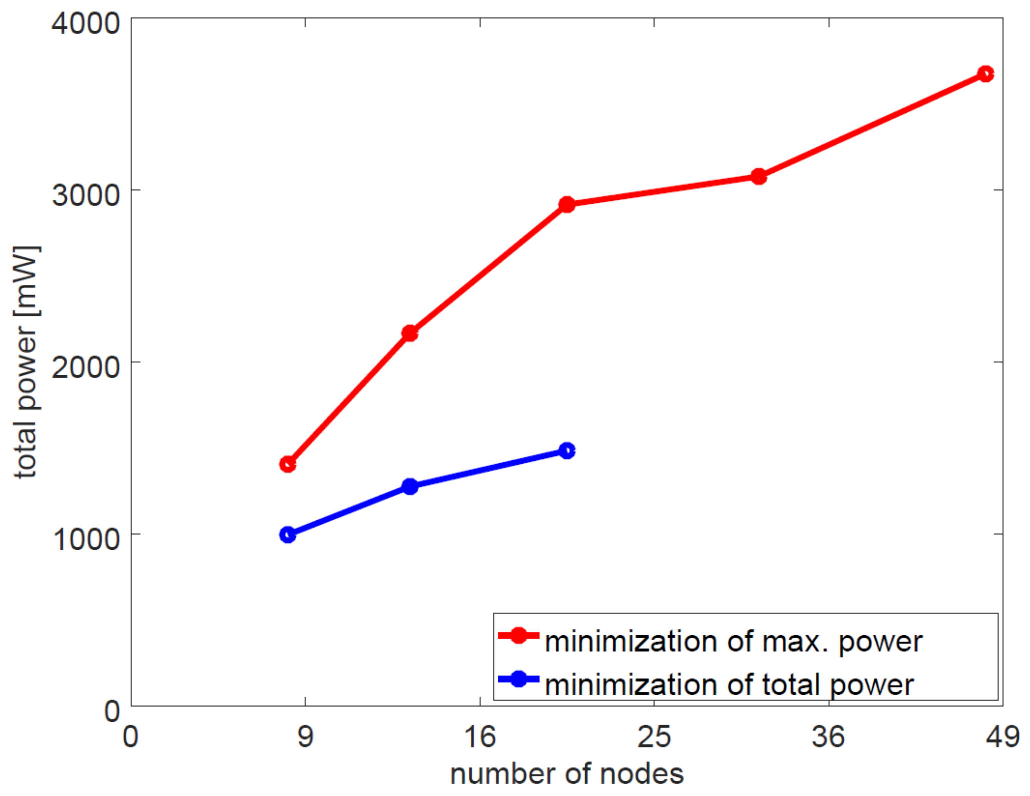
b_i^t - number of data packets for transmission

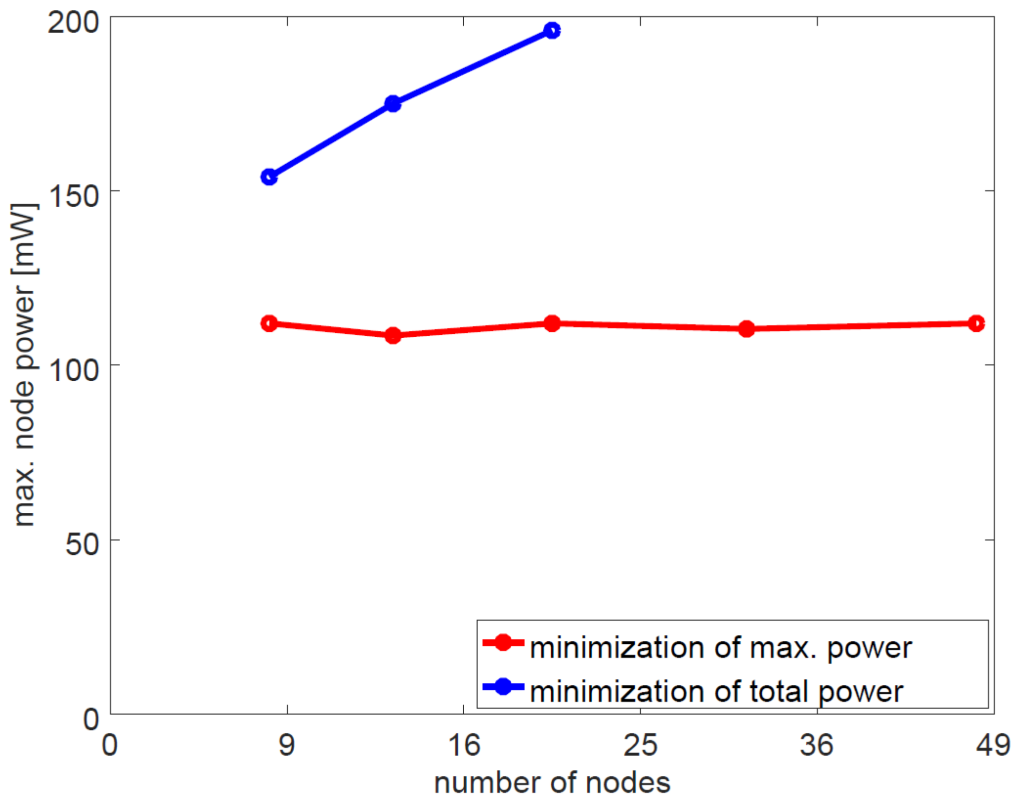
Maximal power consumed by a node

$$\min_{b_i^t, e_i^{kt} z} \{ J_{\max\_n} = z \}$$

$$\sum_{t=1}^{T} \sum_{k=1}^{K} \phi_i^{kt} \, e_i^{kt} \leq z, \qquad i = 1, \dots, N$$

Average total energy consumed by WSN





Maximum energy consumed by a node

Computing and networking architecture

1. Hybrid edge sensor networks (WSNs/MWSNs)

data collection, aggregation, consolidation, categorization, simple analysis, etc.

2. Base stations (BSs)

data fusion, correlation, aggregation, etc.

