Wireless Sensor Networks for Air Pollution Monitoring

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Postdoc at Rice University

Brief Introduction

PhD[1] | Oct. 2015 → Mar. 2019 **| CITI Lab, Lyon (INSA-Lyon and INRIA Agora):**

- **Topic:** Deployment and Scheduling of Wireless Sensor Networks (WSN)
- **Advisors:** Hervé Rivano & Walid Bechkit
- **Project:** Urpolsens (Labex IMU, Lyon)
- **Ph.D. awards:** GDR RSD & ACM ASF, INSA-Lyon, SIF/Gilles-Kahn (accessit)

Mobility[2] during PhD |Feb. 2018 → May 2018 | **University of Ottawa, Canada**

- **Topic:** Scheduling of Wireless Sensor Networks (WSN)
- **Collaboration with:** Azzedine Boukerche

Postdoc[3] | Since Apr. 2019 **| Rice University, Texas, USA**

- **Topic:** Mobility Optimization of Drone Networks
- **Advisor:** Edward Knightly
- **Project:** ASTRO (NSF)
- **Responsibilities:** Scientific lead

[1] Funded by an INRIA CORDI-S scholarship
[2] Funded through the Mitacs Globalink research award
[3] Rice University is ranked **16** in top US universities

Overview on Air Pollution

Pic de pollution de l'air aux particules fines : la circulation différenciée maintenue à Lyon vendredi

Le préfet a pris cette décision en raison du maintien du niveau de « vigilance rouge » dans le bassin lyonnais et le nord de l'Isère pour une durée de vingt-quatre heures.

Le Monde avec AFP • Publié le 28 février 2019 à 19h44

- Diabetes → 3.2 million people **per year**
- Asthma → a 25% increase
- Premature deaths → **127.000** children **per year**

source: sciencenews.org

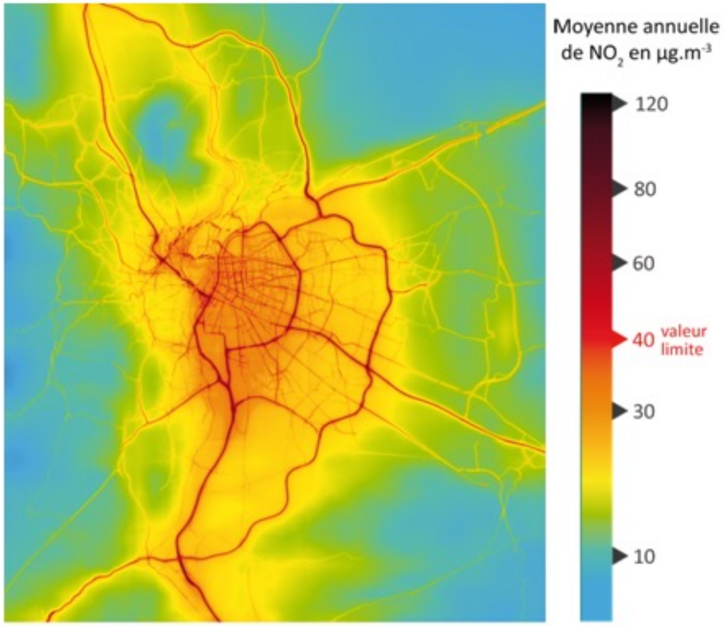
source: theguardian.com

source: citymetric.com

source: lemonde.fr

Air Quality Traditional Monitoring

1. **Modeling :** physicochemical dispersion models (SIRANE, ADMS, etc.)
2. **Measurements:** reference monitoring stations



NO_2 annual concentrations, 2012
Lyon, France (Source **ATMO-AURA**)

Traditional monitoring stations
- Lyon (France) -

RICE

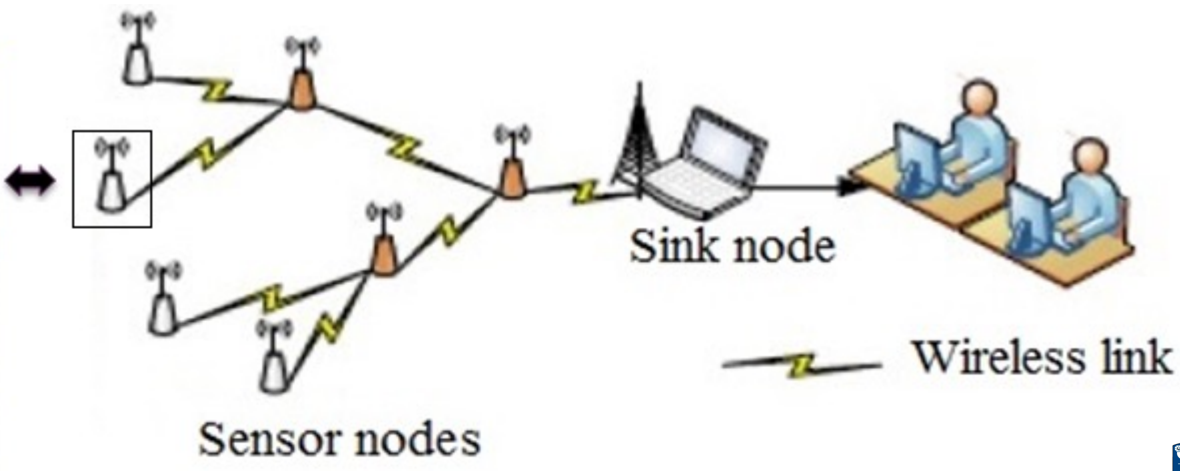
membre de Université de Lyon

Inria informatics mathematics

Using low-cost WSN for Air Quality Monitoring

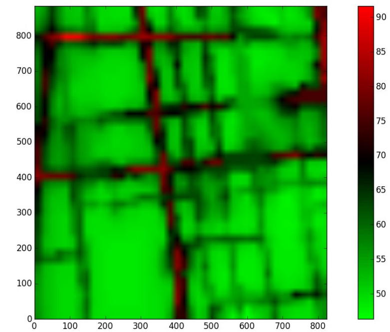
+ Smaller
+ Low-cost
+ Better spatial/temporal granularity

- Less accurate
- Limited lifetime
- Calibration issues

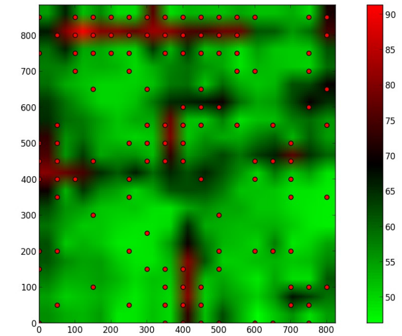


Use cases of Air Pollution Monitoring

1. Air quality regular mapping

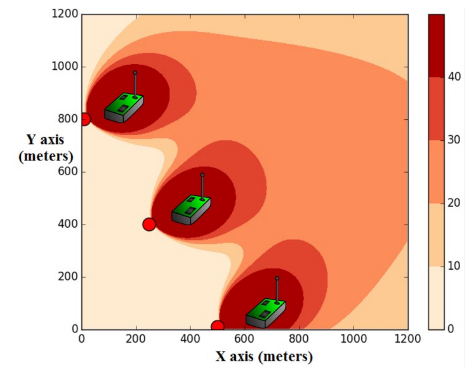


Simulated map

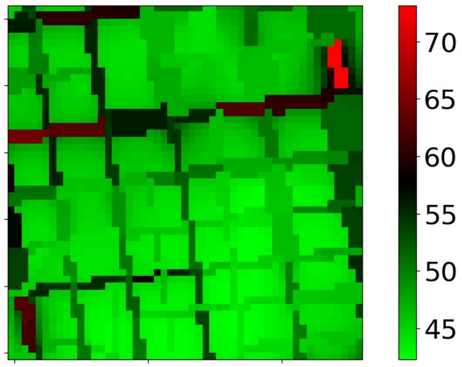


Estimation

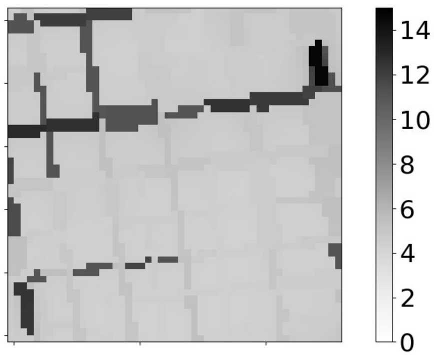
2. Air pollution threshold detection



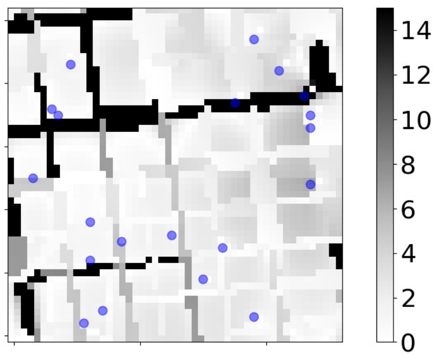
3. Air pollution simulations' correction



Simulated map



Errors before correction



Errors after correction

WSN Deployment and Scheduling

WSN deployment issue:

Q: How many sensors do we need ?

Q: Where should we place these sensors ?

Q: Is the sensor network connected ?

WSN scheduling issue:

Q: Can we turn off some sensors to extend their lifetime ?

Q: Which sensors should be turned off ?

Q: When selected sensors should be turned off ?

