

# Wireless Sensor Networks

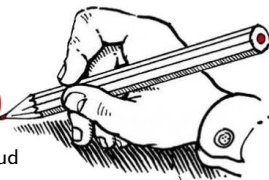
A survey on maximizing lifetime in sensor coverage problems

Marc Sevaux

**ORBEL 29**

Université de Bretagne-Sud

[marc.sevaux@univ-ubs.fr](mailto:marc.sevaux@univ-ubs.fr)



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Team: A. Bounceur, E. Bourreau, F. Castaño, A. Rossi, A. Singh and N. Velasco

# Overview

## Applications

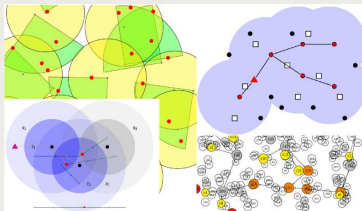


# Overview

## Applications



## Problem & variants

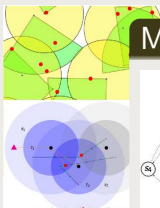


# Overview

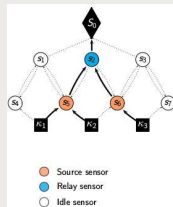
## Applications



## Problem & variants



## Mathematics



Maximize:  $t_1 + t_2 + t_3 + t_4$

$$E_s t_1 + E_i t_2 + E_s t_3 + E_i t_4 \leq \beta$$

$$E_i t_1 + E_s t_2 + E_i t_3 + E_s t_4 \leq \beta$$

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$$E_r t_1 + E_i t_2 + E_r t_3 + E_i t_4 \leq \beta$$

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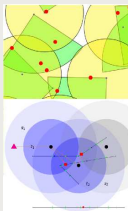
$$t_j \geq 0 \quad \forall j | C_j \in \Omega$$

# Overview

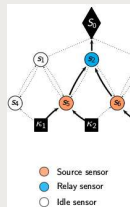
## Applications



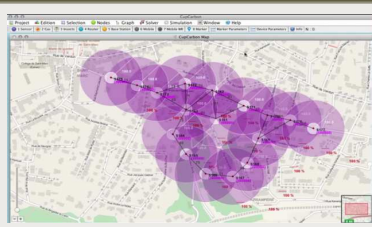
## Problem & variants



## Mathematics



## Demo & simulation

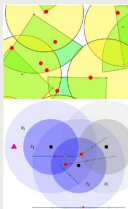


# Overview

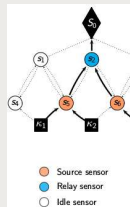
## Applications



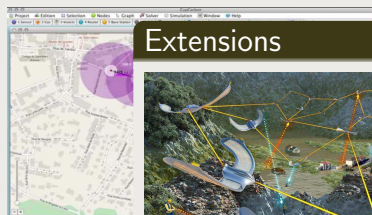
## Problem & variants



## Mathematics



## Demo & simulation



## Extensions



## 1 Introduction to Wireless Sensor Networks

- Motivations
- Applications
- Wireless sensors
- Networks
- Objective functions

# WSN: a growing field of research

## Research fundings

Funding is continuously growing

- NSF \$47M (2003)
- US Military \$1.5B (on RTLS)
- Living PlanIT \$13T (10 years)

## WSN market

2012	2022	2032
\$0.6B	\$2.4B	\$6.5B



# WSN: a growing field of research

## Research fundings

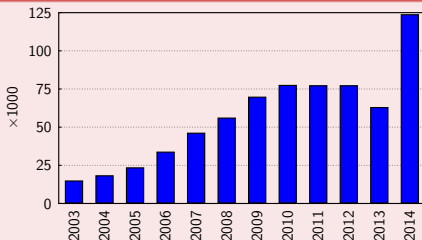
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## WSN market

2012	2022	2032
\$0.6B	\$2.4B	\$6.5B

## A pearl for publishing



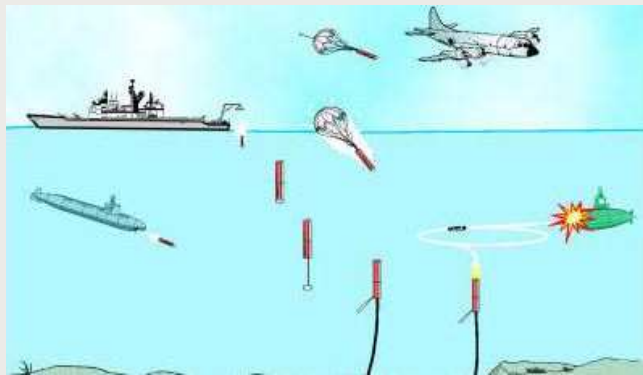
## Definition (Wireless Sensor Network)

A wireless sensor network (WSN) consists of spatially distributed autonomous sensors to cooperatively monitor physical or environmental conditions, such as temperature, vibration, pressure or pollutants. . .

- Military applications
- Environment and civil engineering
- Industry and commerce
- Smart home
- Health

## Military applications

## Submarine movements

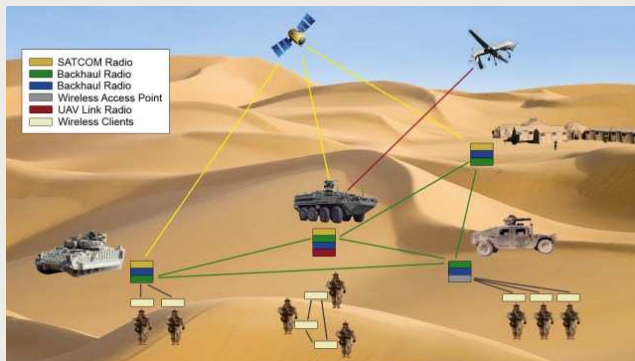


# Military applications

## Submarine movements



## Battlefield surveillance



# Military applications

## Submarine movements



## Battlefield surveillance



## Enemy intrusion



# Military applications

## Submarine movements



## Battlefield surveillance



## Enemy intrusion



# Military applications

## Submarine movements



## Battlefield surveillance



## Enemy intrusion



# Military applications

## Submarine movements



## Battlefield surveillance



- SATCOM Radio
- Backhaul Radio
- Backhaul Radio
- Wireless Access
- UAV Link Radio
- Wireless Clients

## Enemy intrusion





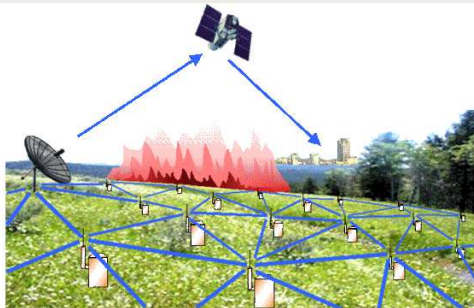
# Military applications (sensors)



# Military applications (sensors)



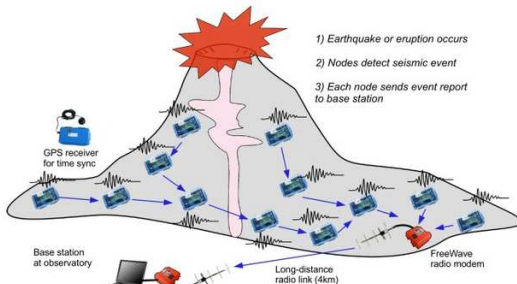
## Forest fire detection



## Forest fire detection



## Volcano eruption prevention

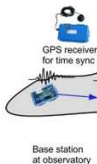


# Environment and civil engineering

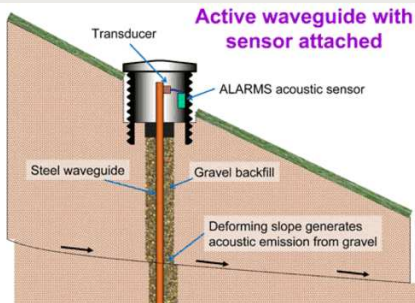
## Forest fire detection



## Volcano eruption prevention



## Land slide early detection



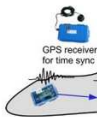
# Environment and civil engineering

## Forest fire detection

## Volcano eruption prevention

## Land slide early detection

## Bridge/Tunnel/Highway monitoring



Base station  
at observatory



Ste



Vibration  
sensor nodes



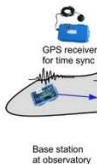
Vibration,  
inclination,  
displacement  
sensor nodes