3. Backbone network

transmitting data from all base stations to the cloud computing servers and/or data center

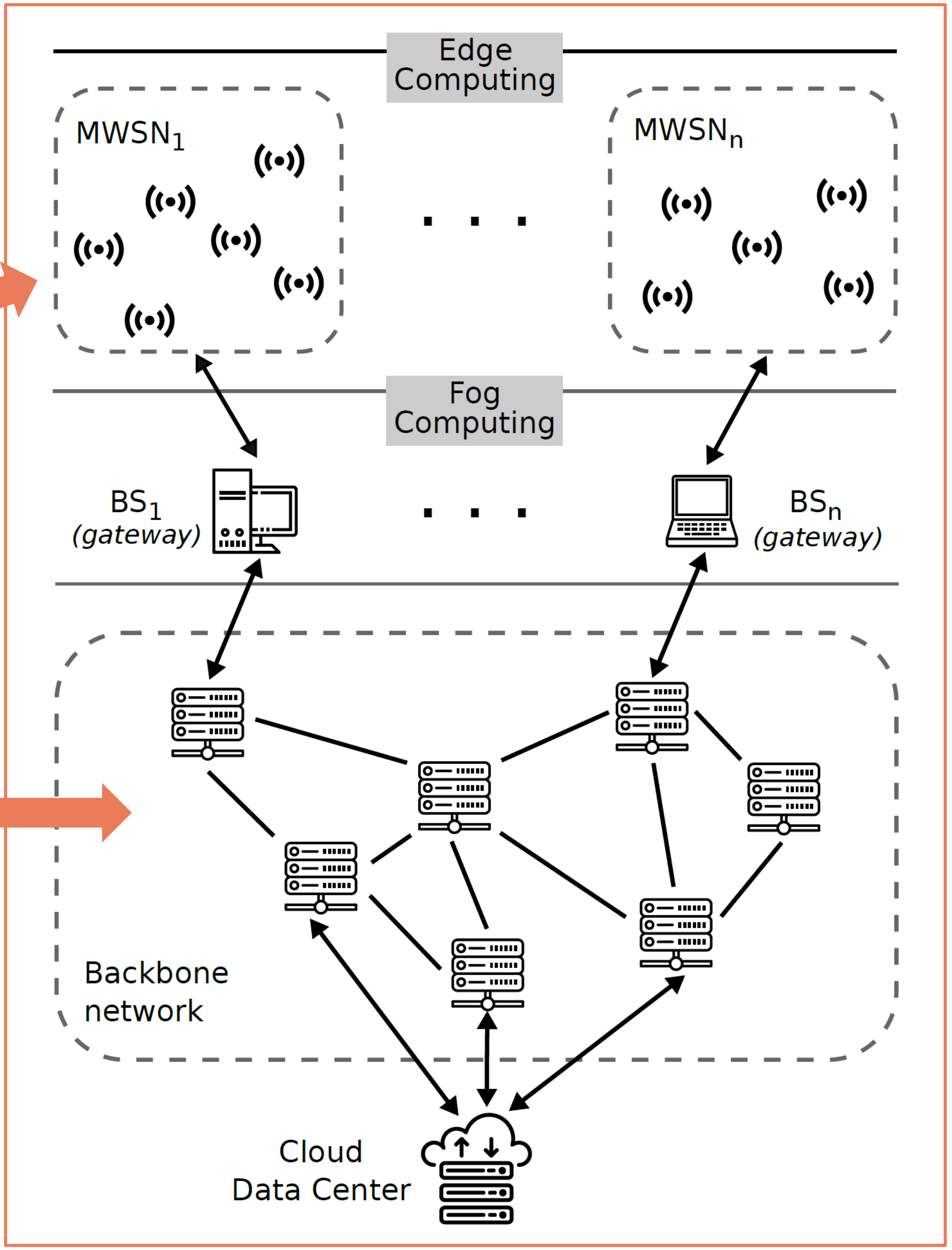
4. Computational cloud

collecting data from all sensing clusters fusion, correlation, large-scale computing, decision-making.

Power control

Activity control

Energy-aware routing



Phenomena cloud detecting and tracking




Object covering significant area characterized by nondeterministic, dynamic variations of shape, size, speed, and direction of motion along multiple axes

- Intelligent Mobile Wireless Network for Toxic Gas Clouds Monitoring and Tracking [M. Krzysztoń, E. Niewiadomska-Szynkiewicz], *Sensors*

- Modeling Mobility in Cooperative Ad Hoc Networks [A. Sikora, E. Niewiadomska-Szynkiewicz, J. Kołodziej], *Mobile Networks and Applications*

Sensing network clusterization

Network divided into K sepearate clusters

$$V_1 \cup V_2 \cup \ \dots \cup V_K = V$$

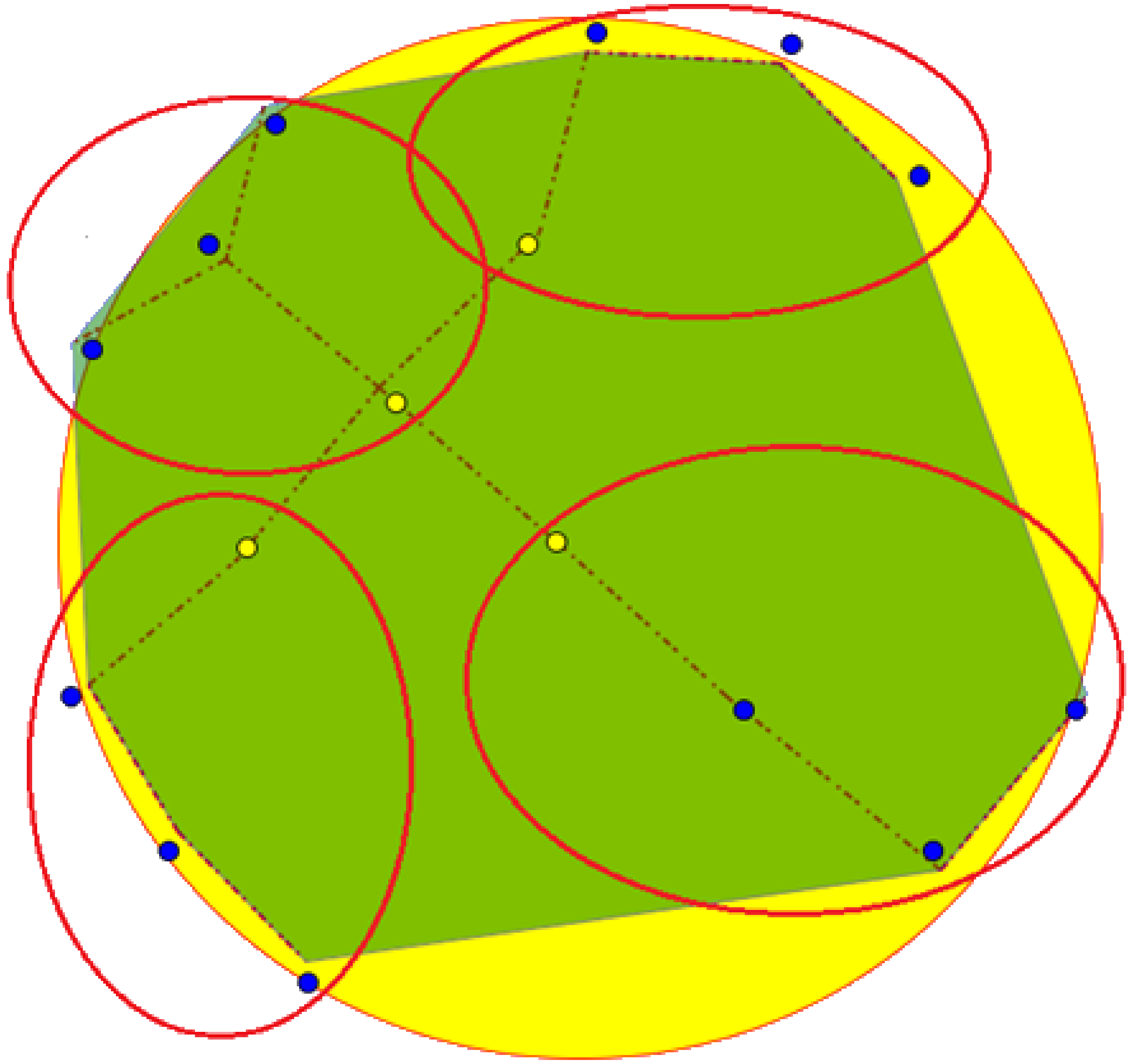
$$V_1 \cap V_2 \cap \ \dots \cap V_K = \emptyset$$