PhD Main Contributions and Outline

- State of the art
- Design and Deployment of an Air Pollution Monitoring Platform
- WSN Deployment for Air Quality Regular Mapping
- WSN Deployment for Air Pollution Detection
- WSN Deployment for Air Pollution Simulations' Correction
- WSN Scheduling for Air Pollution Simulations' Correction
- Latest and Ongoing Research

The UrPolSens Project

General purpose:

Explore the potential of low-cost WSN for fine characterization of air quality

Consortium:

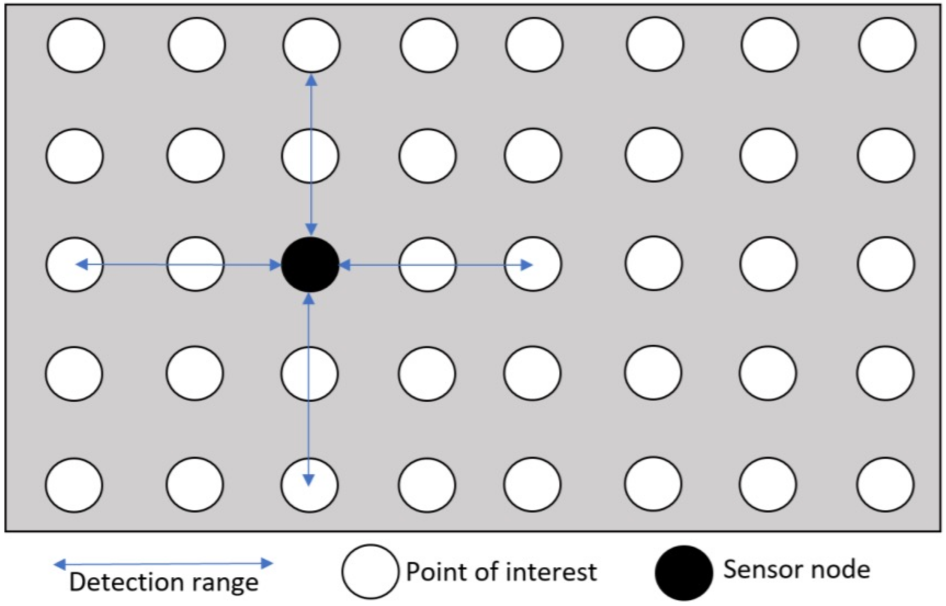
Main objectives:

1. Design and deployment of a WSN platform for air quality monitoring (**NO2 sensing**)
2. Optimization of WSN deployment and scheduling
3. Conduct a sociological study on air quality perception

WSN Deployment and Scheduling

Classification of existing works

- **Event-aware methods:**
  - Based on detection models



- **Correlation-aware methods:**
  - Leverage correlations between sensor measurements
  - Generic methods

WSN Deployment and Scheduling

Summary of existing works

Author(s)	Work class	Deployment	Scheduling	Connectivity	Nodes' Heterogeneity
Chakrabarty et al.	Event-aware	Yes	-	-	Yes
Altinel et al.	Event-aware	Yes	-	-	Yes
Rebai et al.	Event-aware	Yes	-	Yes	-
Sengupta et al.	Event-aware	Yes	-	Yes	-
Hu et al.	Event-aware	-	Yes	-	-
Liaskovitis et al.	Correlation-aware	-	Yes	-	-
Lin et al.	Event-aware	-	Yes	Yes	Yes
Du et al.	Event-aware	-	Yes	-	-
Keskin et al.	Event-aware	Yes	Yes	Yes	Yes
Mini et al.	Event-aware	Yes	Yes	-	Yes
Chen et al.	Event-aware	-	Yes	Yes	-
Deng et al.	Correlation-aware	-	Yes	-	-
Lu et al.	Event-aware	-	Yes	Yes	-
Boubrima et al.	**Air quality mapping**	Yes	-	Yes	Yes
Boubrima et al.	**Air pollution detection**	Yes	-	Yes	Yes
Boubrima et al.	**Air pollution simulations' correction**	Yes	Yes	Yes	Yes

Outline

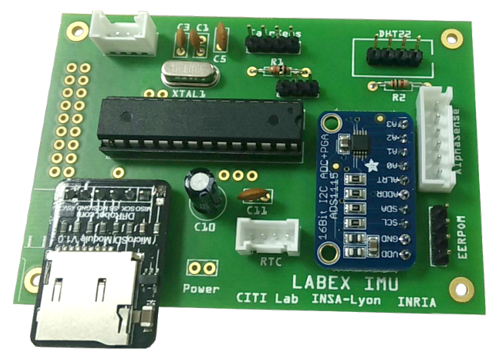
- State of the art
- Design and Deployment of an energy efficient Air Pollution Monitoring Platform
- WSN Deployment for Air Quality Regular Mapping
- WSN Deployment for Air Pollution Detection
- WSN Deployment for Air Pollution Simulations’ Correction
- WSN Scheduling for Air Pollution Simulations’ Correction

The UrPolSens Platform

Energy-efficient design of pollution sensors

- ❑ **NO_2 probes:** Alphasense, CairSens
- ❑ **Wireless communications:** LoRa;
- ❑ **Storage:** EEPROM + SD
- ❑ **Software:** Duty cycling routines
- ❑ **Power:** Batteries and solar panels
  - ➢ Power consumption: **100mW** (vs. Opensense: 40W)

