# Distributed Coverage Optimization Techniques for Improving Lifetime of Wireless Sensor Networks

## PhD Dissertation Defense


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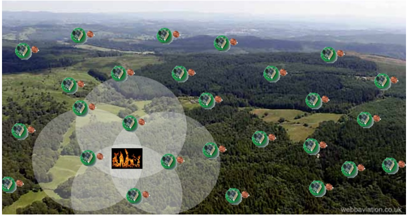
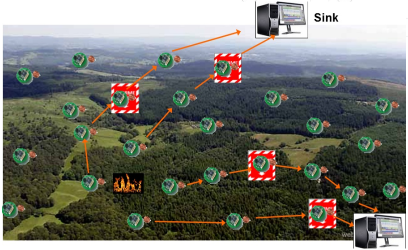
**1 October 2015**

# Problem Definition, Solution, and Objectives





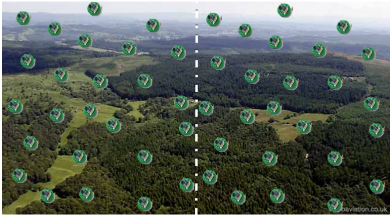

**MAIN QUESTION ?**

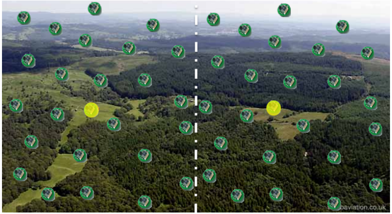
How to minimize the energy consumption and extend the network lifetime during covering a certain area ?

## OUR SOLUTION

**The area of interest is divided into subregions using a divide-and conquer method and then combine two efficient techniques :**

- **Leader Election for each subregion.**

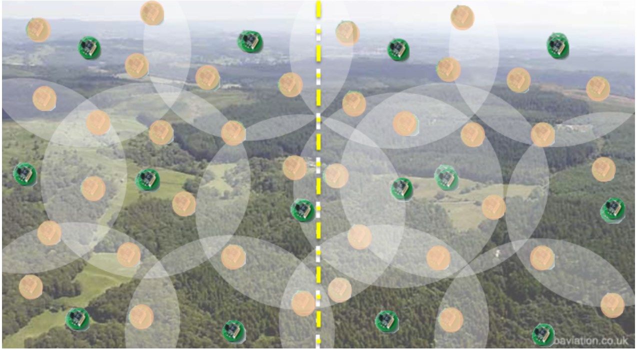




# Problem Definition, Solution, and Objectives

## OUR SOLUTION

- Activity Scheduling based optimization is planned for each subregion.



# Problem Definition, Solution, and Objectives

## Dissertation Objectives

**Develop energy-efficient distributed optimization protocols that should be able to :**

- **Schedule node activities by optimize both coverage and lifetime.**
- **Combine two efficient techniques : leader election and sensor activity scheduling.**
- **Perform a distributed optimization process.**

# Presentation Outline

1. State of the Art

2. Distributed Lifetime Coverage Optimization Protocol (DiLCO)

3. Multiround Distributed Lifetime Coverage Optimization Protocol (MuDiLCO)

4. Perimeter-based Coverage Optimization (PeCO) to Improve Lifetime in WSNs

5. Conclusion and Perspectives

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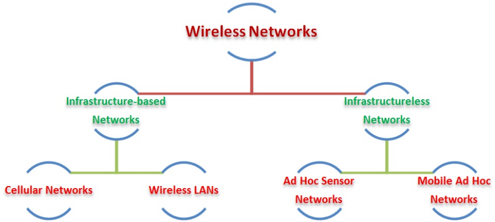
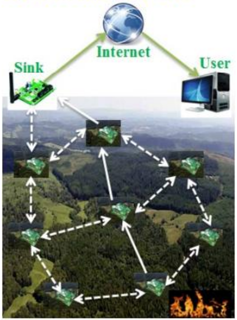
# Wireless Sensor Networks (WSNs)