$D_{H_k} \in V_k$: k-th cluster head

$D_H \in D_{H_1}, D_{H_2}, \dots, D_{H_K}$: head of the whole network

Permanent connectivity maintained

- all members of each cluster with its cluster head
- all cluster heads with the D_H (network head)



Every time step t each device D_i calculates its new position x_i solving the optimization problem

Cloud boundary detection

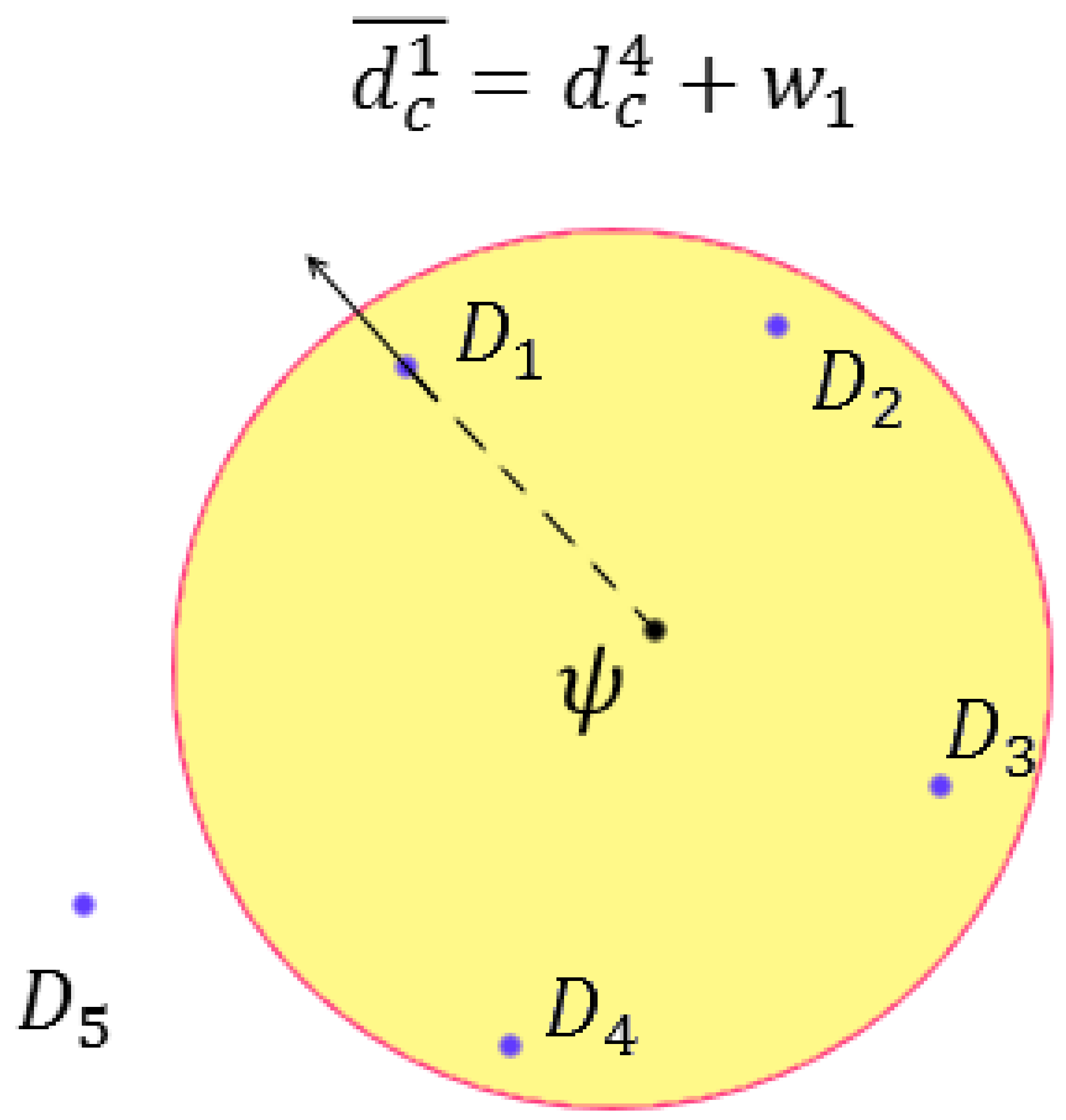
Each node $D_i \in V_m$ calculates its optimal position solving the optimization problem

$$\min_{x_i}[U_i = \epsilon_c U_i^c + \sum_{D_j \in S_i} \epsilon_j U_i^j + \sum_{k \in IC_m} \epsilon_k U_i^k]$$

$$U_i^c = \left(\frac{\overline{d_c^i}}{d_c^i} - 1\right)^2$$

$$\psi = \frac{\sum_{D_i \in V'} x_i}{|V'|}$$

$$\overline{d_c^i} = \max_{D_i \in V'} d_c^i + w_1, w_1 > 0$$



Cloud boundary detection

Each node $D_i \in V_m$ calculates its optimal position solving the optimization problem