First prototype

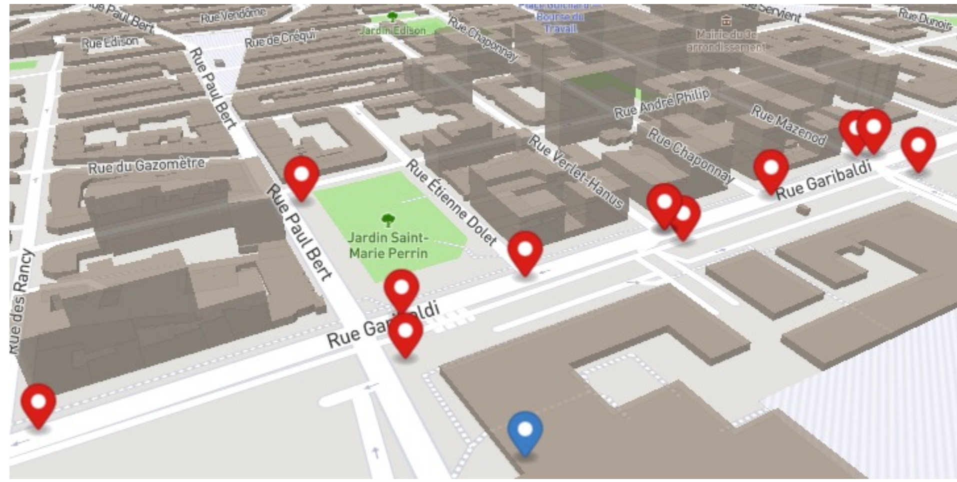


Printed circuit

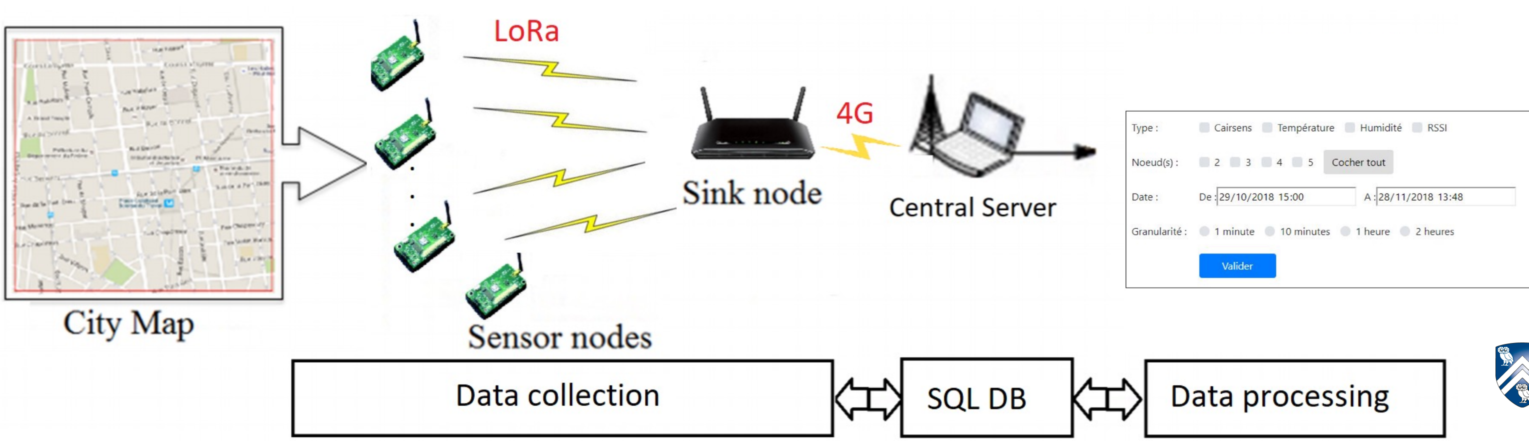
The UrPolSens Platform

Deployment of our nodes in the Lyon city

First tests

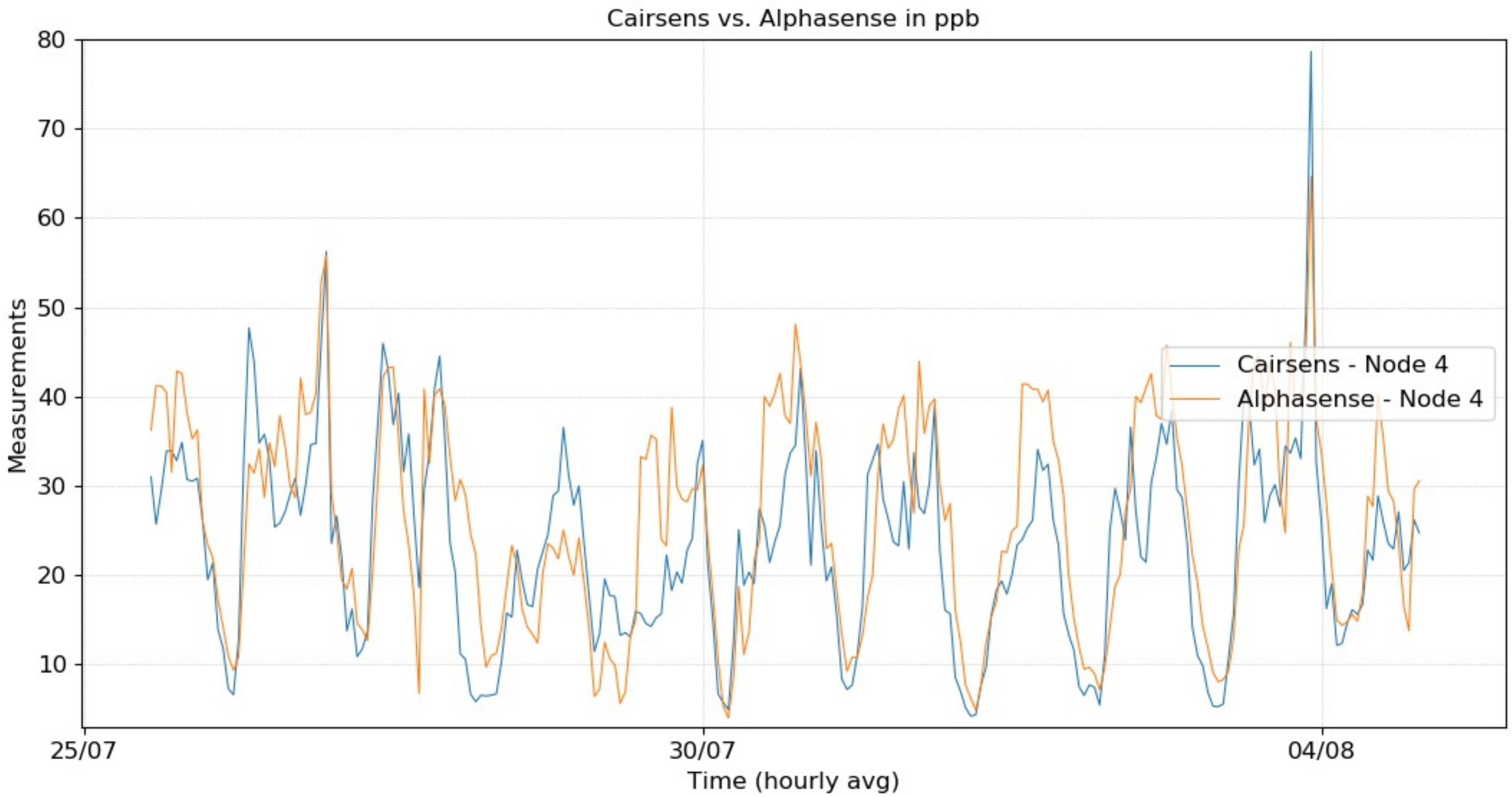


Deployment in Lyon: 12 sensor nodes + 1 gateway



The UrPolSens Platform

Sensing accuracy and low power design



➢ **Normalized RMSE** = 0.10

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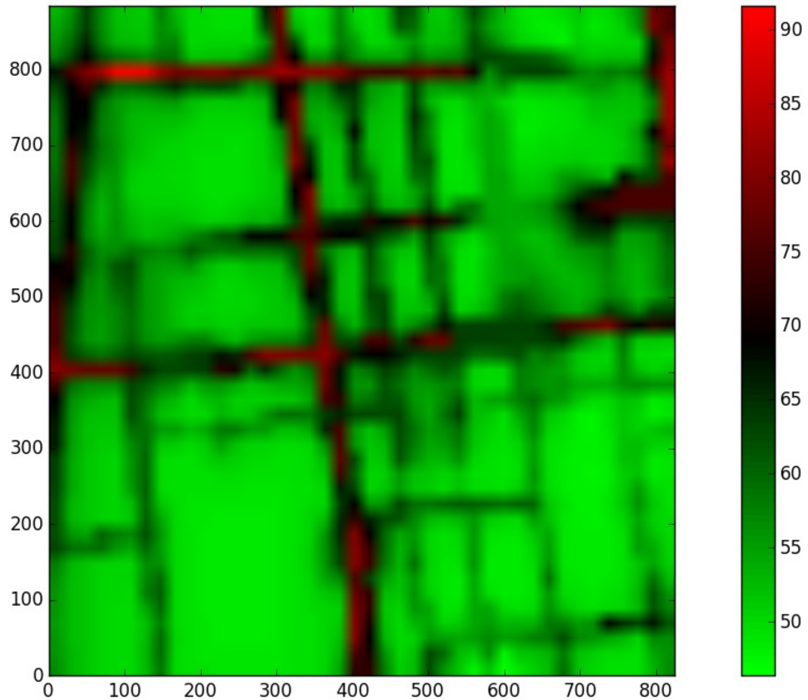
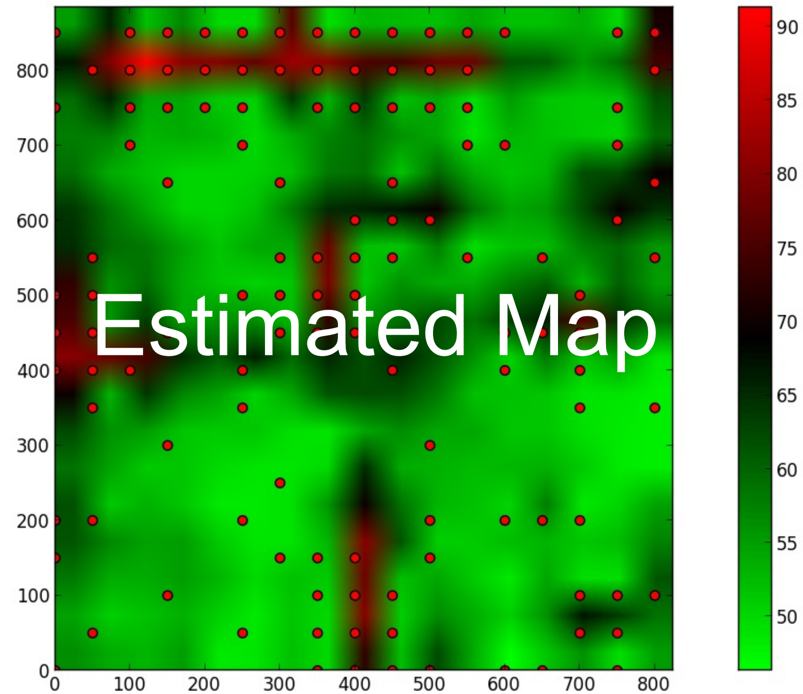
- ❑ WSN Scheduling for Air Pollution Simulations’ Correction

WSN Deployment for Air Quality Regular Mapping

Main idea





Estimation of ground truth

Simulated maps

Maximum simulation error

WSN Deployment for Air Quality Regular Mapping

Problem statement

Find the optimal positions of sensors and sinks while ensuring :

1. Air Quality Mapping with a bounded-interpolation-error
2. Network Connectivity
3. Minimum deployment cost

* Dual problem: Estimation error minimization

WSN Deployment for Air Quality Regular Mapping

Deployment cost

Parameters

$\mathcal{P}$	Set of points approximating the deployment region
c_p^{sensor}	The cost of deploying a sensor at point p
c_p^{sink}	The cost of deploying a sink at point p

Variables

x_p	Define whether a sensor is deployed at point p or not $x_p \in \{0,1\},\ p \in \mathcal{P}$
y_p	Define whether a sink is deployed at point p or not $y_p \in \{0,1\},\ p \in \mathcal{P}$

$$\mathcal{F} = \sum_{p \in \mathcal{P}} c_p^{sensor} * x_p + \sum_{p \in \mathcal{P}} c_p^{sink} * y_p$$

WSN Deployment for Air Quality Regular Mapping

Air quality mapping formulation

Estimated Map:

$$\hat{\mathcal{Z}}_p = x_p \cdot \mathcal{Z}_p + (1 - x_p) \cdot \frac{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q \cdot \mathcal{Z}_q}{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q}$$

| Zp: Sensor measurements

Estimation errors

$$e_p = UB(|\hat{\mathcal{Z}}_p - \mathcal{G}_p|)$$

| Mp: Modeling simulations

$$\begin{aligned} \mathcal{M}_p - \mathcal{G}_p &\in [-m_p, m_p] \\ \mathcal{Z}_p - \mathcal{G}_p &\in [-s_p, s_p] \\ \mathcal{Z}_p - \mathcal{M}_p &\in [-s_p - m_p, s_p + m_p] \end{aligned}$$

after simplification (basic formulation):

$$e_p = x_p \cdot s_p + \frac{(1 - x_p)}{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q} \cdot Max \{ \sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q \cdot (\mathcal{M}_q - \mathcal{M}_p + s_q + m_q + m_p), \sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q \cdot (\mathcal{M}_p - \mathcal{M}_q + s_q + m_q + m_p) \}$$

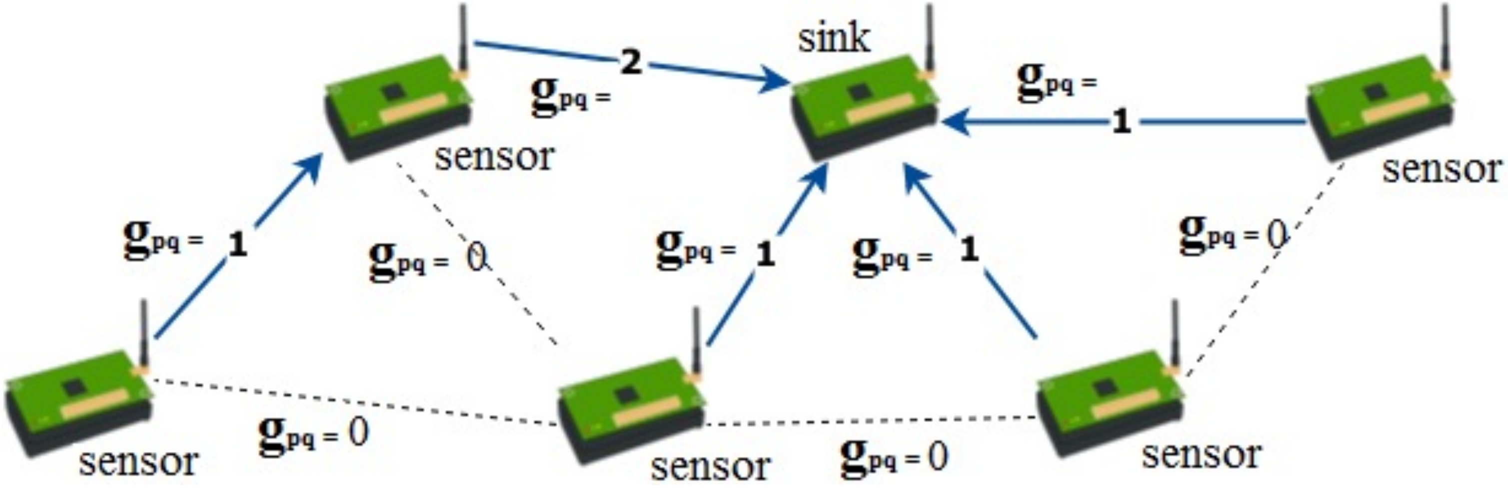
RICE

informatics mathematics

membre de UNIVERSITÉ DE LYON

WSN Deployment for Air Quality Regular Mapping

Network connectivity



$$\sum_{q \in \Gamma(p)} g_{pq} - \sum_{q \in \Gamma(p)} g_{qp} \geq x_p - \mathcal{N} * y_p, \quad p \in \mathcal{P} \qquad (1)$$