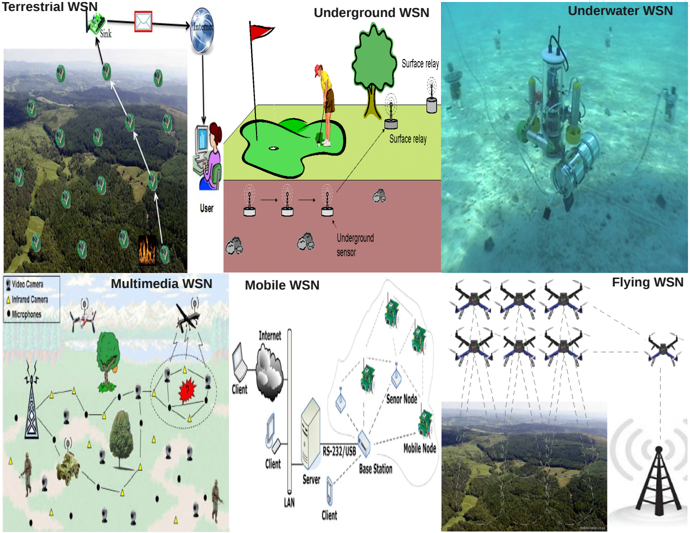

Architecture of WSNs



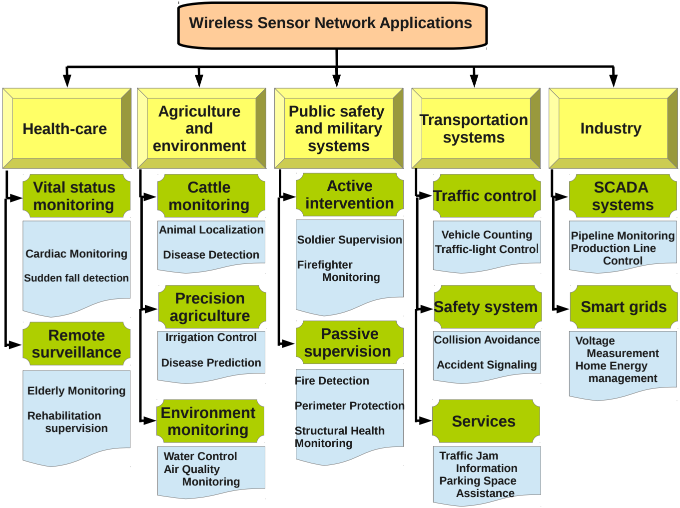

## Sensor

- Electronic Low-cost tiny device.
- Sense, process and transmit data.
- Limited energy, memory and processing capabilities.

# Types of Wireless Sensor Networks



# Applications

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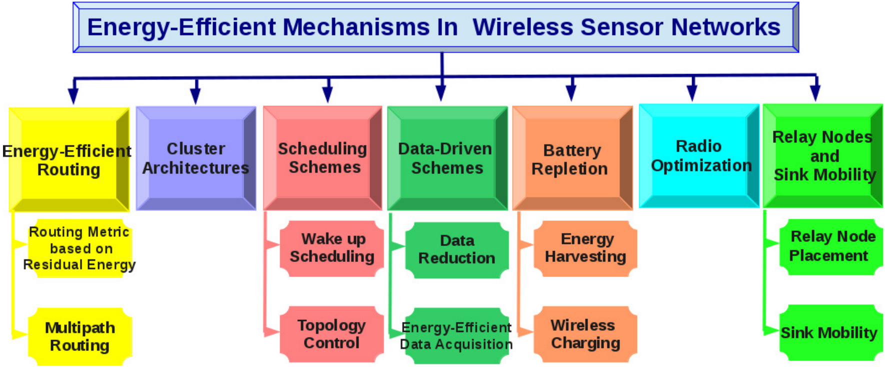
# Energy-Efficient Mechanisms of a working WSN



# Network Lifetime

## Some Network Lifetime Definitions :

i) Time spent until death of the first sensor (or cluster head).
ii) Time spent until death of all wireless sensor nodes in WSN.
iii) Time spent by WSN in covering each target by at least one sensor.
iv) Time during which the area of interest is covered by at least k nodes.
v) Elapsed time until losing the connectivity or the coverage.

## Network lifetime In this dissertation :

Time elapsed until the coverage ratio becomes less than a predetermined threshold $\alpha$.

# Coverage in Wireless Sensor Networks

**Coverage Definition :**

Coverage reflects how well a sensor field is monitored efficiently using as less energy as possible.

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## Coverage Types :

1. Area coverage : every point inside an area has to be monitored.
2. Target coverage : only a finite number of discrete points called targets have to be monitored.
3. Barrier coverage : detection of targets as they cross a barrier such as in intrusion detection and border surveillance applications.