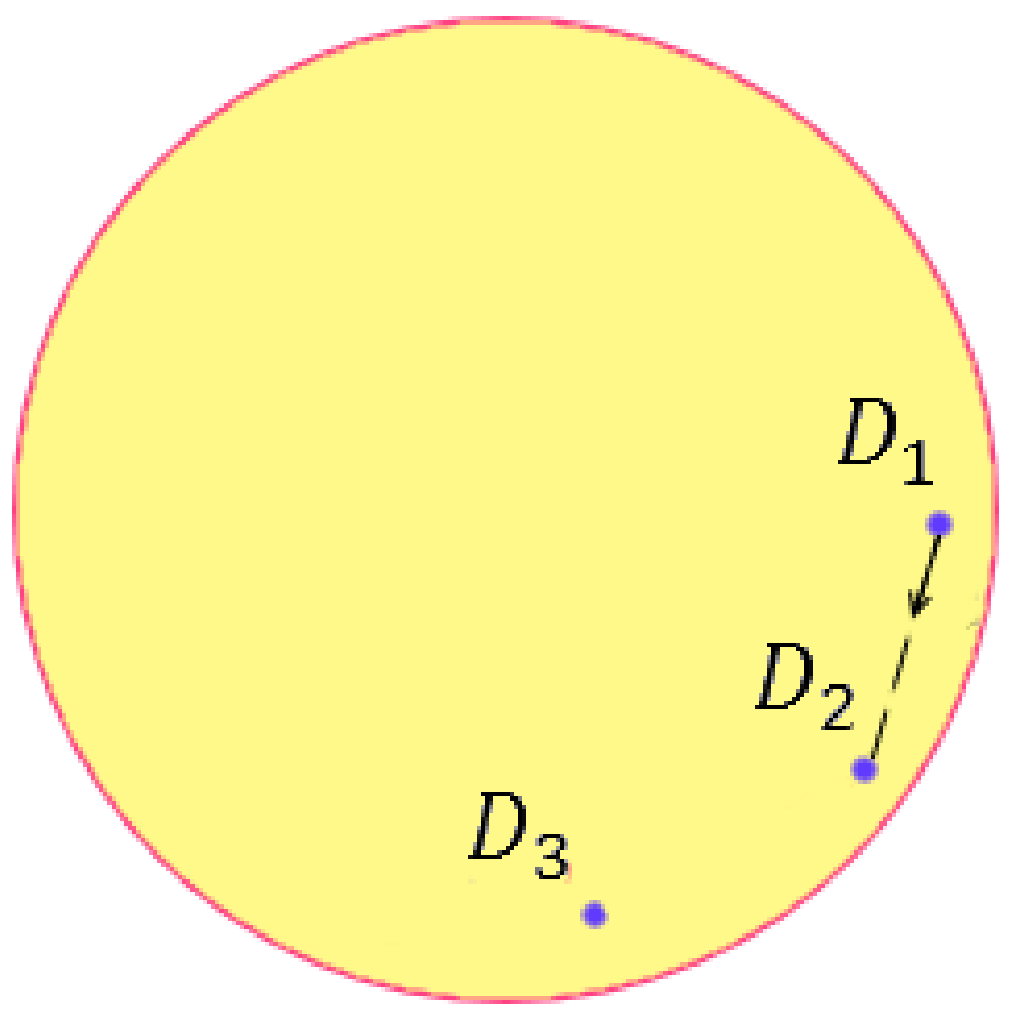
$$\min_{x_i}[U_i = \epsilon_c U_i^c + \sum_{D_j \in S_i} \epsilon_j U_i^j + \sum_{k \in IC_m} \epsilon_k U_i^k]$$

$$S_i = \{D_j : D_j \in SN_i, D_j \in V_m\}$$

$$U_i^j = \left(\frac{\overline{d_j^i}}{d_j^i} - 1\right)^2$$

$$\overline{d_j^i} \leq r_t$$

$S_1 = \{D_2\}$ $\quad d_2^1 > \overline{d_2^1}$

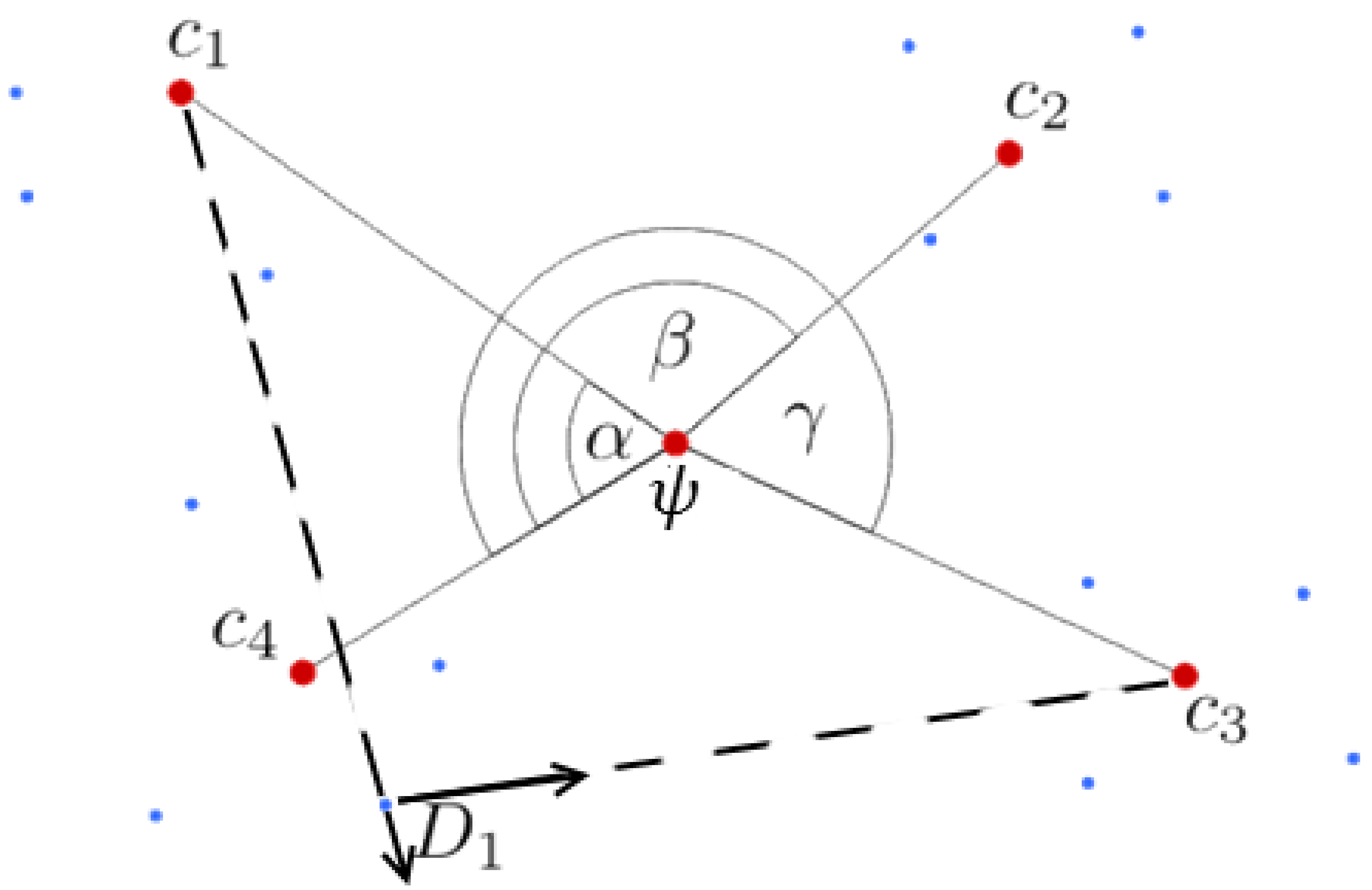


Cloud boundary detection

Each node $D_i \in V_m$ calculates its optimal position solving the optimization problem

$$\min_{x_i}[U_i = \epsilon_c U_i^c + \sum_{D_j \in S_i} \epsilon_j U_i^j + \sum_{k \in IC_m} \epsilon_k U_i^k]$$

$$d_1^1 < \overline{d_1^1} = \overline{d_3^1} < d_3^1$$



$$IC_m = \left\{ \underset{V_j \neq V_m}{argmin} \measuredangle(V_m, V_j) \right\} \cup \left\{ \underset{V_j \neq V_m}{argmax} \measuredangle(V_m, V_j) \right\}$$