$$\sum_{q \in \Gamma(p)} g_{pq} - \sum_{q \in \Gamma(p)} g_{qp} \leq x_p, \quad p \in \mathcal{P} \qquad (2)$$

$$\sum_{q \in \Gamma(p)} g_{pq} \leq N * x_p, \quad p \in \mathcal{P} \qquad (3)$$

$$\sum_{p \in \mathcal{P}} \sum_{q \in \Gamma(p)} g_{pq} = \sum_{p \in \mathcal{P}} \sum_{q \in \Gamma(p)} g_{qp} \qquad (4)$$

WSN Deployment for Air Quality Regular Mapping

Optimization models

[MIN_COST]

Objective: minimize $\mathcal{F}$

Mapping error linearized equations

$f \le E_{thr}$

$f \ge e_p, p \in \mathcal{P}$ OR $f = \sum_{p \in \mathcal{P}} e_p / N$

Connectivity constraints

Decision variables: $x_p, y_p \in \{0, 1\}$

Auxiliary variables: $e_p, g_{pq} \in \mathbb{R}^+$

[MIN_ERROR]

Objective: minimize f

Mapping error linearized equations

$\mathcal{F} \le \mathcal{J}$

$f \ge e_p, p \in \mathcal{P}$ OR $f = \sum_{p \in \mathcal{P}} e_p / N$

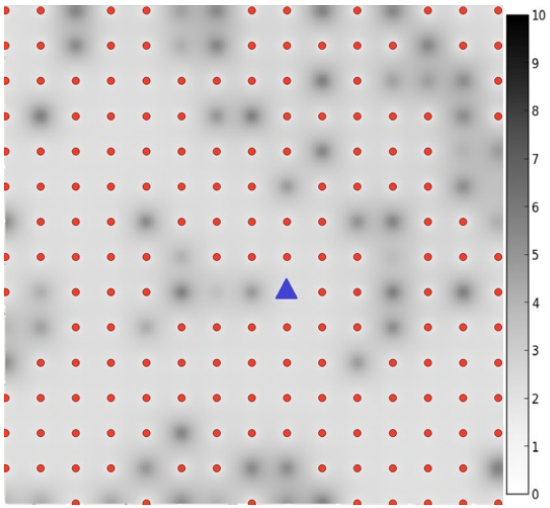
Connectivity constraints

Decision variables: $x_p, y_p \in \{0, 1\}$

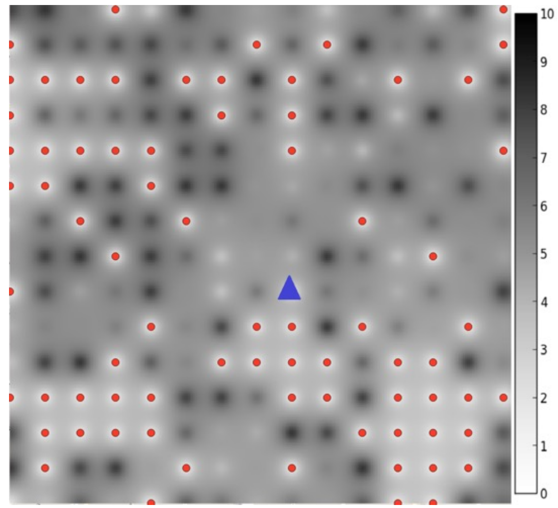
Auxiliary variables: $e_p, g_{pq} \in \mathbb{R}^+$