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**Coverage type in this dissertation :**

The work presented in this dissertation deals with area coverage.

# Existing Works

## Coverage Approaches :

Most existing coverage approaches in literature classified into

A) Full centralized coverage algorithms.

- Optimal or near optimal solution.
- low computation power for the sensors (except for base station).
- Higher energy consumption for communication in large WSN.
- Not scalable for large WSNs.

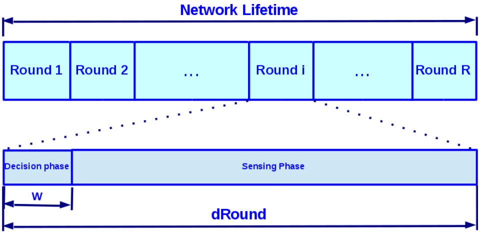
B) Full distributed coverage algorithms.

- Lower quality solution.
- less energy consumption for communication in large WSN.
- Reliable and scalable for large WSNs.

## Coverage protocols in this dissertation :

The protocols presented in this dissertation combine between the two above approaches.

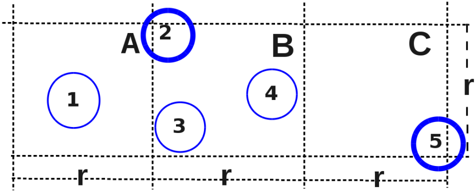
# Existing Works : DESK algorithm

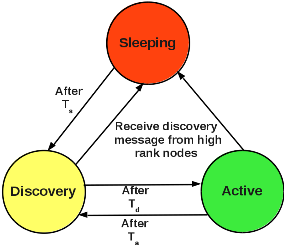



- developed by Vu et al.
- works in rounds.
- requires only one-hop neighbor information.
- each sensor decides its status (Active or Sleep) based on the perimeter coverage model.
- whole area is K-covered if and only if the perimeters of all sensors are K-covered.

**DESK is chosen for comparison because it works into rounds fashion similar to our approaches, as well as DESK is a full distributed coverage approach.**

# Existing Works : GAF algorithm




- developed by Xu et al.
- uses geographic location information to divide the area of interest into a fixed square grids.
- Within each grid, only one node staying awake to take the responsibility of sensing and communication.
- the fixed grid is square with r units on a side.
- $r \leq \frac{R_c}{\sqrt{5}}$
- Distance(2,5) $\leq$ Communication Range ($R_c$).

- enat : estimated node active time
- enlt : estimated node lifetime
- Td,Ta, Ts : discovery, active, and sleep timers
- Ta = enlt/2
- Ts = [enat/2, enat]

**GAF is chosen for comparison because it is famous and easy to implement, as well as many authors referred to it in many publications.**

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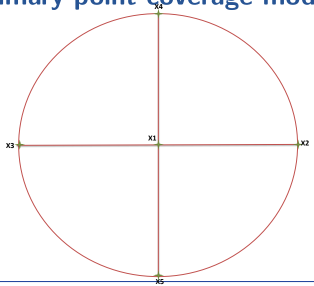
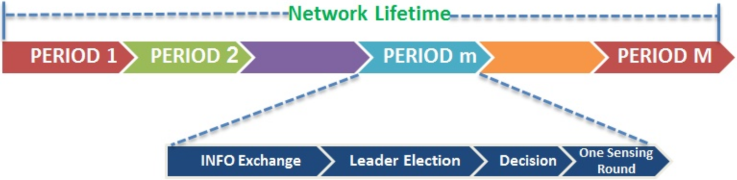
- ⋇ Static Wireless Sensors.
- ⋇ Uniform deployment.
- ⋇ High density deployment.
- ⋇ Homogeneous in terms of :
  - Sensing, Communication, and Processing capabilities
- ⋇ Heterogeneous Energy.
- ⋇ Its $R_c \geq 2R_s$.
- ⋇ Multi-hop communication.
- ⋇ Known location by :
  - Embedded GPS or
  - Location Discovery Algorithm.

- ⋇ Using two kinds of packet :
  - INFO packet.
  - ActiveSleep packet.
- ⋇ Five status for each node :
  - LISTENING, ACTIVE, SLEEP, COMPUTATION, and COMMUNICATION.