$$U_i^k = \gamma_k \left(\frac{\overline{d_k^i}}{d_k^i} - 1 \right)^2$$

$$\overline{d_k^i} = \frac{\sum_{l \in IC_m} d_l^i}{2} + w_2, w_2 > 0$$

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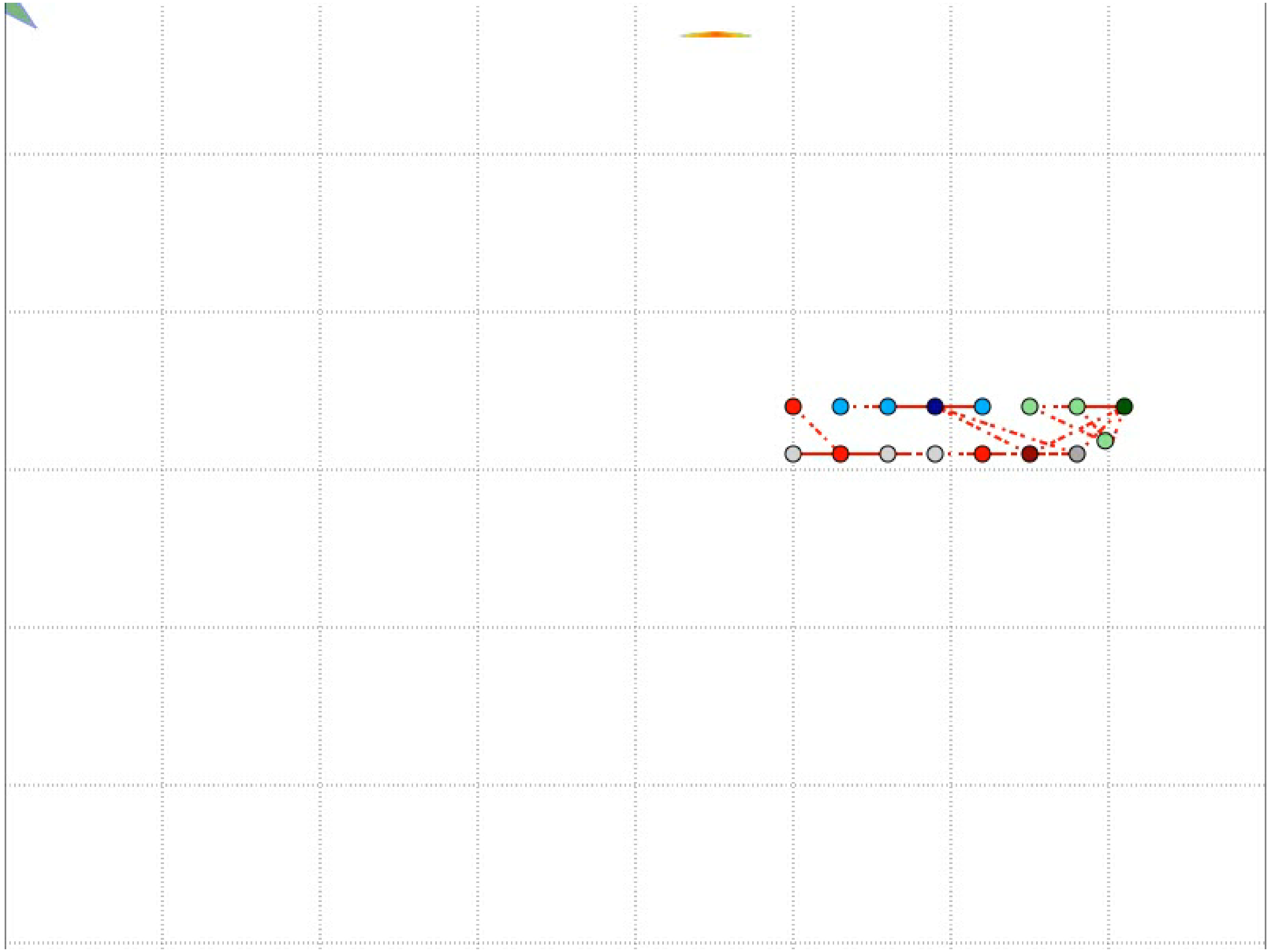
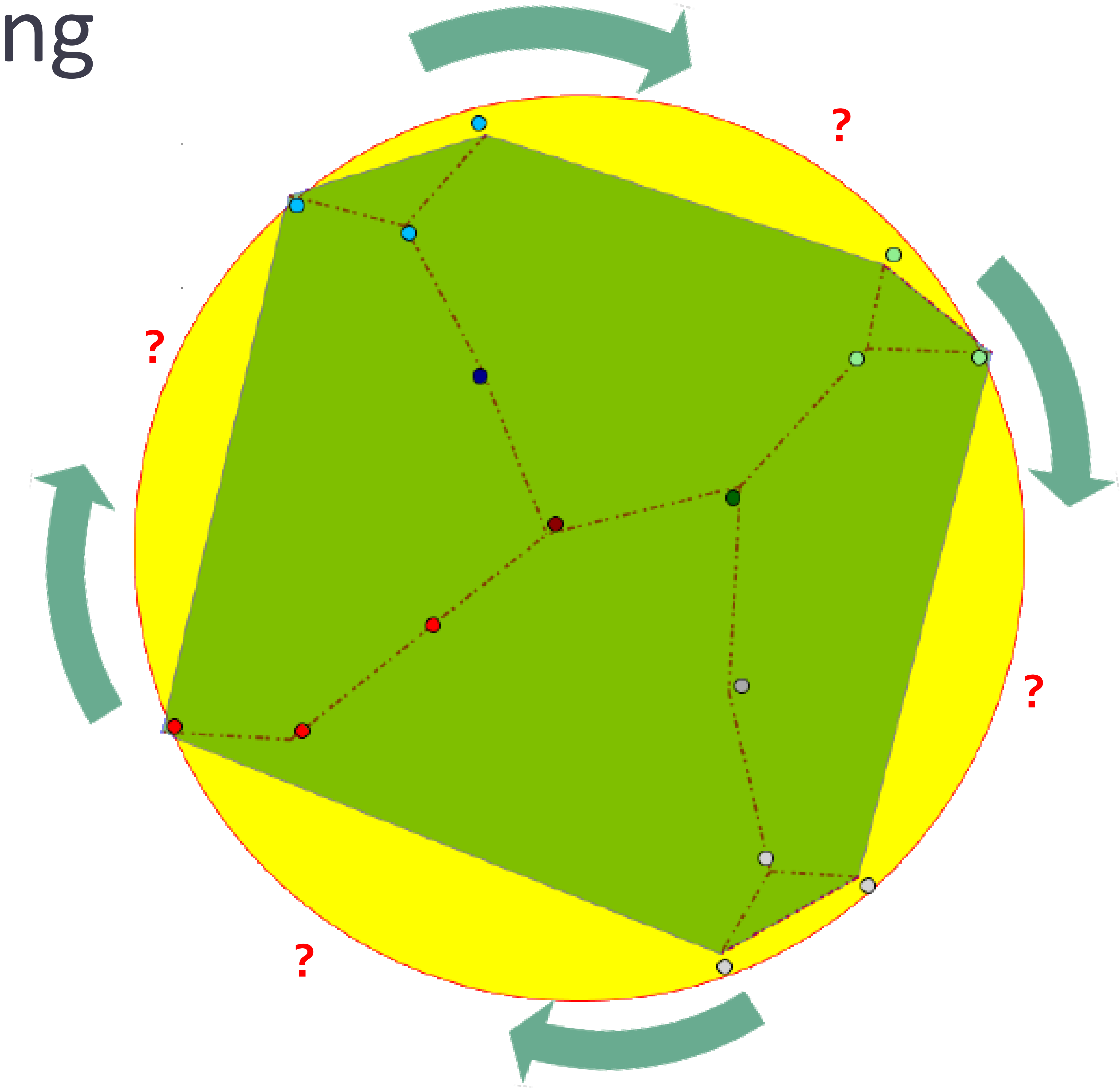
Cloud boundary detection - simulation