WSN Deployment for Air Quality Regular Mapping

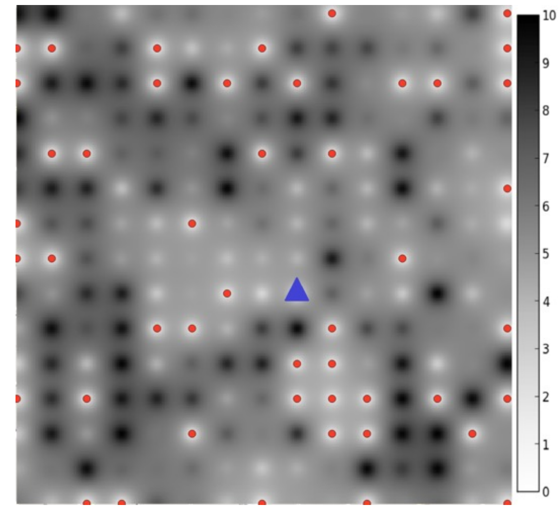
Proof-of-concept: La-Part-Dieu district



E_{thr}=5µg/m^3 181 sensors



E_{thr}=8µg/m^3 → 85 sensors



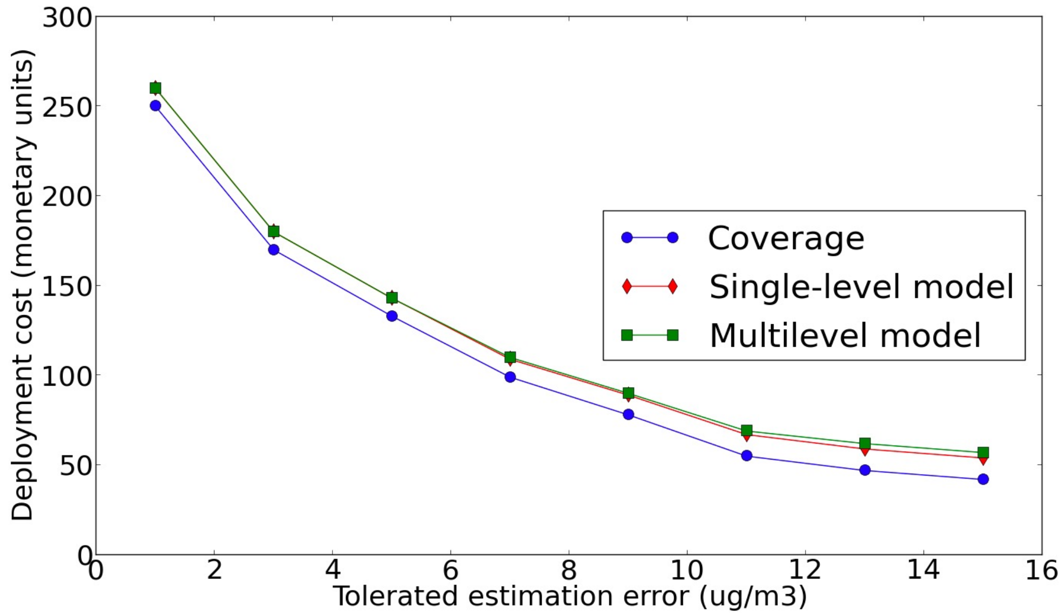
E_{thr}=10µg/m^3 → 58 sensors

Error maps with optimal positions

**error map (ug/m3): the absolute difference between the reference map and the estimated map*

WSN Deployment for Air Quality Regular Mapping

Performance evaluation

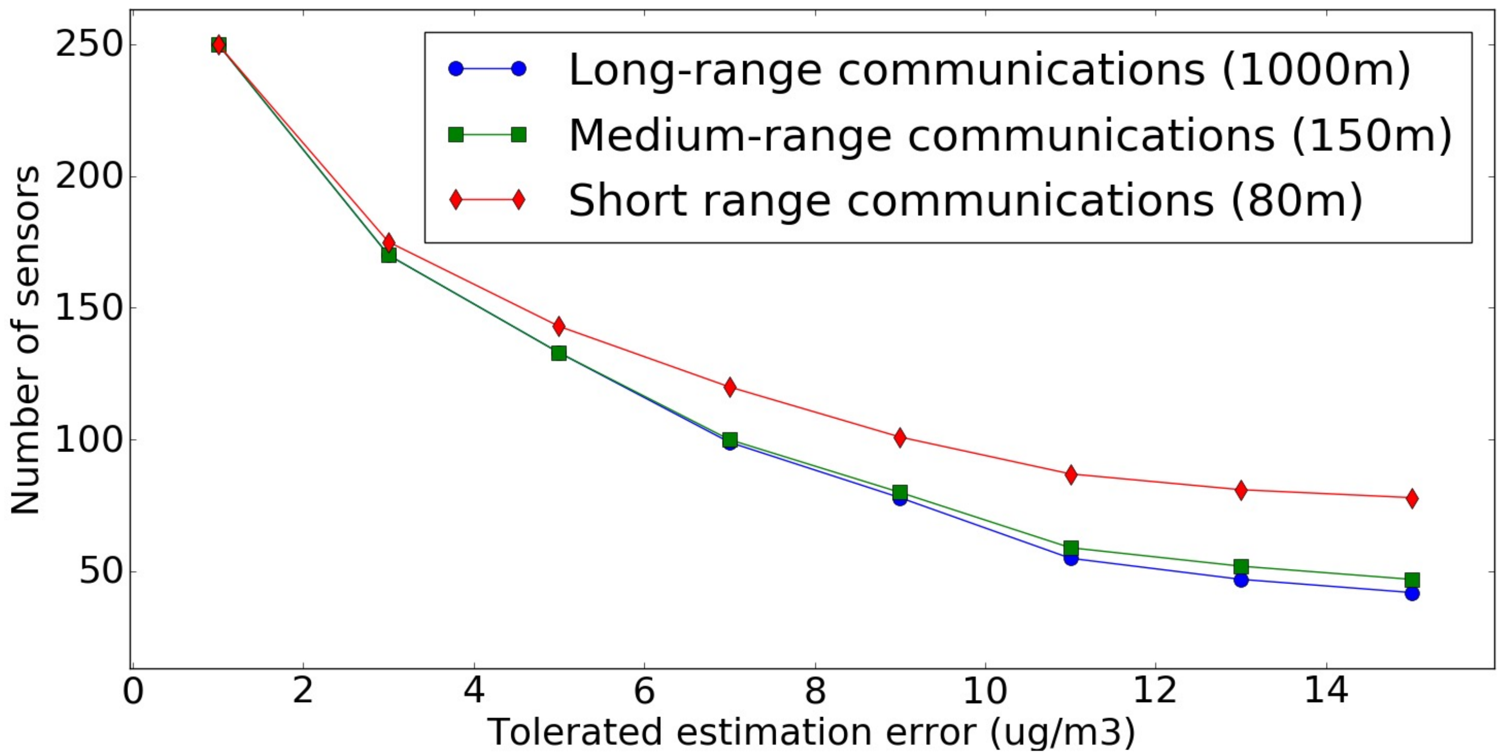


Tolerated estimation error	Single-level Model	Multilevel Model
3 $\mu g/m^3$	1.59 s	0.16 s
6 $\mu g/m^3$	25.23 s	0.19 s
9 $\mu g/m^3$	32.45 s	0.27 s
12 $\mu g/m^3$	6.74 10^2 s	1.65 s

Single-level resolution Vs multi-level resolution

WSN Deployment for Air Quality Regular Mapping

Impact of the communication range of sensors



WSN Deployment for Air Quality Regular Mapping

Extensions

- Impact of Weather conditions
  - Multiple simulated maps
- Nodes' heterogeneity
  - Multiple sensor brands
  - Different sensing errors
- Heuristic algorithm based on linear relaxation
  - Polynomial algorithm
  - x100 faster than optimization models

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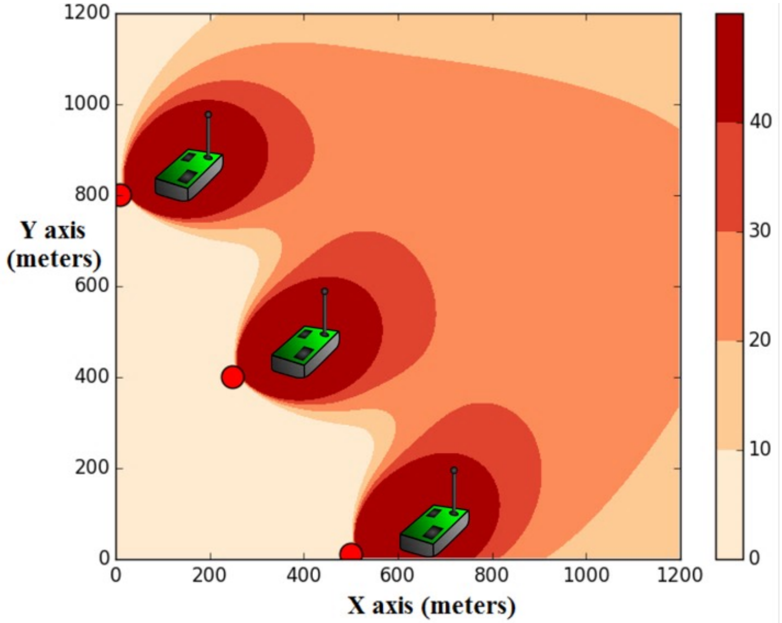
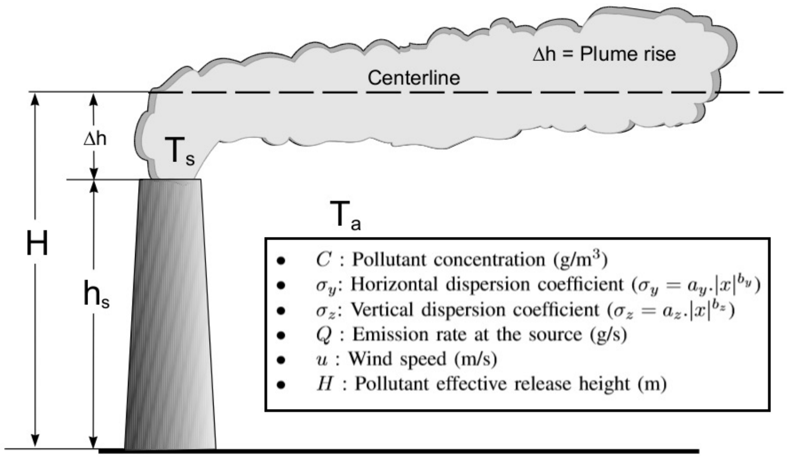
WSN Deployment for Air Pollution Threshold Detection

Main idea





Gaussian pollution dispersion model

WSN Deployment for Air Pollution Threshold Detection

Problem statement

Given:

1. A Set $\mathcal{P}$ of $\mathcal{N}$ potential positions where sensors and sinks can be deployed
2. A Set $\mathcal{I}$ of $\mathcal{M}$ pollution sources that have to be monitored

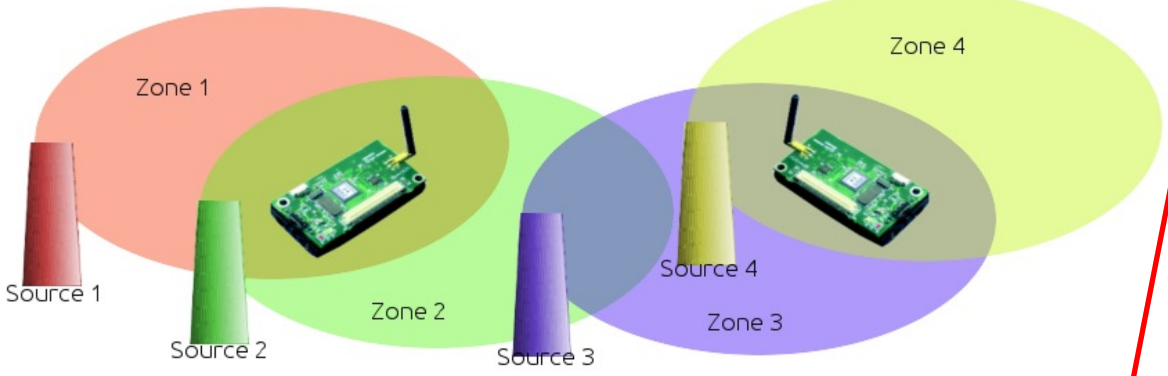
Find the optimal positions of sensors and sinks among $\mathcal{P}$ so as:

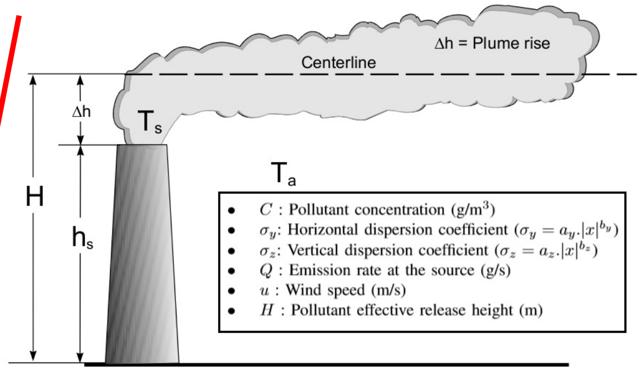
1. The deployment cost is minimized
2. Each pollution source in $\mathcal{I}$ is K-Covered
3. The positioned sensors and sinks form a connected network

WSN Deployment for Air Pollution Threshold Detection

Basic deployment model

1. Pollution coverage constraint: Set Cover





$$W_{ip} = 1 \text{ if } C(x,y,z) >= C_{threshold}$$

$$\mathcal{Z}_i = \{p \in \mathcal{P} \text{ where } C_{ip} \geq C_0\}$$

$$\sum_{p \in \mathcal{P}} \mathcal{W}_{ip} * (x_p + y_p) \geq K, \quad i \in \mathcal{I}$$

2. Network connectivity

- Using the **flow** formalism

WSN Deployment for Air Pollution Threshold Detection

Enhanced deployment model

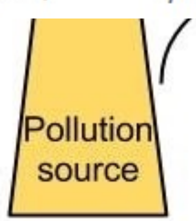
- Joint modeling of coverage and connectivity
- Using only the flow concept

$$\sum_{p \in \mathcal{Z}_i} f_{ip} = K, \quad i \in \mathcal{I} \tag{5}$$

$$\sum_{i \in \mathcal{I} \,:\, p \in \mathcal{Z}_i} f_{ip} + \sum_{q \in \Gamma(p)} (g_{qp} - g_{pq}) \leq K * \mathcal{M} * y_p, \quad p \in \mathcal{P} \tag{6}$$

$$\sum_{i \in \mathcal{I} \,:\, p \in \mathcal{Z}_i} f_{ip} + \sum_{q \in \Gamma(p)} (g_{qp} - g_{pq}) \geq 0, \quad p \in \mathcal{P} \tag{7}$$

$$\sum_{p \in \mathcal{P}} \Big(\sum_{i \in \mathcal{I} \,:\, p \in \mathcal{Z}_i} f_{ip} + \sum_{q \in \Gamma(p)} g_{qp} \Big) = \sum_{p \in \mathcal{P}, q \in \Gamma(p)} g_{pq} + K * \mathcal{M} \tag{8}$$