# Environment and civil engineering

## Forest fire detection



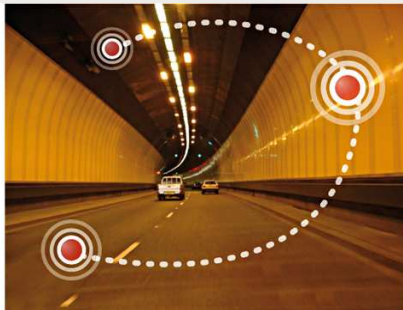
## Volcano eruption prevention



## Land slide early detection



## Bridge/Tunnel/Highway monitoring

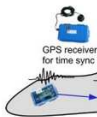


# Environment and civil engineering

## Forest fire detection



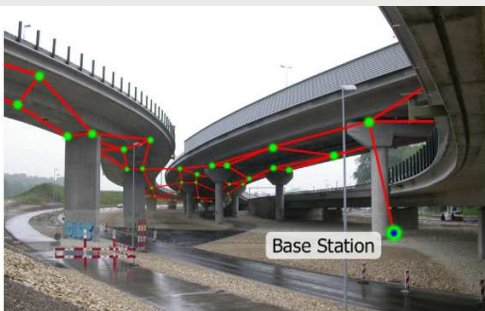
## Volcano eruption prevention



## Land slide early detection

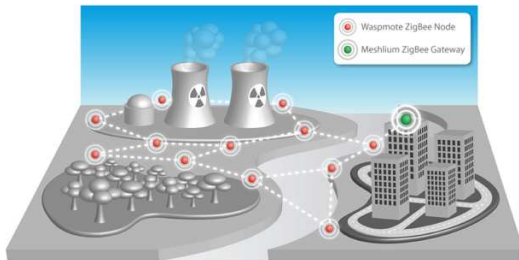


## Bridge/Tunnel/Highway monitoring





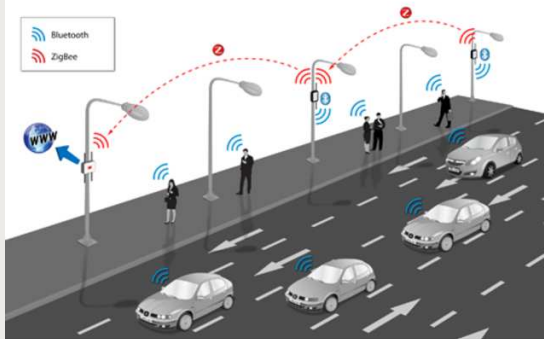
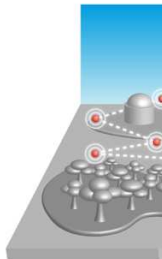
## Monitoring security elements



# Industry and commerce

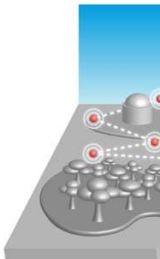
## Monitoring security elements

### Sensors in cities



# Industry and commerce

## Monitoring security elements



## Sensors in cities



## Inventory (RFID)



## Intrusion alarm



## Intrusion alarm

## Fire/gaz detectors

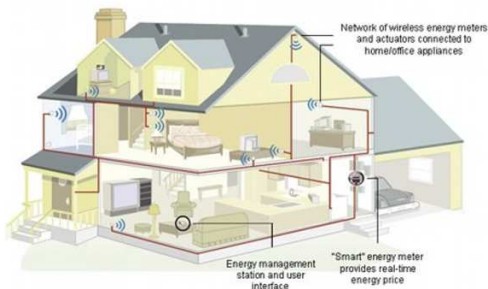


# Smart home

## Intrusion alarm

## Fire/gaz detectors

## Smart energy/passive house



# Smart home

## Intrusion alarm

## Fire/gaz detectors

## Smart energy/passive house

## Connected objects



# Smart home

## Intrusion alarm

## Fire/gaz detectors

## Smart energy/passive house

## Connected objects

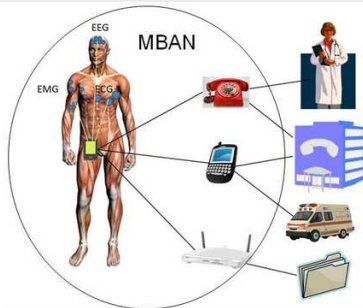


HOME  
by SFR





## Body embedded sensors



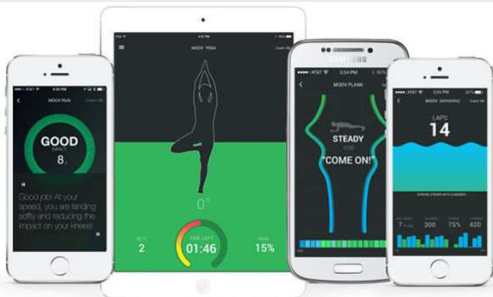
## Body embedded sensors

### Sensors for sports



## Body embedded sensors

### Sensors for sports



## Body embedded sensors

### Sensors for sports



## Body embedded sensors

## Sensors for sports

## Artery exploration



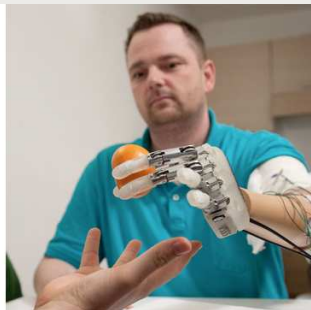
# Health

Body embedded sensors

Sensors for sports

Artery exploration

Disable people





Electronic device:

- sensing module
- short-range communication
- self powered
- limited processing capabilities