Boundary detection and tracking

- A temporarily optimal topology for boundary tracking
- Boundary tracking



Network topology quality measure

Operation

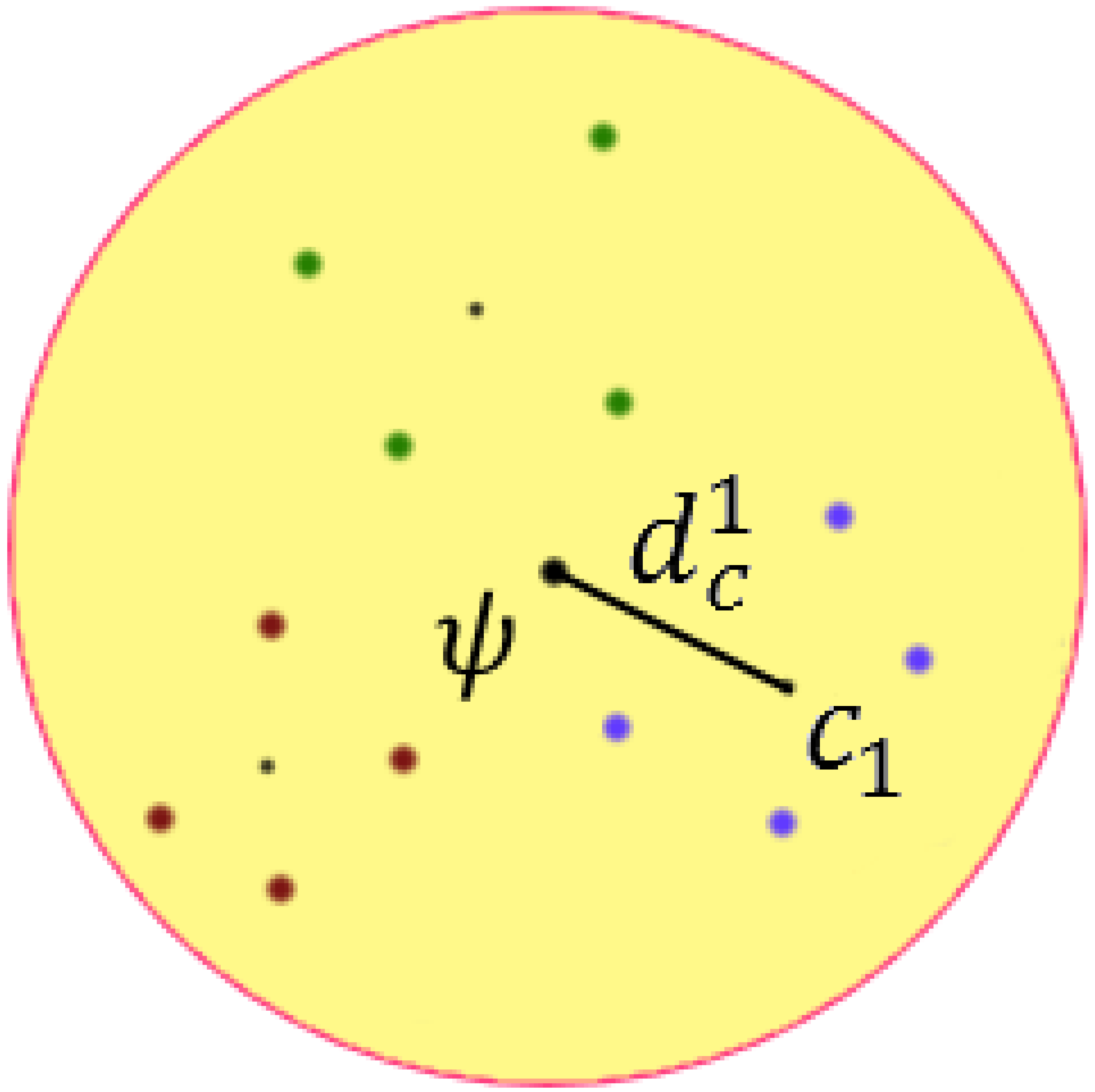
move cluster towards the boundary

Measure

distance between a centroid of the *m*-th cluster to the estimated centroid of a cloud:

$$d_c^m = \|c_m - \Psi\|_2$$

The bigger value the better topology



Network topology quality measure

Operation

deploy clusters on the boundary evenly

Measure

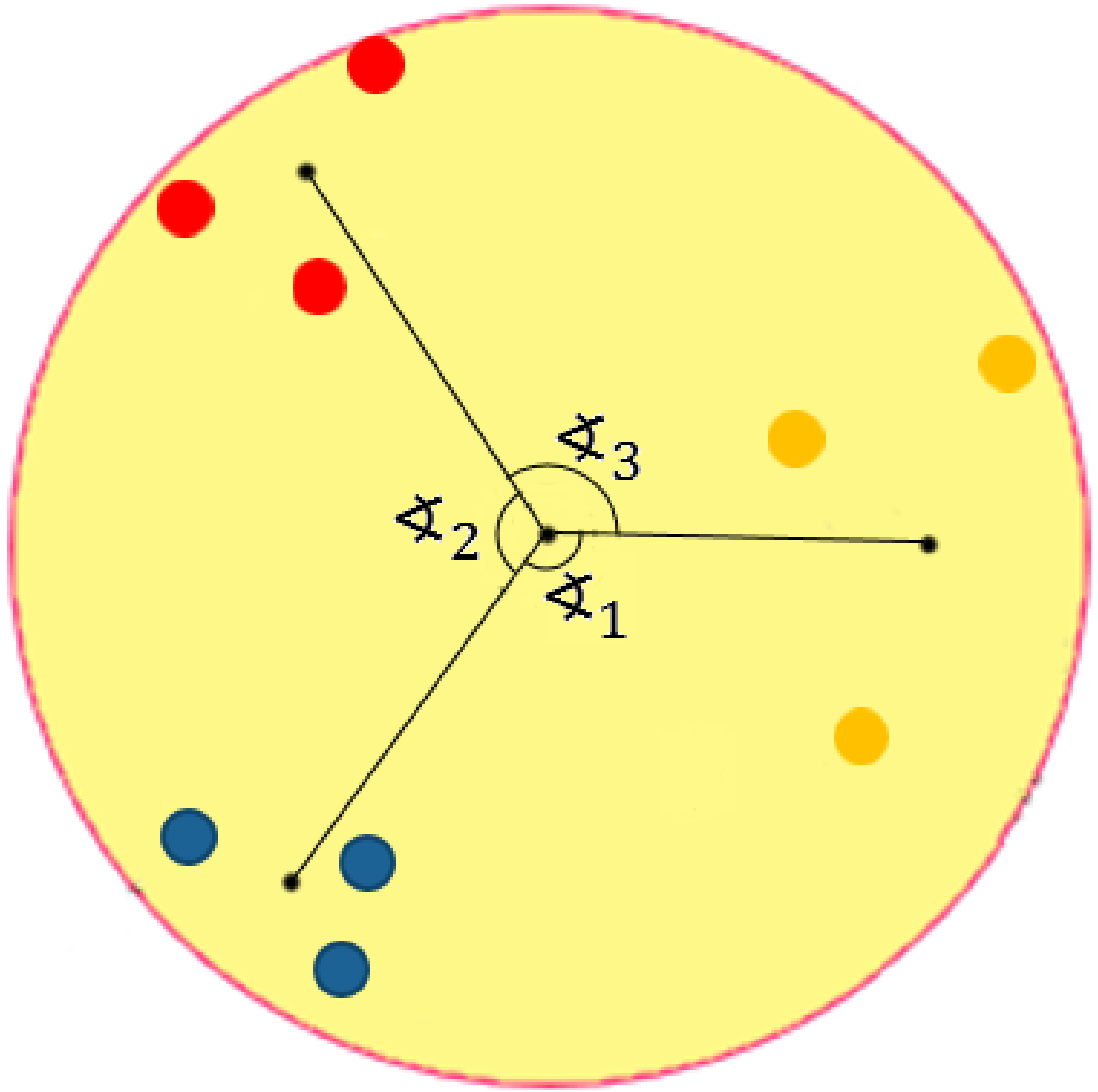
standard deviation of angles between neighboring clusters

$$\sigma_{\sphericalangle} = \sqrt{\frac{\sum_{m=1}^{K}(\sphericalangle_m - \mu_{\sphericalangle})^2}{K-1}}$$

$$\mu_{\sphericalangle} = \frac{\sum_{m=1}^{K} \sphericalangle_m}{K}$$

$$\sphericalangle_m = \sphericalangle(V_m, V_j), \mathrm{j} = \underset{k \neq m}{\operatorname{argmin}} \sphericalangle(V_m, V_k)$$

The smaller value the better topology



Network topology quality measure

Operation

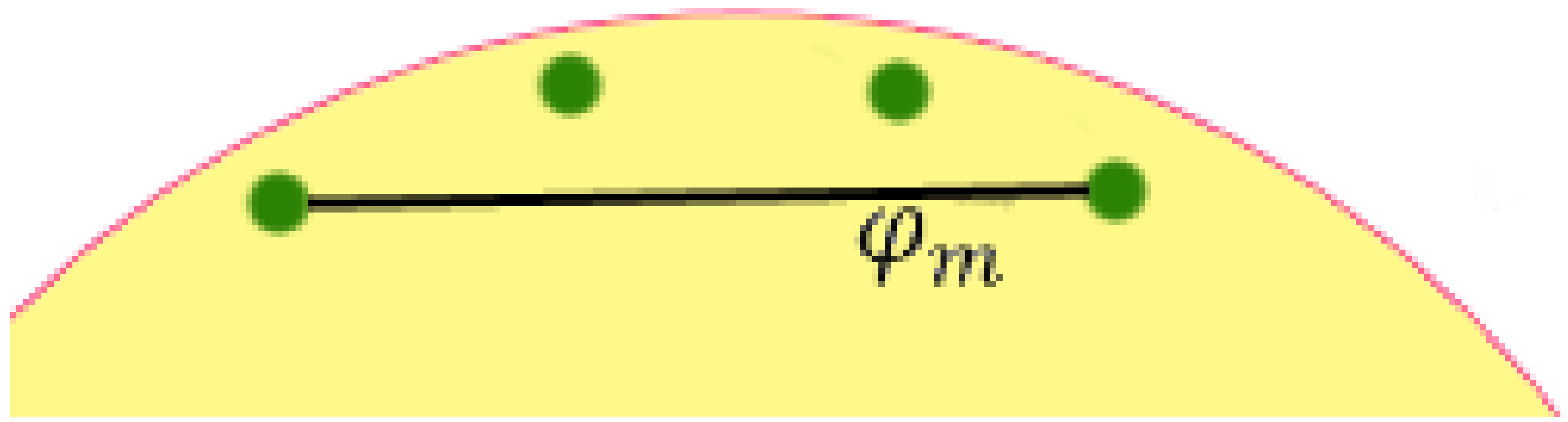
expand an area monitored by the cluster

Measure

m-th cluster diameter

$$\varphi_m = \max_{D_i, D_j \in V_m} d_j^i$$

The bigger value the better topology



Experimental verification

Test scenario

Uncontrolled instantaneous release of vapor LNG (Liquefied Natural Gas)