WSN Deployment for Air Pollution Threshold Detection

Performance evaluation

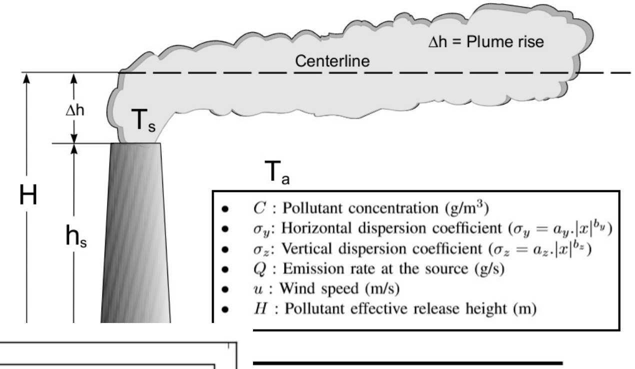
CPU time (seconds)	
Basic Model	**Enhanced Model**
7.460	0.890
20.400	2.810
29.830	3.360
68.200	8.820
31.470	**3.970**

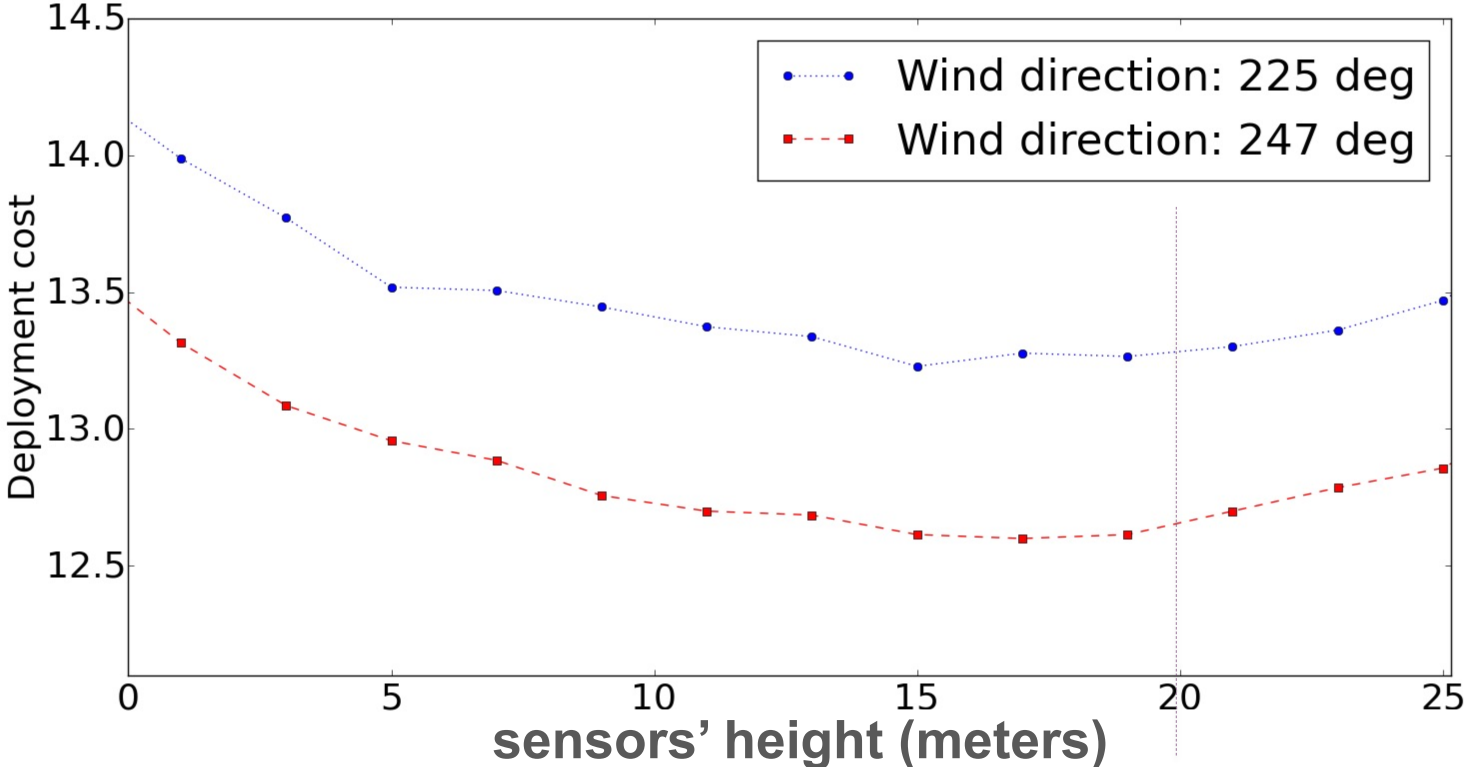
Area of interest (km^2)	Compactness (nb. of vars. and consts)		Tightness (int. gap)	
	Basic Model	**Enhanced Model**	**Basic Model**	**Enhanced Model**
[0.00 – 0.20[	2193	2275	0.880	0.070
[0.20 – 0.45[	2194	2354	0.870	0.080
[0.45 – 0.70[	2195	2429	0.850	0.120
[0.70 – 0.95[	2196	2474	0.830	0.180
Mean	**2194.5**	**2383**	**0.860**	**0.110**

***Integrality gap**: $(Z_{ILP} - Z_{LP})/Z_{ILP}$

WSN Deployment for Air Pollution Threshold Detection

Impact of sensors' height





Pollution sources effective height

WSN Deployment for Air Pollution Threshold Detection

Extensions

- Taking into account the impact of weather conditions
  - Multiple scenarios
- Taking into account sensing errors
  - Probabilistic vs. binary formulation
- Data aware localization of pollution zones
  - An adapted spatiotemporal clustering algorithm

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- ❑ State of the art
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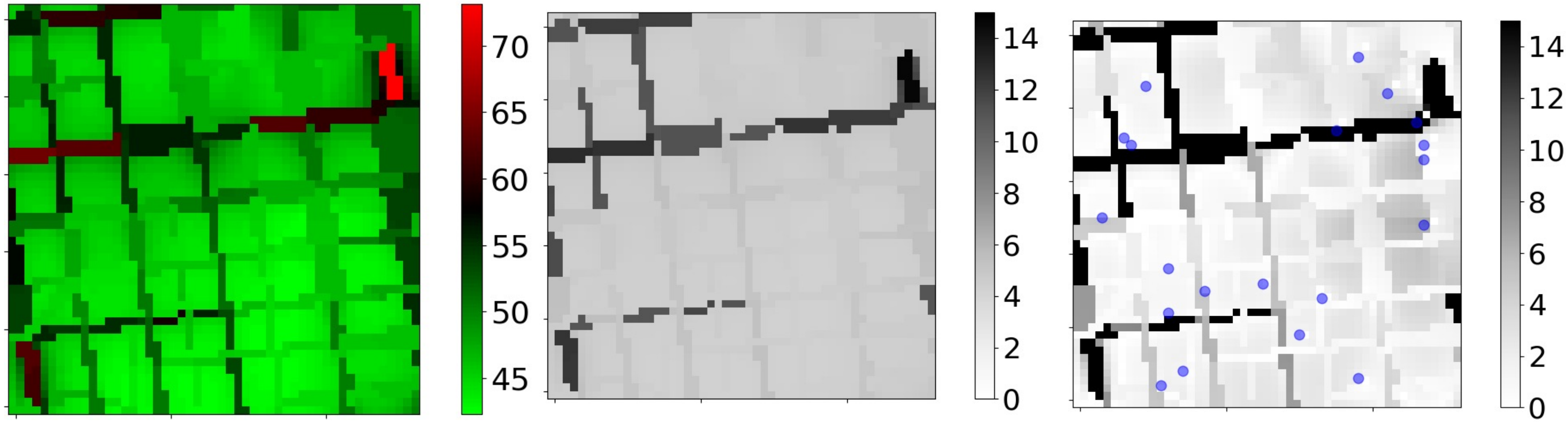
- ❑ WSN Deployment for Air Pollution Simulations' Correction
- ❑ WSN Scheduling for Air Pollution Simulations' Correction

WSN Scheduling for Air Pollution Simulations' Correction

Main idea

- Data assimilation vs. Interpolation
- New coverage metric formulation
- **Deployment vs. Scheduling**

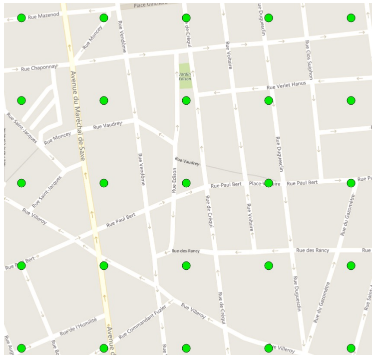


Simulated map   Errors before correction   Errors after correction

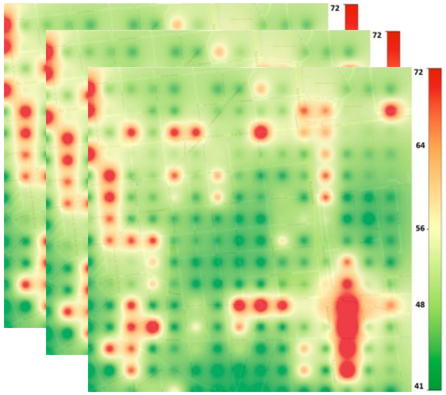
WSN Scheduling for Air Pollution Simulations' Correction

Problem statement

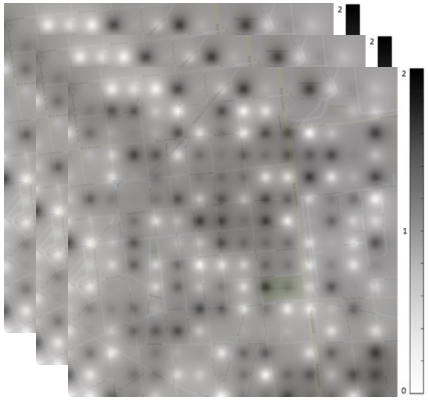
Given a set of already deployed sensor nodes with:



Positions of nodes



Set of time simulated maps



Set of co-variance of simulation errors

$\mathcal{P}$'	Set of points where sensors are deployed
x_p^t	Define whether sensor p is active during t or not ; $x_p^t \in \{0, 1\}$