# Many types of wireless sensors





# Many types of wireless sensors

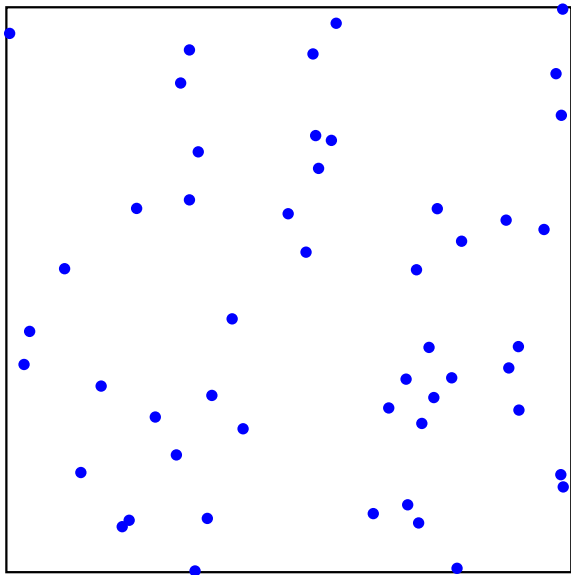


# Many types of wireless sensors



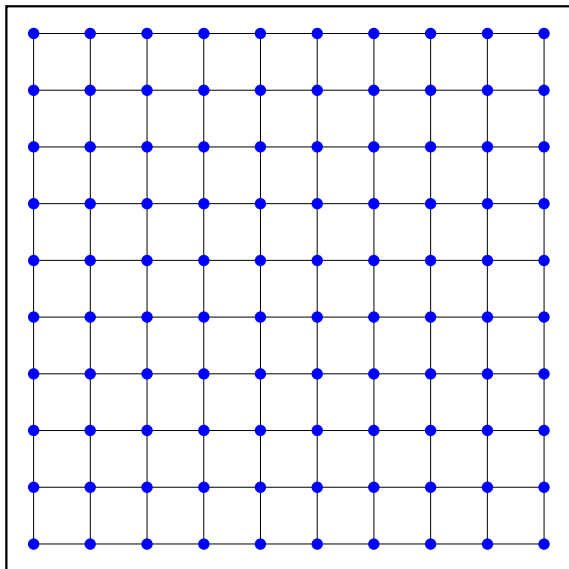
# Different types of networks

Random network



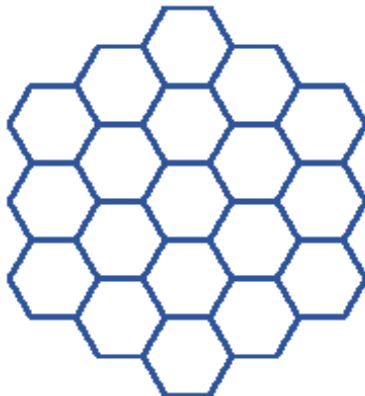
# Different types of networks

Mesh 2D regular



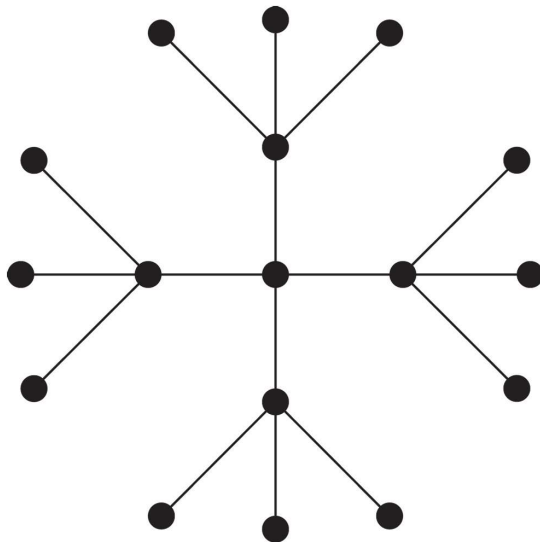
# Different types of networks

Hexagon regular



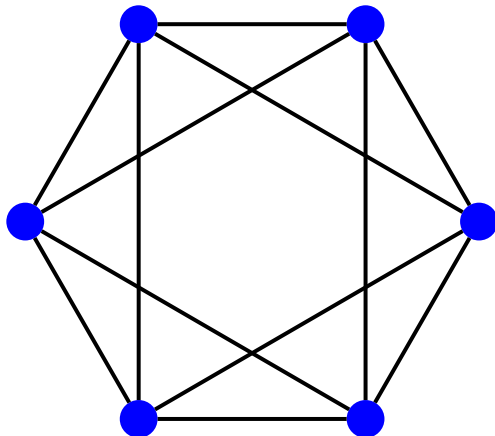
# Different types of networks

Star



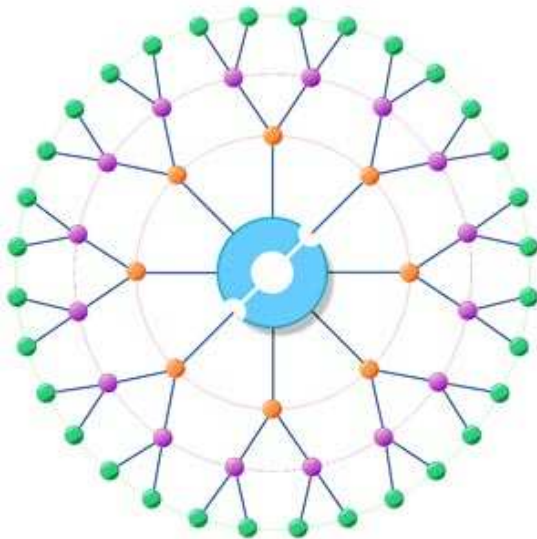
# Different types of networks

Ring



# Different types of networks

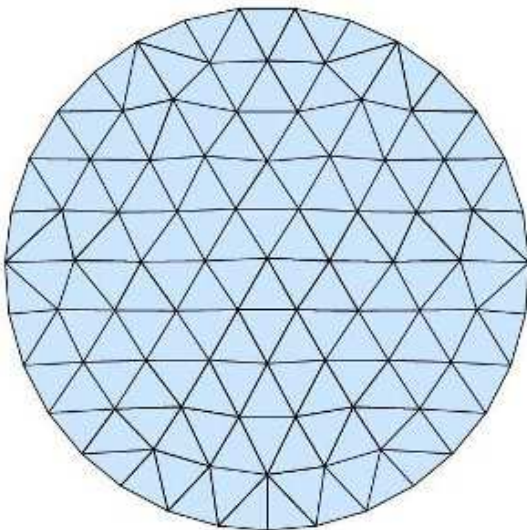
Ring-star





# Different types of networks

Ad-hoc



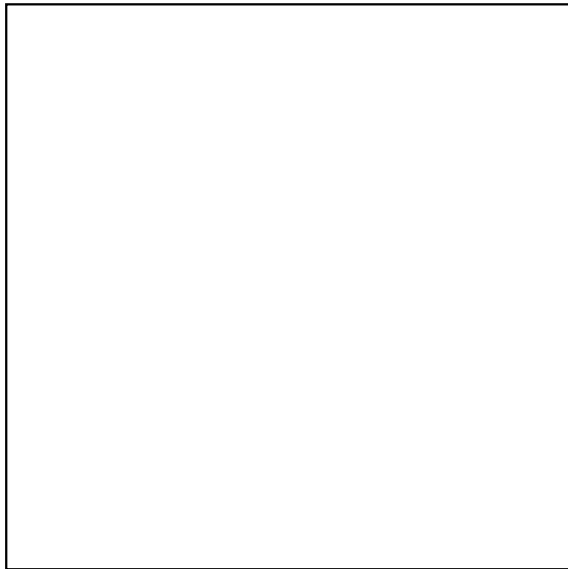
# Objective functions

- **Minimization** of the covering breach
- **Minimization** of energy consumption
- **Minimization** of deployment cost
- **Maximization** of area monitoring
- **Maximization** of the network lifetime

## 2 Problem and variants

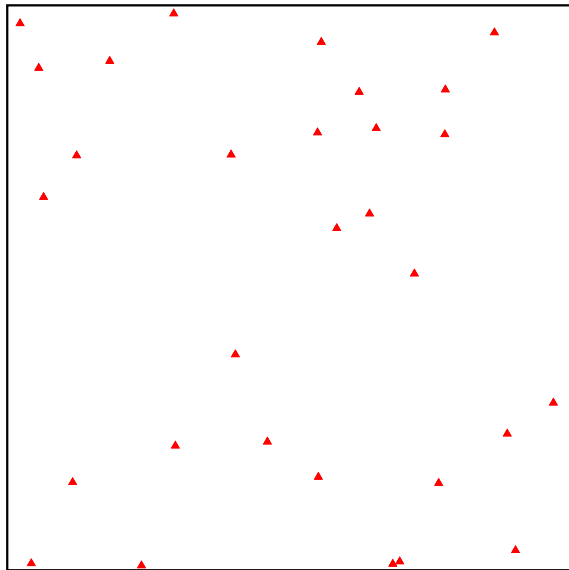
- Our case study
- MNLB
- Classical variants of the problem

# Wireless Sensor Networks: example



In a specific area

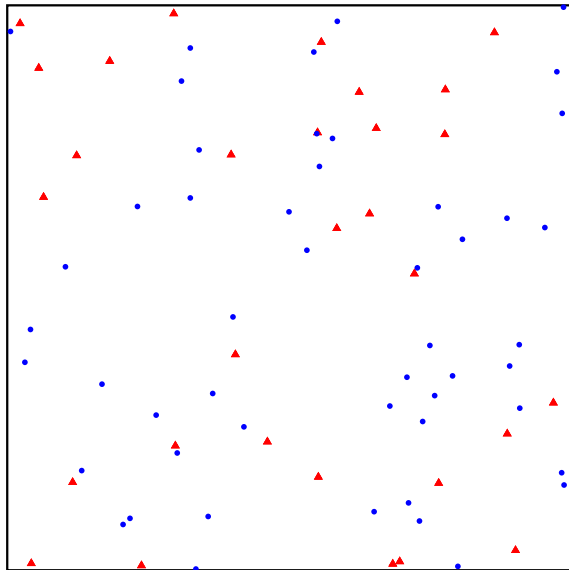
# Wireless Sensor Networks: example



In a specific area

- a set of **targets** to monitor over time

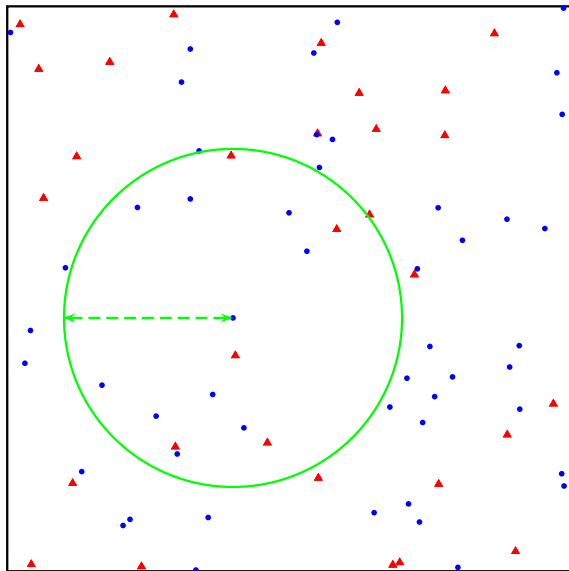
# Wireless Sensor Networks: example



In a specific area

- a set of **targets** to monitor over time
- a set of **sensors** to cover the targets

# Wireless Sensor Networks: example



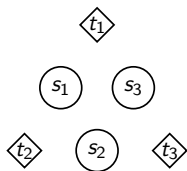
In a specific area

- a set of **targets** to monitor over time
- a set of **sensors** to cover the targets
- a sensor maximum **range** for detection

# Wireless Sensor Networks

Wireless **sensors** are [randomly] deployed for covering the set of **targets**

- all sensors are identical
- they operate on a battery, whose lifetime is normalized to one
- when a sensor is **inactive**, it consumes no energy
- when a sensor is **active**, it covers all the targets under its sensing range  $R_s$

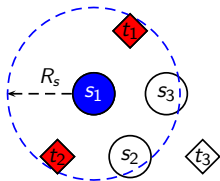




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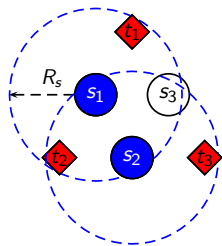


$s_1$  covers  $t_1$  and  $t_2$  when it is active

# Wireless Sensor Networks

Wireless **sensors** are [randomly] deployed for covering the set of **targets**

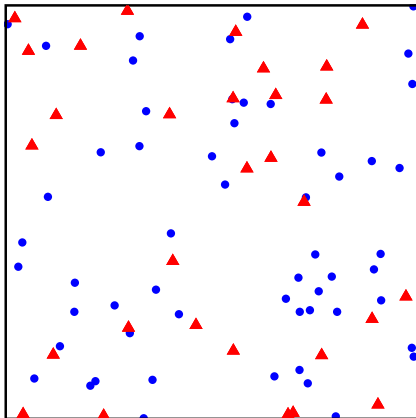
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$s_1$  covers  $t_1$  and  $t_2$  when it is active

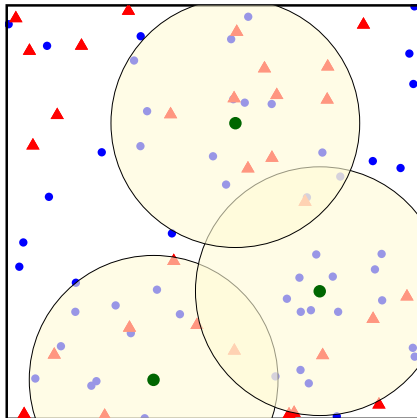
when  $s_1$  and  $s_2$  are active, they cover all the targets