Simulation platform

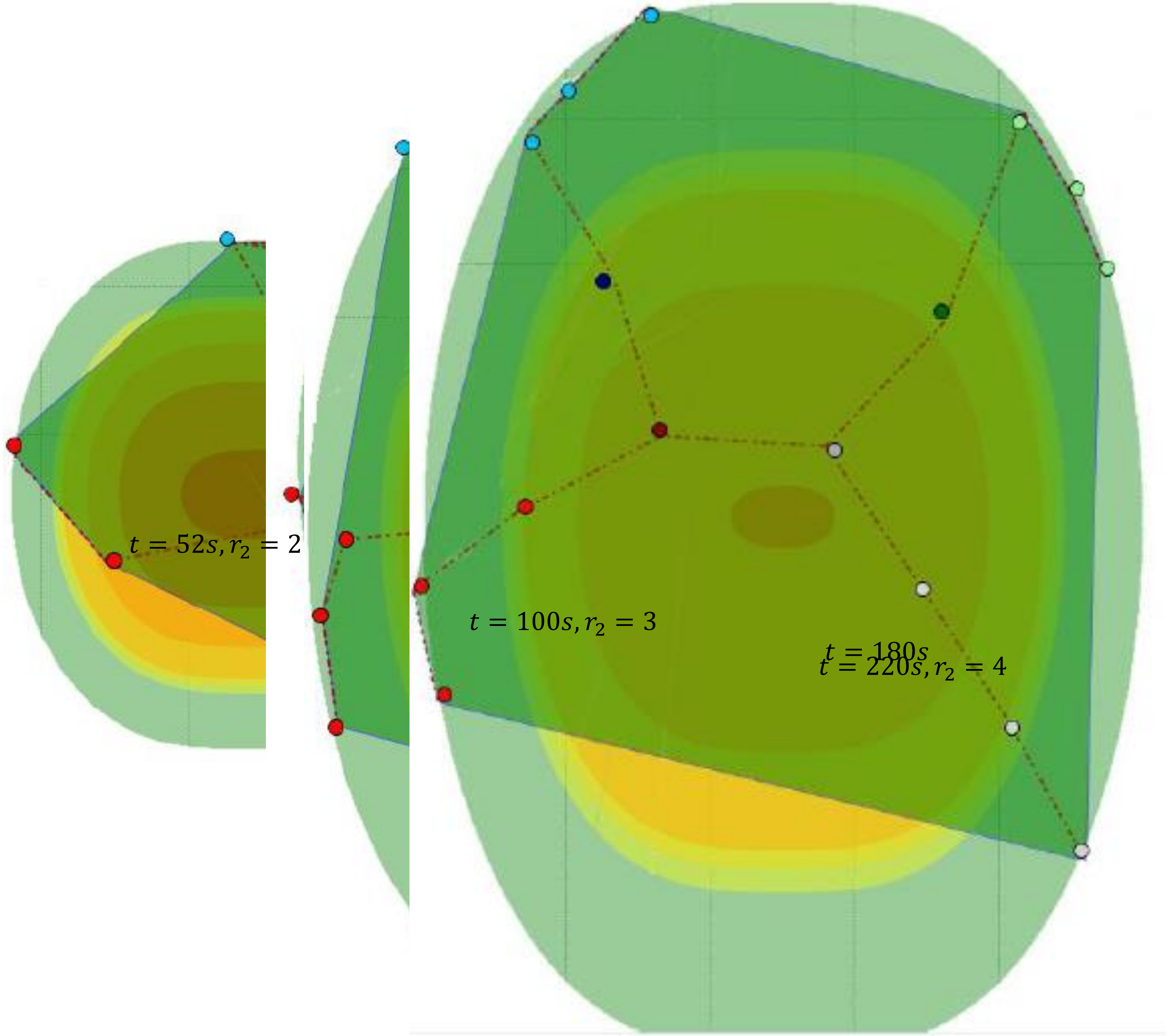
Heavy gas cloud dispersion simulator: SLAB

Sensor network

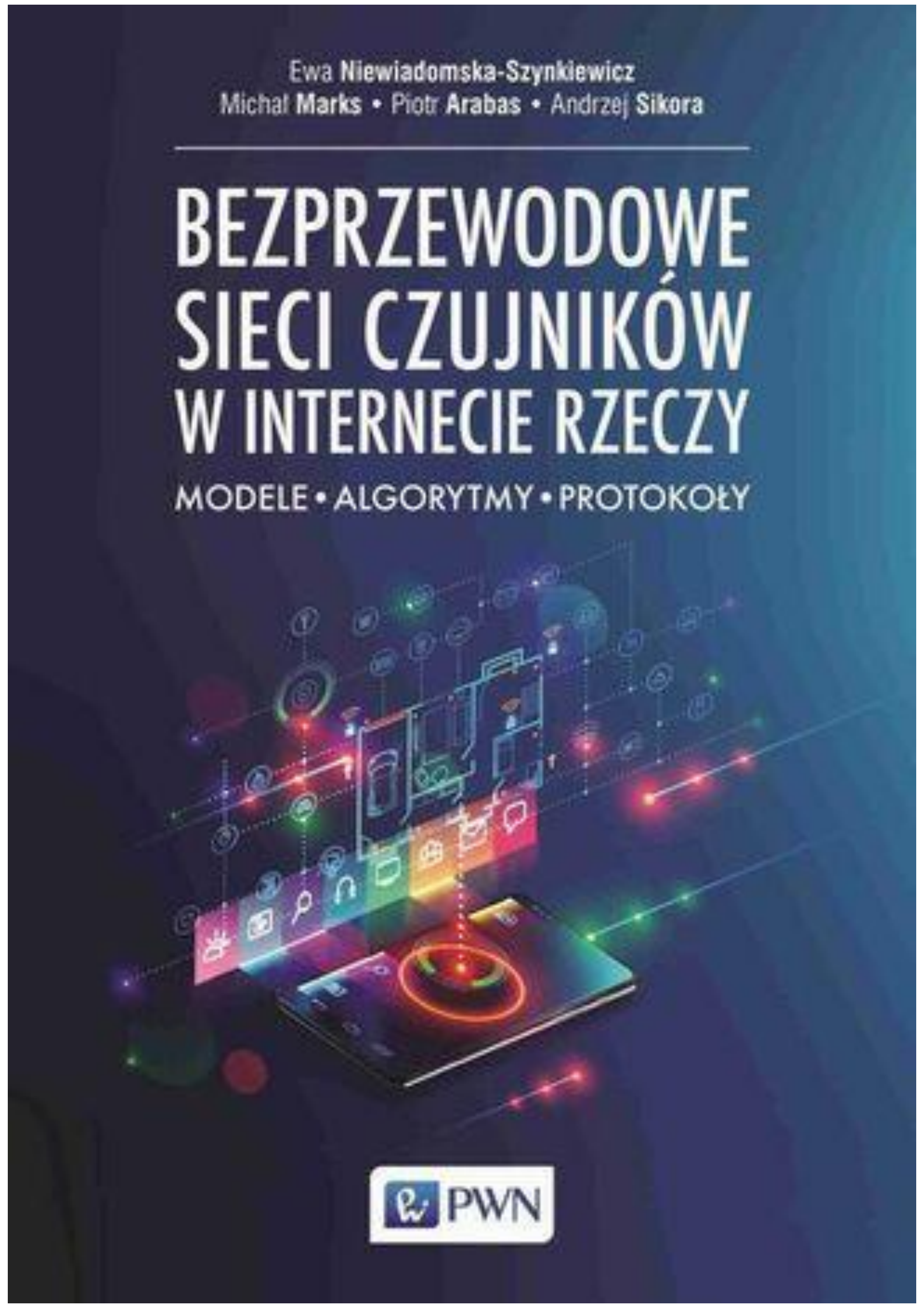
- 16 mobile devices (4 clusters)
- $v_{max} = 10\frac{m}{s}$

$r_2 \in \{2,3,4\}$

Vapor LNG cloud-tracking sensor network



Book



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CyberMine project

NCBR
National Centre for Research and Development

Monitoring center for industrial networks in underground mining plants and detection of cyber threats

The project aims to improve IT/OT security in underground mine workings

Main results

- new cybersecurity tools for industrial networks (detection attacks against controllers and sensors, links)
- application of AI methods

Contractors:

JSW IT Systems (leader)
Warsaw University of Technology
Central Mining Institute GIG

Duration: January - December 2023

Technology readiness level (TRL): IX

Warsaw University of Technology

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Thank you for your attention

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