Find the optimal scheduling of the sensing activity of the nodes such that:

1. The network lifetime is maximized
2. The network remains connected
3. The required estimation error remains ensured

WSN Scheduling for Air Pollution Simulations' Correction

Formulation of estimated concentrations

$$\widehat{\mathcal{Z}}_p^t = \mathcal{M}_p^t + \frac{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t \cdot (\mathcal{Z}_q^t - \mathcal{M}_q^t)}{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t}$$

$$\widehat{\mathcal{Z}}_p^t = \mathcal{M}_p^t - \frac{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t \cdot (m_q^t - s_q^t)}{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t}$$

$\widehat{\mathcal{Z}}_p^t$	Estimated pollution concentrations
$\mathcal{Z}_p^t$	Measured pollution concentrations
$\mathcal{M}_p^t$	Simulated pollution concentrations
$\mathcal{W}_{pq}$	Correlation coefficients
s_p^t	Sensing errors
m_p^t	Simulation errors

WSN Scheduling for Air Pollution Simulations' Correction

Formulation of estimation errors

$$\mathcal{E}_p^t = m_p^t - \frac{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t \cdot (m_q^t - s_q^t)}{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t}$$

$$\begin{aligned} Var(\mathcal{E}_p^t) = Var(m_p^t) &+ \frac{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq}^2 \cdot x_q^t \cdot (Var(m_q^t) + Var(s_q^t))}{(\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t)^2} \\ &- 2 \cdot \frac{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t \cdot Cov(m_p^t, m_q^t)}{\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t} \\ &+ \frac{\sum_{q_1 \neq p} \sum_{q_2 \neq p, q_1} \mathcal{W}_{pq_1} \cdot \mathcal{W}_{pq_2} \cdot x_{q_1}^t \cdot x_{q_2}^t \cdot Cov(m_{q_1}^t, m_{q_2}^t)}{(\sum_{q \in \mathcal{P}} \mathcal{W}_{pq} \cdot x_q^t)^2} \end{aligned}$$

WSN Scheduling for Air Pollution Simulations' Correction

Network lifetime and energy constraints

Network Lifetime: $\sum_{t \in \mathcal{T}} \alpha_t$

α_t Equals to 1 if coverage and connectivity are ensured during 't'

$$\alpha_0 \geq \alpha_1 \geq \alpha_2 \geq \ldots$$

Energy contraint:

$$\forall p \in \mathcal{P} \sum_{t} ES_p^t * x_p^t + \sum_{t,q} ET_{pq}^t * g_{pq}^t + \sum_{t,q} ER_{pq}^t * g_{qp}^t \leq EI$$

ES_p^t Energy amount used during a sensing cycle

ET_{pq}^t Energy amount used during the transmission of a packet

ER_{pq}^t Energy amount used during the reception of a packet

EI Initial amount of energy

WSN Scheduling for Air Pollution Simulations' Correction

Optimization model

Objective: $$Maximize \sum_{t \in \mathcal{T}} \alpha_t$$

Energy consumption:

$$\forall p \in \mathcal{P} \; \sum_{t} ES_p^t * x_p^t + \sum_{t,q} ET_{pq}^t * g_{pq}^t + \sum_{t,q} ER_{pq}^t * g_{qp}^t \leq EI$$

Coverage:

$$\mathcal{E}_p^t \leq E, \; p \in \mathcal{P}$$

Connectivity: flow concept

WSN Scheduling for Air Pollution Simulations' Correction

Heuristic Algorithm: Iterative rounding

- Complexity of the model → time snapshots
- Polynomial algorithm

Algorithm 1 Scheduling heuristic

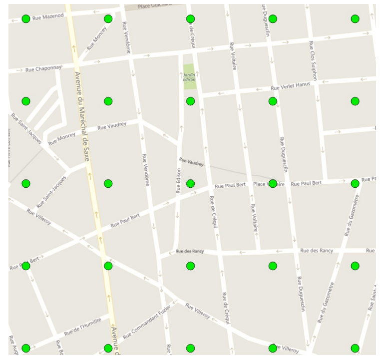
Inputs: $\mathcal{P}$
Outputs: $\{x_p^t, \alpha_t\}$

repeat
  Solve the LP scheduling model
  Let f be the maximum fractional variable among x_p^t
  Add constraint $f = 1$ to the LP model
until all the variables are binary

WSN Scheduling for Air Pollution Simulations' Correction

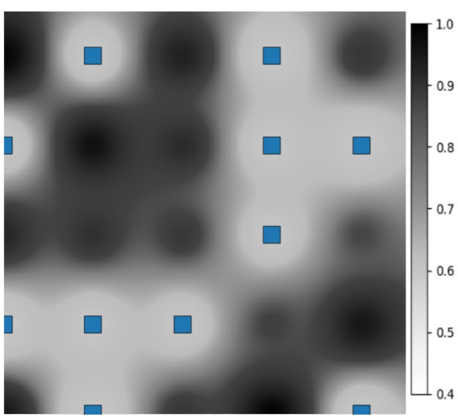
Proof of concept: La Part Dieu District

Initial deployment:

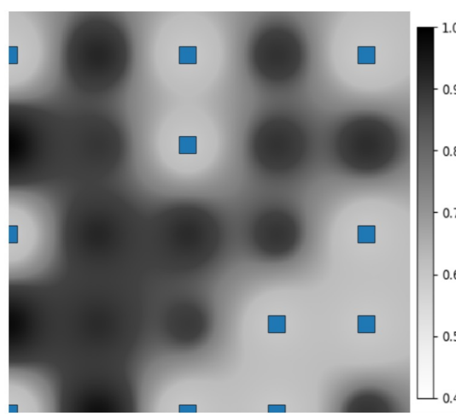


Power consumption model:
- Urpolsens nodes

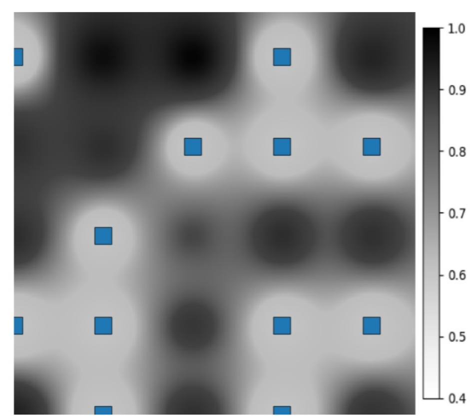
Optimal scheduling results (Var(Eth)=1 $(\mu g)^2/m^6$):