# What we are looking for!



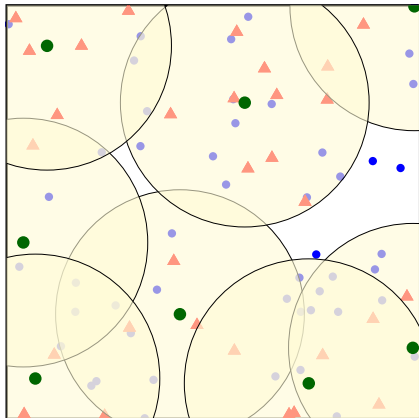
Initial situation

# What we are looking for!



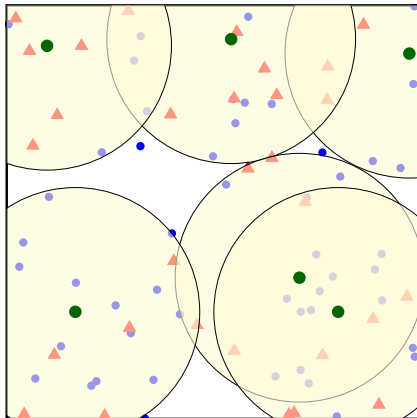
**Not Good**

# What we are looking for!



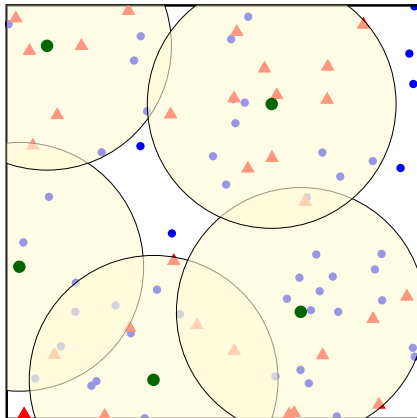
Good

# What we are looking for!



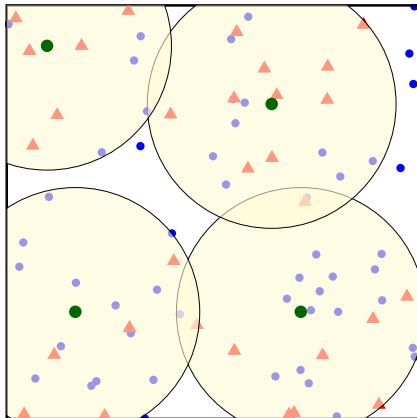
Good

# What we are looking for!



**Almost Good**

# What we are looking for!



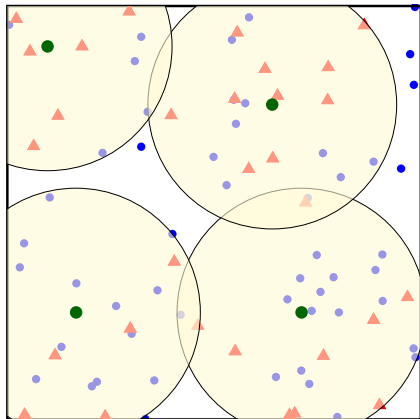
**Very Good!!!**



## Maximization of the Network Lifetime under Bandwidth constraints

- the network lifetime is the objective to maximize
- all targets should be covered at any time
- bandwidth constraint is modeled as follows:  
any subset of active sensors must be made of at most  $W$  sensors

# Lifetime maximization: MNLB



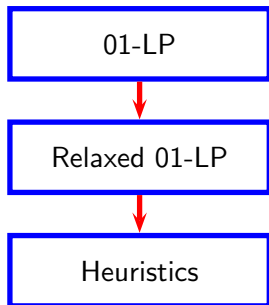
- all targets are covered
- if the bandwidth constraint is  $W = 5$ , ok
- we have to find other similar subsets to maximize lifetime

# Lifetime maximization: MNLB

 C. Wang, M.T. Thai, Y. Li, F. Wang, and W. Wu

Optimization scheme for sensor coverage scheduling with bandwidth constraints.

*Optimization Letters*, 3:63–75, 2009.

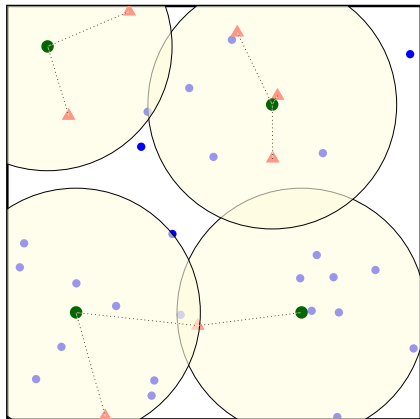


- first to solve MNLB
- MNLB  $\mathcal{NP}$ -complete
- solve relaxed MCBB
- transform into MNLB
- heuristic approach
- 4 instances only
- 50 sensors

## Maximization of the Network Lifetime **with $Q$ -coverage constraint**

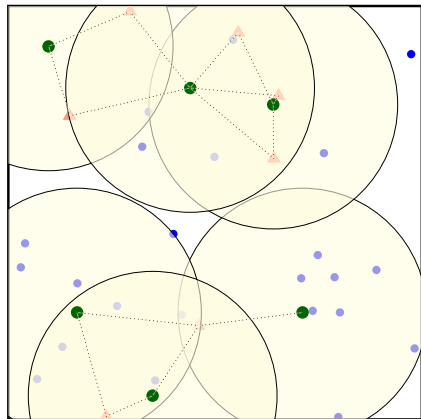
- the network lifetime is the objective to maximize
- all targets should be **covered by  $Q$  sensors** at any time

# Lifetime maximization: $Q$ -coverage



- all targets are now covered by  $Q$  sensors at any time ( $Q = 1$ )

# Lifetime maximization: $Q$ -coverage



- all targets are now covered by  $Q$  sensors at any time ( $Q = 2$ )
- we have to find plenty of similar subsets to maximize lifetime

# Lifetime maximization: $Q$ -coverage



Y. Gu, H. Liu, and B. Zhao.

Target coverage with QoS requirements in wireless sensor networks.

*International Conference on Intelligent Pervasive Computing*, 35–38, 2007.

Column generation

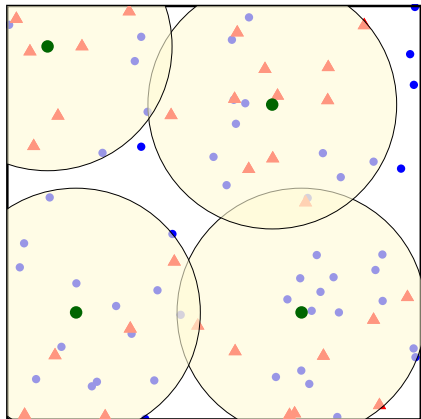
- $Q$ -coverage  $\mathcal{NP}$ -complete
- exact approach
- efforts on initial columns
- results on small instances
- 30-75 sensors
- only compare to MNLB  
( $Q = 1$ )

## Maximization of the Network Lifetime **with connectivity constraint**

- the network lifetime is the objective to maximize
- all targets should be covered at any time
- all activated targets should be **connected to a base station**

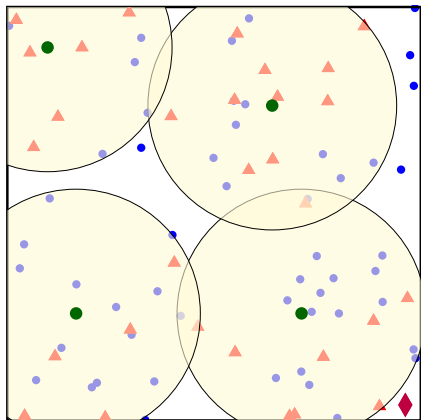


# Lifetime maximization: base station



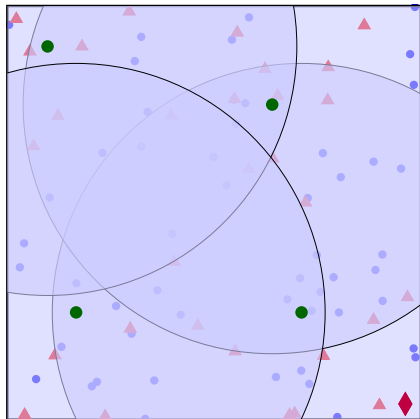
- all targets are covered by a sensor, when activated

# Lifetime maximization: base station



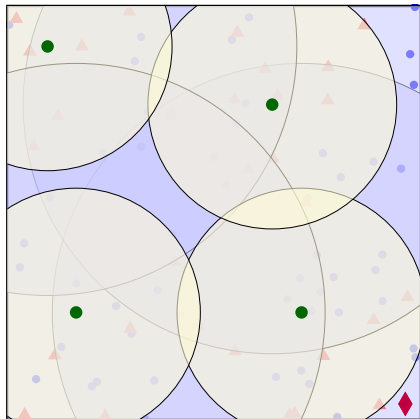
- all targets are covered by a sensor, when activated
- a base station is present in the network

# Lifetime maximization: base station



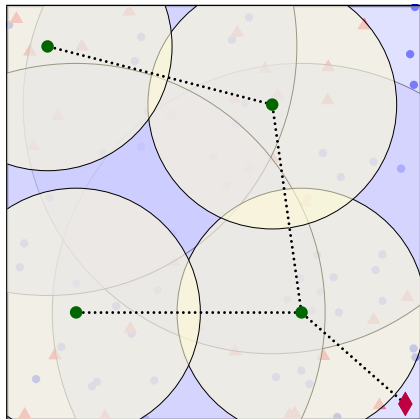
- all targets are covered by a sensor, when activated
- a base station is present in the network
- every sensor has a large communication range

# Lifetime maximization: base station



- all targets are covered by a sensor, when activated
- a base station is present in the network
- every sensor has a large communication range
- all activated sensors should be connected to the base station

# Lifetime maximization: base station



- all targets are covered by a sensor, when activated
- a base station is present in the network
- every sensor has a large communication range
- all activated sensors should be connected to the base station



M. Gentili and A. Raiconi.

$\alpha$ -Coverage to extend network lifetime on wireless sensor networks.