January



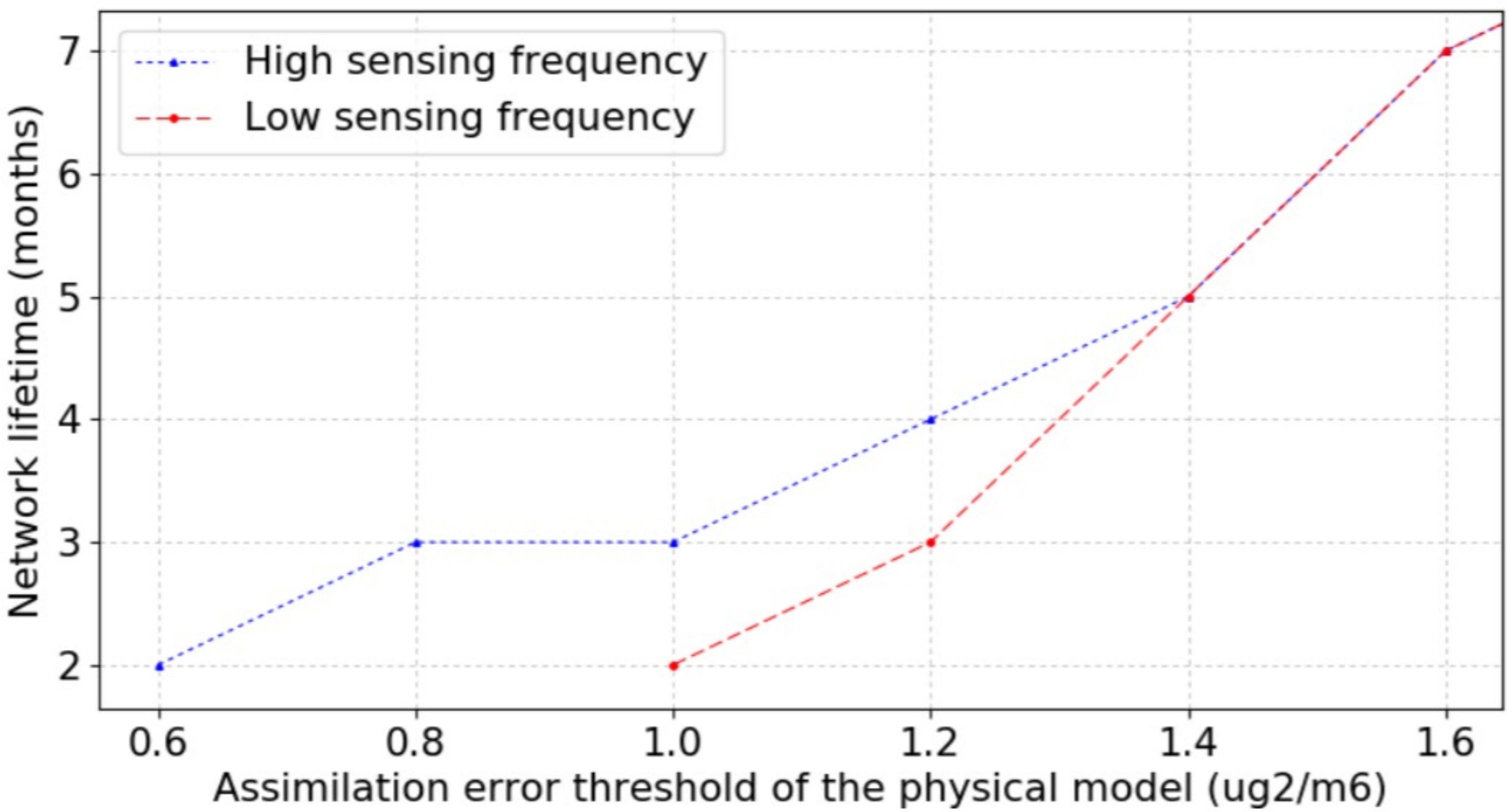
February



March

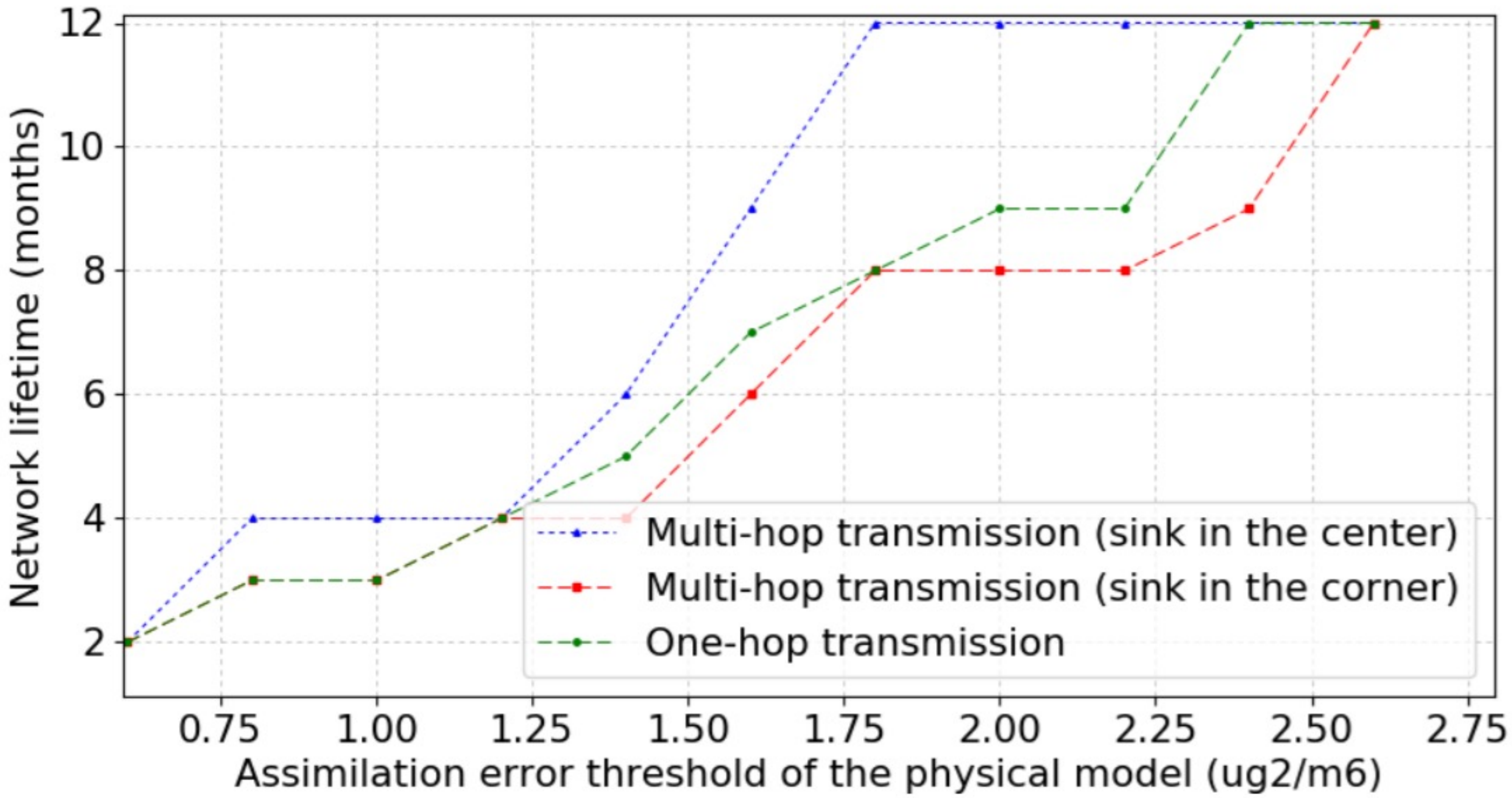
WSN Scheduling for Air Pollution Simulations' Correction

Impact of sensing frequency



WSN Scheduling for Air Pollution Simulations' Correction

Impact of transmission power



Latest and Ongoing Research

Mobility Optimization of Drone Networks

Problem: UAV mission planning

Optimization of the drones' limited sensing resources

→ **Output:** optimal drone sensing locations

Challenges:

→ Sensing quality: dynamic and context-dependent

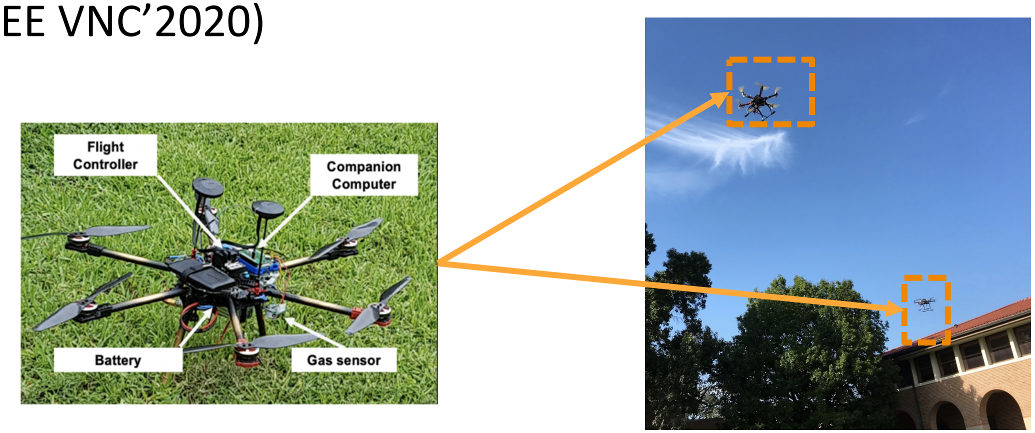
→ Communication constraints: mobile networks' complexity

→ Energy constraints

Proposed solutions:

→ **Environmental mapping** (ACM TIOT'2021, ACM DroNet@MobiSys'2020)

→ **RF targets' localization** (IEEE VNC'2020)



Publications

[J1] **Ahmed Boubrima** and Edward W. Knightly. Robust Environmental Sensing using UAV Networks. To appear in ACM **Transactions** on Internet of Things, 2021 **(specialized transaction journal in Internet of Things).**

[J2] **Ahmed Boubrima**, Walid Bechkit and Hervé Rivano. On the Deployment of Wireless Sensor Networks for Air Quality Mapping: Optimization Models and Algorithms. In IEEE/ACM **Transactions** on Networking, 2019 (**A* and Q1 journal rank).**

[J3] **Ahmed Boubrima**, Walid Bechkit and Hervé Rivano. Optimal WSN Deployment Models for Air Pollution Monitoring. In IEEE **Transactions** on Wireless Communications, 2017 **(Q1 journal rank).**

[J4-r] Zhambyl Shaikhanov, **Ahmed Boubrima** and Edward W. Knightly. FALCON: a Networked Drone System for Sensing, Localizing, and Approaching RF targets. **Under review** at IEEE Internet of Things Journal.

[B1] **Ahmed Boubrima**, Walid Bechkit and Hervé Rivano. On the Optimization of WSN Deployment for Sensing Physical Phenomena: Applications to Urban Air Pollution Monitoring. **Book chapter**, Springer, 2019.

[W1] Ahmed Boubrima and Edward W. Knightly. Robust Mission Planning of UAV Networks for Environmental Sensing. In the 6th ACM Workshop Dronet @ MobiSys 2020, Toronto, Canada **(Best paper award).**

[C1] Zhambyl Shaikhanov, **Ahmed Boubrima** and Edward W. Knightly. Autonomous Drone Networks for Sensing, Localizing and Approaching RF Targets. In the 2020 IEEE Vehicular Networking Conference (IEEE VNC), 2020. **(B4 rank).**

[C2] **Ahmed Boubrima**, Walid Bechkit, Hervé Rivano and Lionel Soulhac. Leveraging the Potential of WSN for an Efficient Correction of Air Pollution Fine-Grained Simulations. In ICCCN/IC3N 2018, Hangzhou, China. **(A rank).**

[C3] **Ahmed Boubrima**, Azzedine Boukerche, Walid Bechkit and Hervé Rivano. WSN Scheduling for Energy-Efficient Correction of Environmental Modelling. In IEEE MASS 2018), Chengdu, China **(A/B rank)**.

[C4] **Ahmed Boubrima**, Walid Bechkit and Hervé Rivano. A New WSN Deployment Approach for Air Pollution Monitoring. In the 14th IEEE CCNC 2017, Las Vegas, Nevada, USA. **(B rank).**

[C5] **Ahmed Boubrima**, Walid Bechkit and Hervé Rivano. Error-Bounded Air Quality Mapping Using Wireless Sensor Networks. In the 41st IEEE LCN 2016, Dubai, UAE **(A rank)**.

[C6] **Ahmed Boubrima**, Frédéric Matigot, Walid Bechkit, Hervé Rivano and Anne Ruas. Optimal Deployment of Wireless Sensor Networks for Air Pollution Monitoring. In ICCCN/IC3N 2015, Las Vegas, Nevada, USA **(A rank)**.

[C7] **Ahmed Boubrima**, Walid Bechkit, Hervé Rivano and Anne Ruas. Wireless Sensor Networks Deployment for Air Pollution Monitoring. In the 21st International Transport and Air Pollution Conference (TAP 2016), Lyon, France.

[C8] **Ahmed Boubrima**, Walid Bechkit, Hervé Rivano and Lionel Soulhac. Cost-precision Tradeoffs in 3d Air Pollution Mapping using WSN. In the Second International Symposium on Ubiquitous Networking (UNET 2016), Casablanca, Morocco. **(best paper award).**

Thank You

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