*Optimization Letters*, 7(1):157–172, 2013

Column generation

+

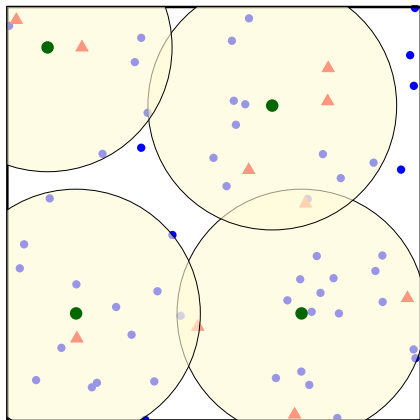
Heuristics

- exact approach
- greedy heuristics
- test bench 480 instances
- 25-150 sensors
- can solve  $\alpha$ -coverage

## Maximization of the Network Lifetime **with adjustable sensing range**

- the network lifetime is the objective to maximize
- all targets should be covered at any time
- **sensing range can be adjusted** to reduce energy consumption
  - ad-hoc sensing ranges
  - predefined sensing ranges

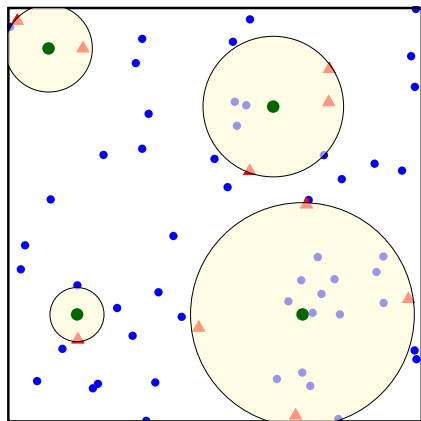
# Lifetime maximization: adjustable sensing range



- all targets are covered by a sensor, when activated



# Lifetime maximization: adjustable sensing range



- all targets are covered by a sensor, when activated
- but the sensing range is reduced to the minimum value for covering the same targets and saving energy

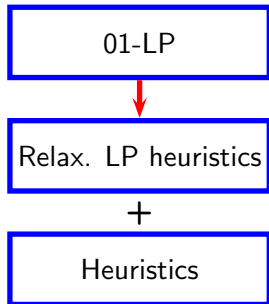
# Lifetime maximization: adjustable sensing range



M. Cardei, J. Wu, M. Lu, and M.O. Pervaiz.

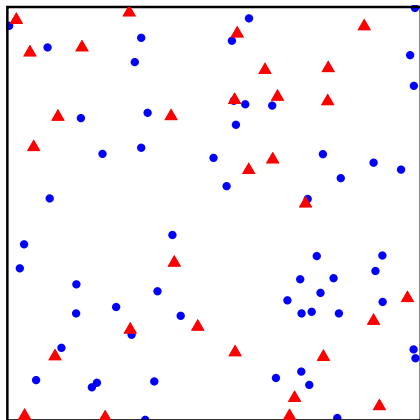
Maximum network lifetime in WSN with adjustable sensing ranges

*Wireless And Mobile Computing, Networking And Communications*, 438–445, 2005



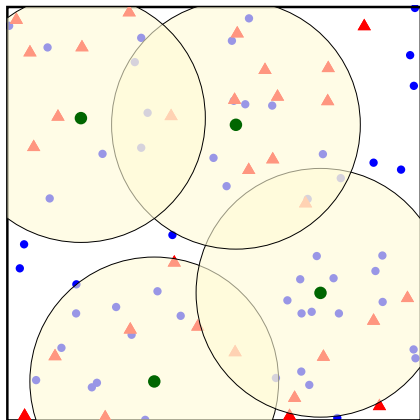
- nice study on sensing ranges
- only 16 instances
- 25-250 sensors

# Lifetime maximization: $\alpha$ -coverage



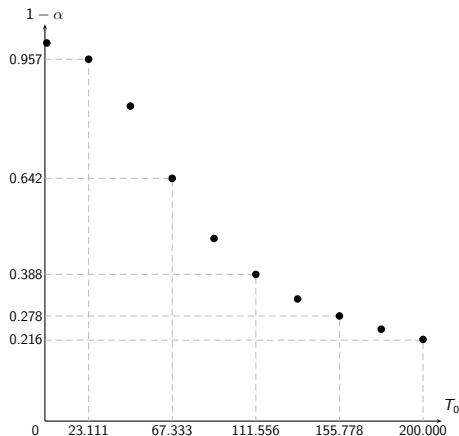
- sensors and targets are randomly placed

# Lifetime maximization: $\alpha$ -coverage



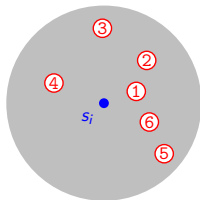
- sensors and targets are randomly placed
- a fraction  $\alpha$  of the targets are not covered
- here,  $\alpha = 4/30 = 0.13$

# Lifetime maximization: trade-off



- a decision maker can choose between lifetime and  $\alpha$
- 200 sensors, 120 targets

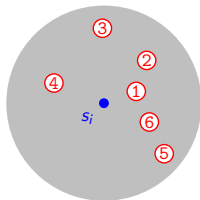
# Lifetime maximization: directional sensors and focal lens



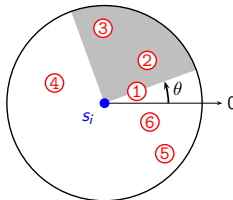
Omnidirectional sensor

Decide when to set the sensor to active state

# Lifetime maximization: directional sensors and focal lens



Omnidirectional sensor

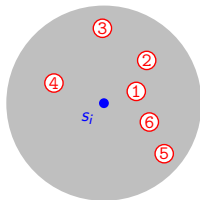


Directional sensor

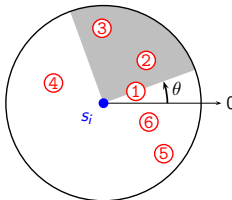
Decide when to set the sensor to active state

Set working direction  $\theta$

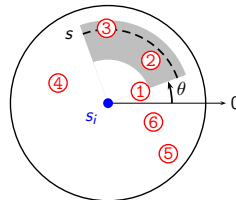
# Lifetime maximization: directional sensors and focal lens



Omnidirectional sensor



Directional sensor



Camera sensor

Decide when to set the sensor to active state

Set working direction  $\theta$

Set focal distance  $s$



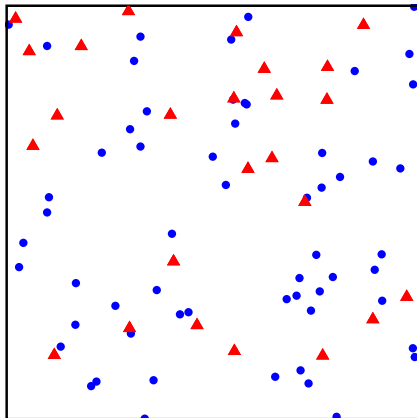
## 3 Mathematics and general framework

- Our problem
- Covers
- Reformulation of the problem
- Column generation
- Pricing subproblem
- Matheuristics

# Our current problem

## $\alpha$ -CMLP

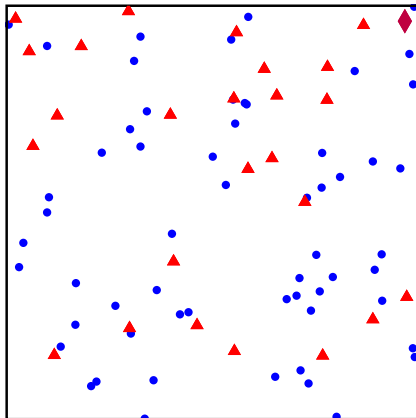
- set of targets and sensors



# Our current problem

## $\alpha$ -CMLP

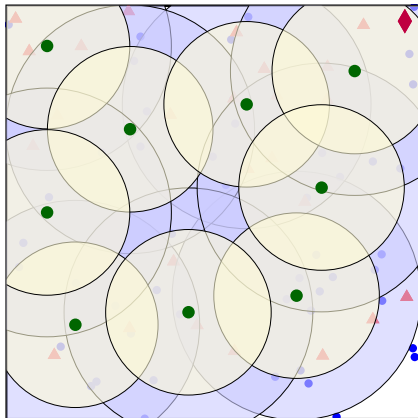
- set of targets and sensors
- base station



# Our current problem

## $\alpha$ -CMLP

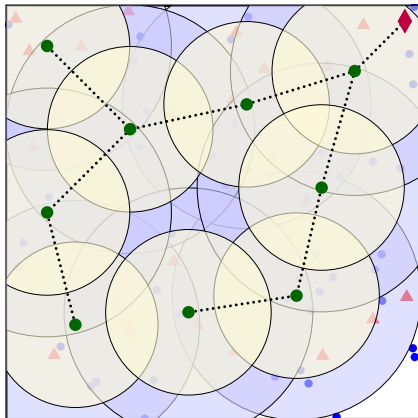
- set of targets and sensors
- base station
- activated sensors



# Our current problem

## $\alpha$ -CMLP

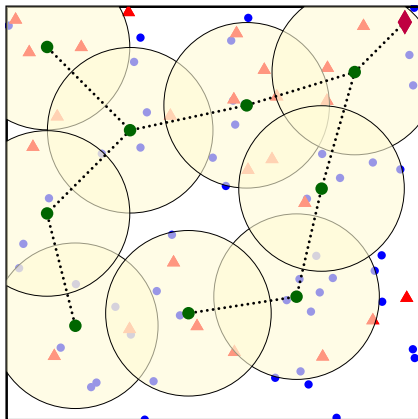
- set of targets and sensors
- base station
- activated sensors
- communication links



# Our current problem

## $\alpha$ -CMLP

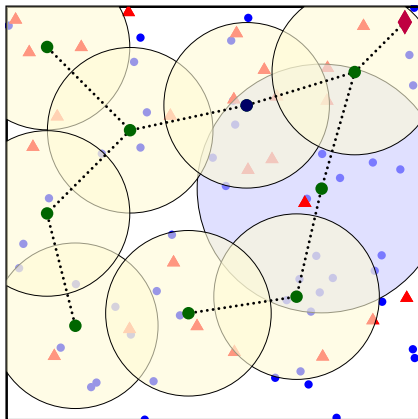
- set of targets and sensors
- base station
- activated sensors
- communication links
- $\alpha$ -coverage



# Our current problem

## $\alpha$ -CMLP-MR

- set of targets and sensors
- base station
- activated sensors
- communication links
- $\alpha$ -coverage
- some sensors can be used for communication only!

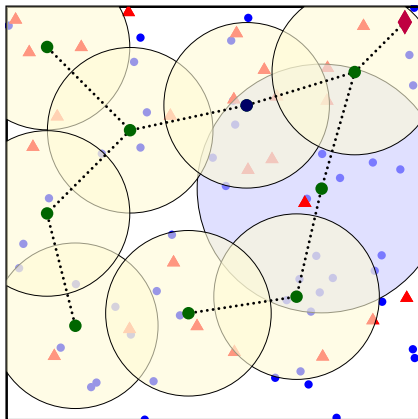


# Our current problem

## $\alpha$ -CMLP-MR

- set of targets and sensors
- base station
- activated sensors
- communication links
- $\alpha$ -coverage
- some sensors can be used for communication only!

We are now looking for  
subsets of active sensors  
and their role



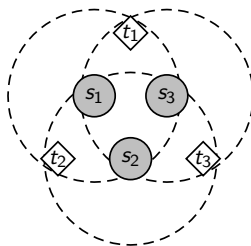


## Definition (Cover)

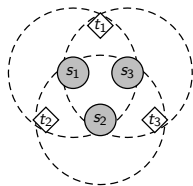
A **cover** is a subset of sensors used at the same time for covering a subset of targets

Examples:

- cover  $\{s_1\}$  covers  $t_1$  and  $t_2$
- cover  $\{s_1, s_2\}$  covers all the targets
- cover  $\{s_1, s_3\}$  also covers all the targets

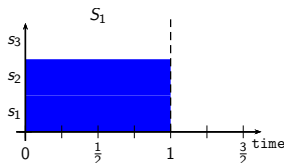
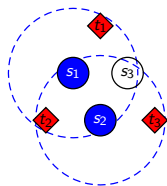


# Scheduling the covers (disjoint covers)



In that small example, we have 3 covers  
 $S_1 = \{s_1, s_2\}$ ,  $S_2 = \{s_1, s_3\}$  and  $S_3 = \{s_2, s_3\}$   
that cover all the targets

## Continuous use of covers (disjoint covers)

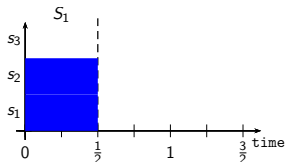
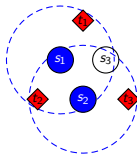


Battery depleted for  $s_1$   
and  $s_2$ , other covers  
cannot be used.

If we want to cover **all the targets** with disjoint covers, maximum network lifetime is equal to 1

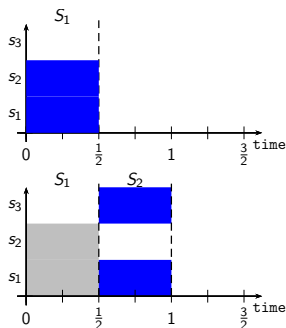
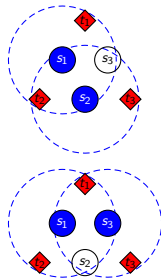
# Scheduling the covers (non-disjoint covers)

Sequentially use  $\{s_1, s_2\}$ ,  $\{s_1, s_3\}$  and  $\{s_2, s_3\}$  for 0.5 units of time each



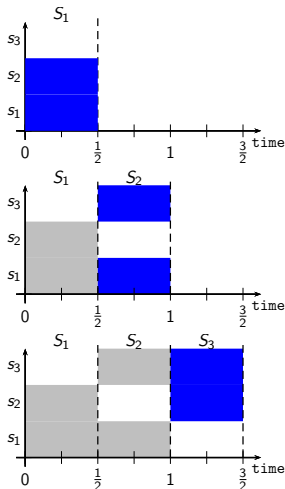
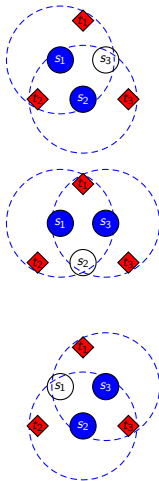
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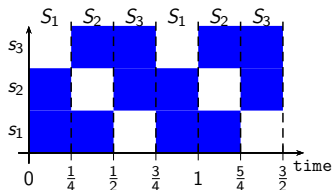
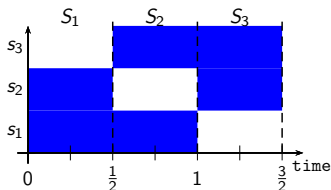
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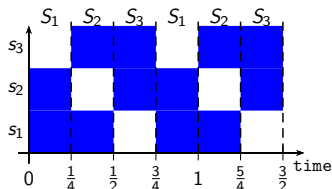
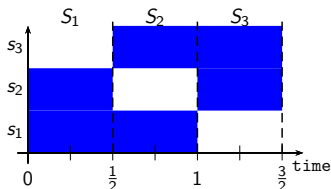
# Scheduling the covers

Different schedules can conduct to equivalent solutions



# Scheduling the covers

Different schedules can conduct to equivalent solutions



## Questions:

- How can we find these covers?
- How long are we going to use them?

# A very simple model

If we know how to build the covers,  $\alpha$ -CMLP-MR is simply formulated by:

## General LP model

$$\text{Maximize: } \sum_{j|C_j \in \Omega} t_j$$

$$\sum_{j|C_j \in \Omega} (E_{s_v}) t_j \leq \beta_{s_v} \quad \forall s_v \in S$$

$$t_j \geq 0 \quad \forall j|C_j \in \Omega$$



# A simple model, but...

## Remarks:

- Too many columns  
15 sensors  $\approx$  14 million columns



# A simple model, but...

## Remarks:

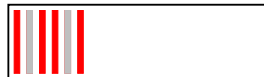
- Too many columns  
15 sensors  $\approx$  14 million columns
- Few columns are useful  
15 sensors: at most 15 columns



# A simple model, but...

## Remarks:

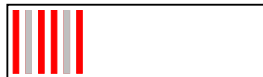
- Too many columns  
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15 sensors: at most 15 columns
- Strategy: generate them on the fly



# A simple model, but...

## Remarks:

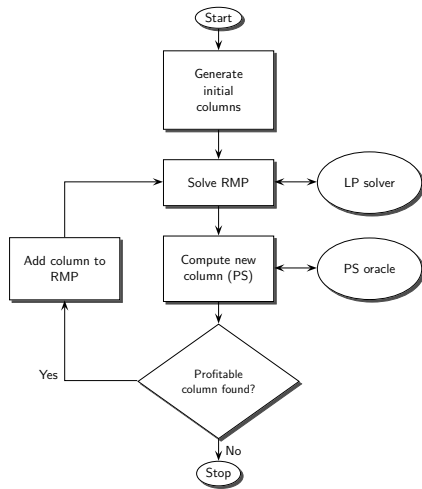
- Too many columns  
15 sensors  $\approx$  14 million columns
- Few columns are useful  
15 sensors: at most 15 columns
- Strategy: generate them on the fly



## Solution approach

Column generation is a natural approach to solve the problem

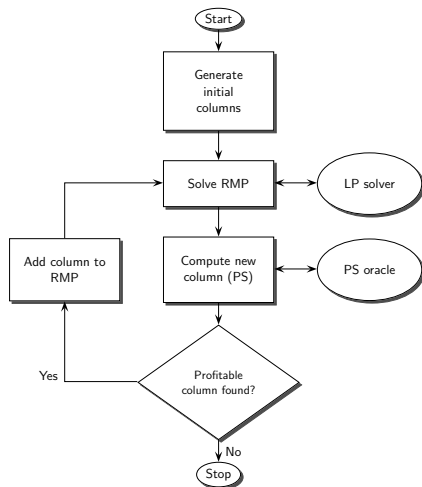
# Principle of column generation approaches (CG)



## Master Problem (RMP)

Maximizes network lifetime for the **available set of columns**

# Principle of column generation approaches (CG)



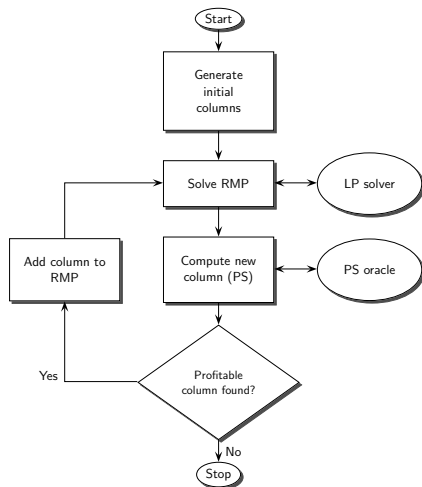
## Master Problem (RMP)

Maximizes network lifetime for the **available set of columns**

## Pricing Subproblem (PS)

Identifies **new** columns that can help to extend lifetime

# Principle of column generation approaches (CG)



## Master Problem (RMP)

Maximizes network lifetime for the **available set of columns**

## Pricing Subproblem (PS)

Identifies **new** columns that can help to extend lifetime

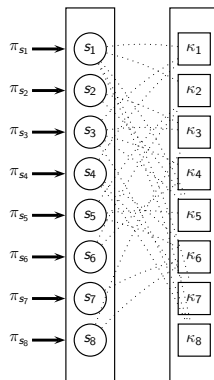
## Performance might be poor...

- PS implementation issues
- Heading-in effect
- Tail-off effect

# Solving the pricing subproblem

## Data

- $\pi_{s_i}$ : Dual variable value associated to battery constraint for sensor  $s_i$





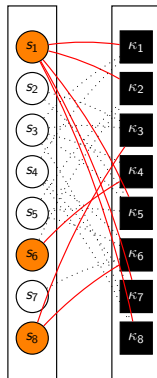
# Solving the pricing subproblem

## Decision variables

- sensor activity
  - $y_{s_i} \in \{0, 1\}$

## Objective

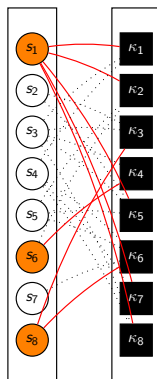
- Min:  $\sum_{s_i \in \mathcal{S}} y_{s_i} \pi_{s_i}$
- Identify a subset of sensors with interesting reduced cost



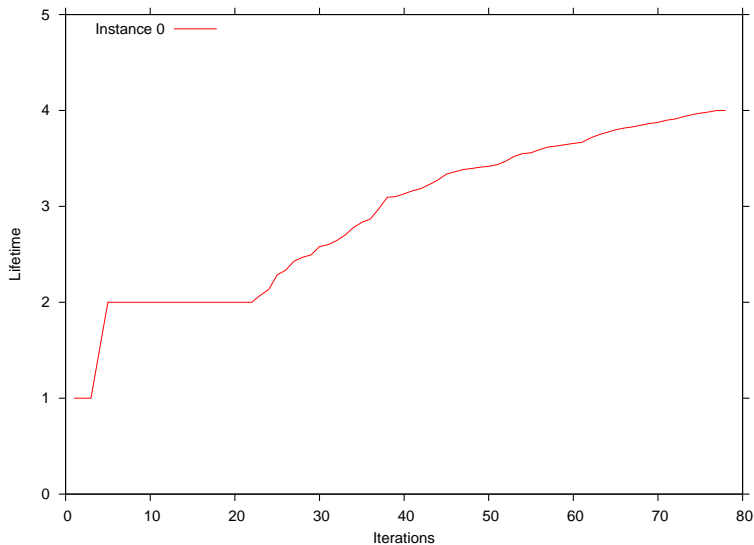
# Solving the pricing subproblem

## Remarks

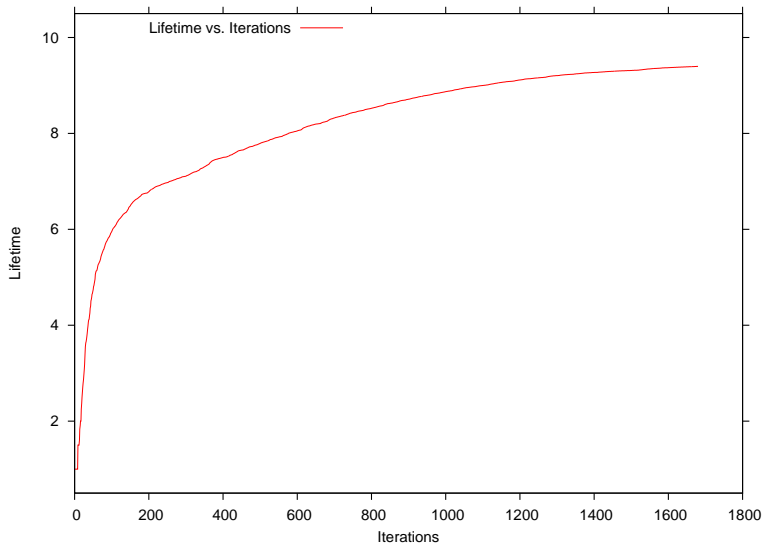
- Weighted set covering  
**NP-Hard**
- One column per iteration
- Approximations lead to premature convergence



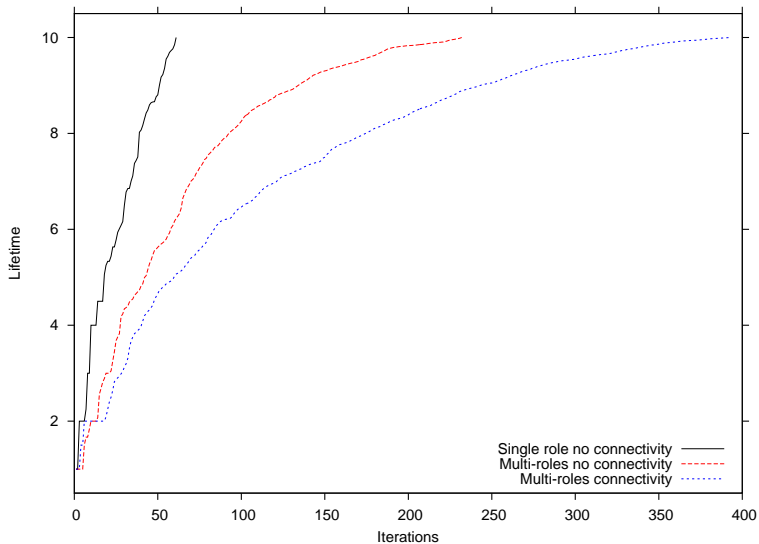
# Heading-in effect



# Tail-off effect



# Tail-off effect



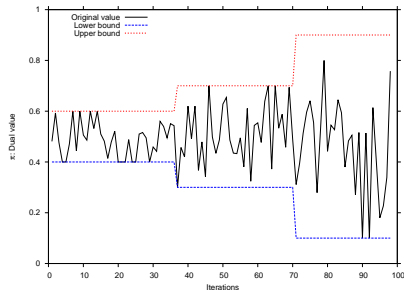
# Improvements – Stabilization

Classical stabilization strategies are explored

## Stabilized CG

Manage dual variables:

- Dual variable stabilization
- Dual variable smoothing



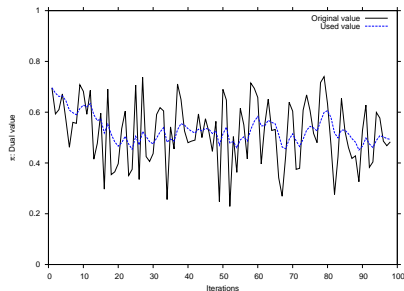
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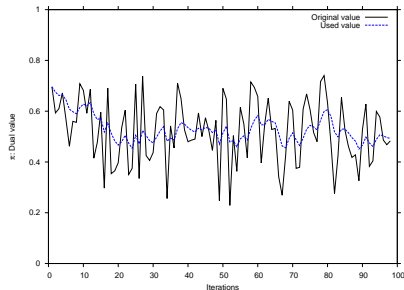
# Improvements – Stabilization

Classical stabilization strategies are explored

## Stabilized CG

Manage dual variables:

- Dual variable stabilization
- Dual variable smoothing



Nice, but not very efficient. . .



# Improvements – Intensification & diversification

Metaheuristics are used to intensify/diversify the search

## Intensification

- GRASP
- VNS



# Improvements – Intensification & diversification

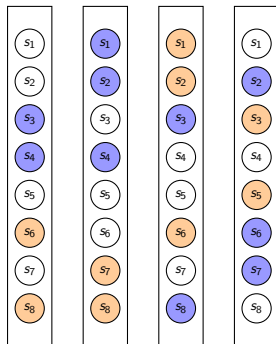
Metaheuristics are used to intensify/diversify the search

## Intensification

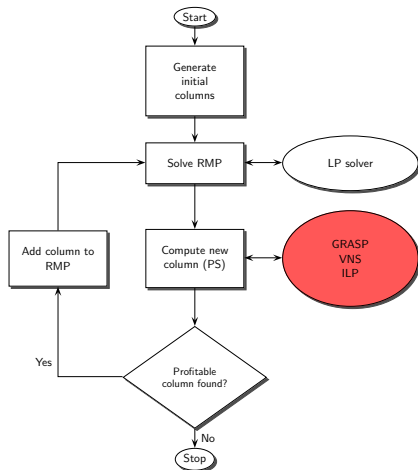
- GRASP
- VNS
- Evolutionary algorithms

## Diversification

- Return multiple profitable columns



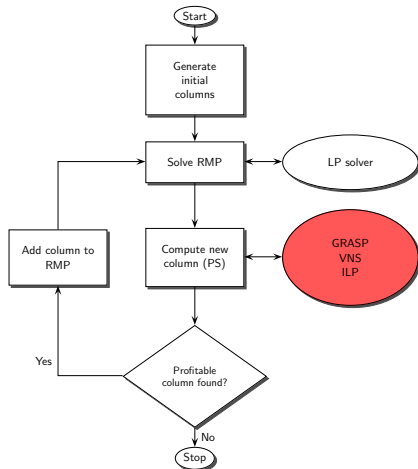
# A new matheuristic framework



## GRASP

Set covering with relaxed connectivity constraints + repair

# A new matheuristic framework



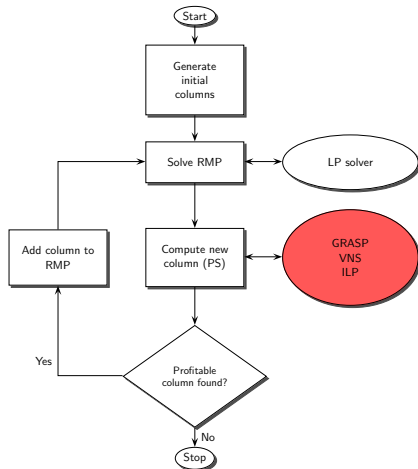
## GRASP

Set covering with relaxed connectivity constraints + repair

## VNS

Considering connectivity and coverage constraints

# A new matheuristic framework



## GRASP

Set covering with relaxed connectivity constraints + repair

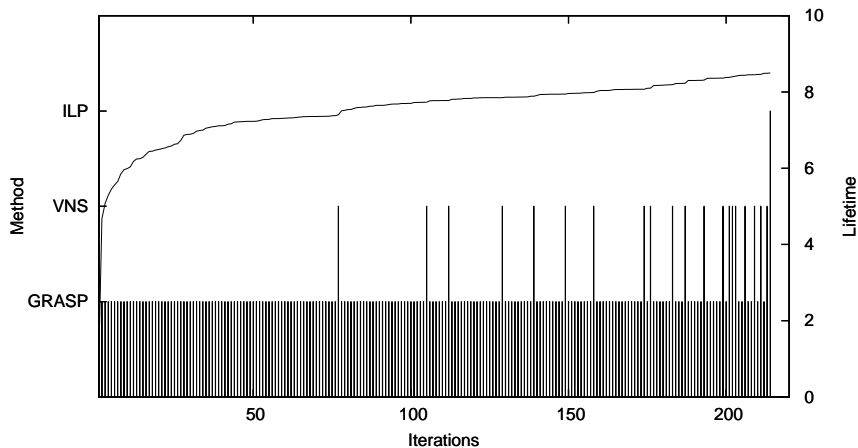
## VNS

Considering connectivity and coverage constraints

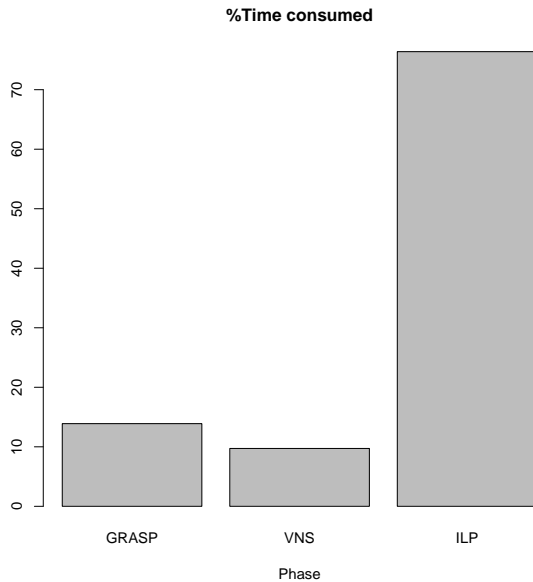
## ILP solver

Used to check optimality or discover difficult columns

# Results



# Results



## Techniques used for the pricing subproblem

- Evolutionary algorithm – find quickly several columns
- Constraint Programming – prove optimality  
use specific tree variables and propagation



# Other techniques and variants

## Techniques used for the pricing subproblem

- Evolutionary algorithm – find quickly several columns
- Constraint Programming – prove optimality use specific tree variables and propagation

## Variants of the problem

- Multiple base stations
- Irregular shapes
- Directional sensors
- Obstacles
- Area coverage



A. Rossi, A. Singh, and M. Sevaux.

Column generation algorithm for sensor coverage scheduling under bandwidth constraints.  
*Networks*, 60(3):141–154, 2012.



A. Rossi, A. Singh, and M. Sevaux.

An exact approach for maximizing the lifetime of sensor networks with adjustable sensing ranges.  
*Computers and Operations Research*, 39(12):3166–3176, 2012.



A. Rossi, A. Singh, and M. Sevaux.

Lifetime maximization in wireless directional sensor network.  
*European Journal of Operational Research*, 231(1):229–241, 2013.



A. Singh, A. Rossi, and M. Sevaux.

Matheuristic approaches for Q-coverage problem versions in wireless sensor networks.  
*Engineering Optimization*, 45(5):609–626, 2013.



F. Castaño, A. Rossi, M. Sevaux, and N. Velasco.

A column generation approach to extend lifetime in wireless sensor networks with coverage and connectivity constraints.  
*Computers and Operations Research*, 52(B):220–230, 2014.



F. Castaño, E. Bourreau, N. Velasco, A. Rossi, and M. Sevaux.

Exact approaches for lifetime maximization in connectivity constrained wireless multi-role sensor networks.  
*European Journal of Operational Research*, 241(1):28–38, 2015.



M. Sevaux, M. Vecchio, and A. Bounceur, editors.

*Special issue on Algorithms for Wireless Sensor Networks*, volume x of *Algorithms*.  
MDPI, 2015. Available online.



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## Two important references



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*Special issue on Algorithms for Wireless Sensor Networks*, volume x of *Algorithms*.  
MDPI, 2015. Available online.

- 4 Simulation and Demo
  - [www.cupcarbon.com](http://www.cupcarbon.com)
  - a simulation tool
  - open source
  - java-based platform



[www.cupcarbon.org](http://www.cupcarbon.org)

Launch the demo movie, if it works!!!

- 5 Conclusion & perspectives
  - On our work
  - Future trends

# Conclusions and perspectives

## Our matheuristic framework

- is well suited for WSN lifetime maximization
- can adapt to many variants
- is fully customisable

## And after...

- combination of all variants?
- moving targets (→ target tracking)
- moving sensors
- full integration in cup-carbon

# And now, what's next?

## UAV for professionals and for all





# And now, what's next?

## UAV for professionals and for all



# And now, what's next?

## UAV for professionals and for all

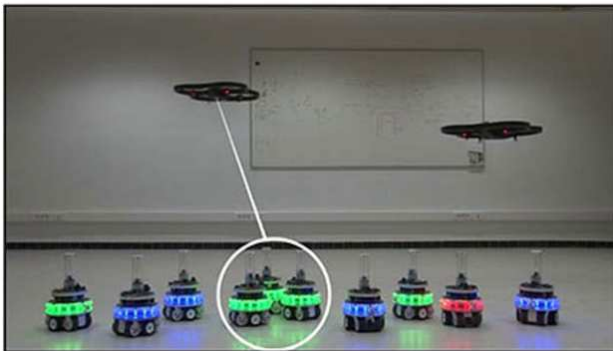


# And now, what's next?

UAV for professionals and for all



Cooperation among robots and UAV

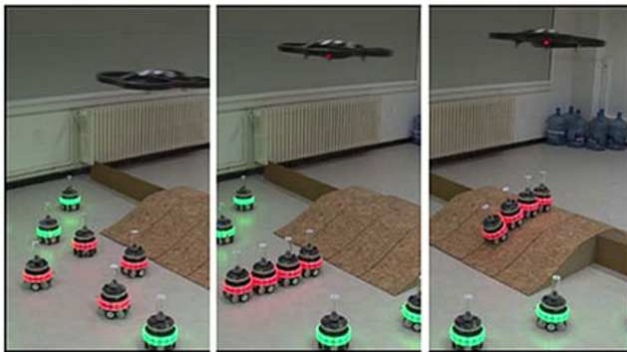


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UAV Swarms



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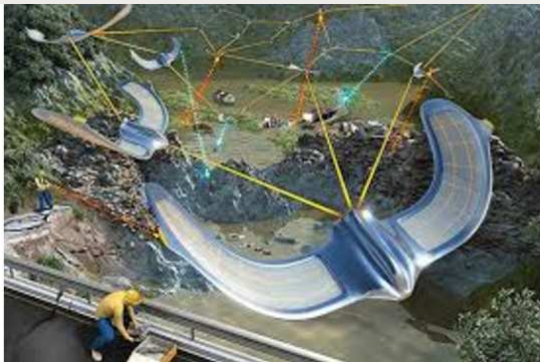
UAV for professionals and for all



Cooperation among robots and UAV



UAV Swarms



Are we aware?<sup>1</sup>



**THE GLOBAL STAGE FOR INNOVATION**

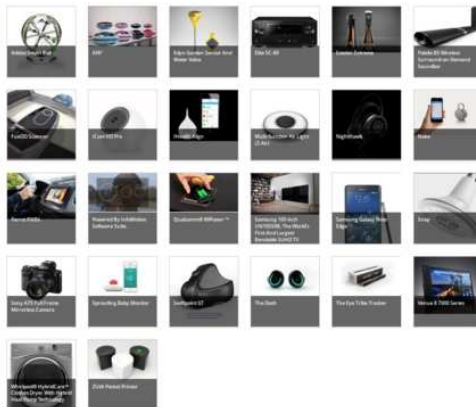
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<sup>1</sup>Quote from a famous Belgian actor!



# Are we aware?<sup>1</sup>

Among the 19 categories for innovation, 10 are related to sensors, wireless sensors or wireless sensor networks. . .



<sup>1</sup>Quote from a famous Belgian actor!

# Wireless Sensor Networks

A survey on maximizing lifetime in sensor coverage problems

Marc Sevaux

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February 5, 2015

**JE SUIS  
CHARLIE**

**IK BEN  
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