**Primary point coverage model**






1. **INFORMATION EXCHANGE :**
   Sensors exchanges through multi-hop communication, their :
   - Position coordinates,
   - current remaining energy,
   - sensor node ID, and
   - number of its one-hop live neighbors.

2. **LEADER ELECTION :**
   The selection criteria are, in order of importance :
   - larger number of neighbors,
   - larger remaining energy, and then in case of equality,
   - larger ID.
3. **DECISION :**
   Leader solves an integer program (see next slide) to :
   - Select which sensors will be activated in the sensing phase.
   - Send Active-Sleep packet to each sensor in the subregion.
4. **SENSING :**
   Based on Active-Sleep Packet Information :
   - Active sensors will execute their sensing task.
   - Sleep sensors will wait a time equal to the period of sensing to wakeup.

$$\left\{\begin{array}{ll} \min \sum_{p \in P} (w_{\theta}\Theta_p + w_U U_p) & \\ \text{subject to :} & \\ \sum_{j \in J} \alpha_{jp} X_j - \Theta_p + U_p = 1, & \forall p \in P \\ \Theta_p \in \mathbb{N}, & \forall p \in P \\ U_p \in \{0,1\}, & \forall p \in P \\ X_j \in \{0,1\}, & \forall j \in J \end{array}\right.$$

- $P$ : the set of primary points.
- $J$ : the set of sensors.
- $X_j$ : indicates whether or not the sensor $j$ is actively sensing (1 if yes and 0 if not).
- $\Theta_p$ : *overcoverage*, the number of sensors minus one that are covering the primary point $p$.
- $U_p$ : *undercoverage*, indicates whether or not the primary point $p$ is being covered (1 if not covered and 0 if covered).
- $\alpha_{jp}$ : denotes the indicator function of whether the primary point p is covered.

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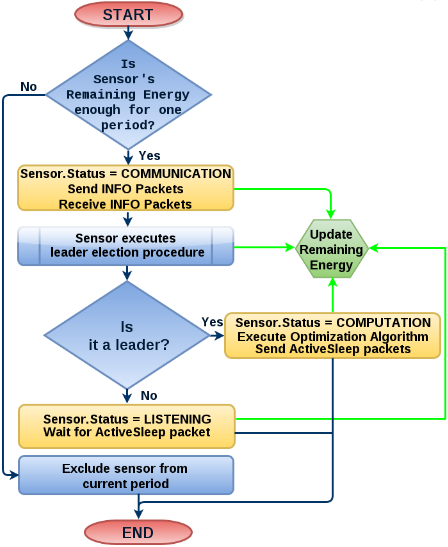
START
Is Sensor's Remaining Energy enough for one period?
No
Yes
Sensor.Status = COMMUNICATION
Send INFO Packets
Receive INFO Packets
Sensor executes leader election procedure
Update Remaining Energy
Is it a leader?
Yes
Sensor.Status = COMPUTATION
Execute Optimization Algorithm
Send ActiveSleep packets
No
Sensor.Status = LISTENING
Wait for ActiveSleep packet
Exclude sensor from current period
END

TABLE: Relevant parameters for simulation.

| Parameter | Value |
| --- | --- |
| Sensing Field | $(50 \times 25)\ m^2$ |
| Nodes Number | 50, 100, 150, 200 and 250 nodes |
| Initial Energy | 500-700 joules |
| Sensing Period | 60 Minutes |
| $E_{th}$ | 36 Joules |
| $R_s$ | 5 m |
| $R_c$ | 10 m |
| $w_{\Theta}$ | 1 |
| $w_U$ | $\|P\|^2$ |
| Modeling Language | A Mathematical Programming Language (AMPL) |
| Optimization Solver | GNU linear Programming Kit (GLPK) |
| Network Simulator | Discrete Event Simulator OMNeT++ |

## Energy Consumption Model

| **Sensor status** | MCU | Radio | Sensing | *Power (mW)* |
|---|---|---|---|---|
| LISTENING | On | On | On | 20.05 |
| ACTIVE | On | Off | On | 9.72 |
| SLEEP | Off | Off | Off | 0.02 |
| COMPUTATION | On | On | On | 26.83 |
| Energy needed to send or receive a 2-bit content message | | | | 0.515 |

## Performance Metrics

- ↦ **Coverage Ratio (CR)**
- ↦ **Number of Active Sensors Ratio (ASR)**
- ↦ **Energy Consumption**
- ↦ **Network Lifetime**

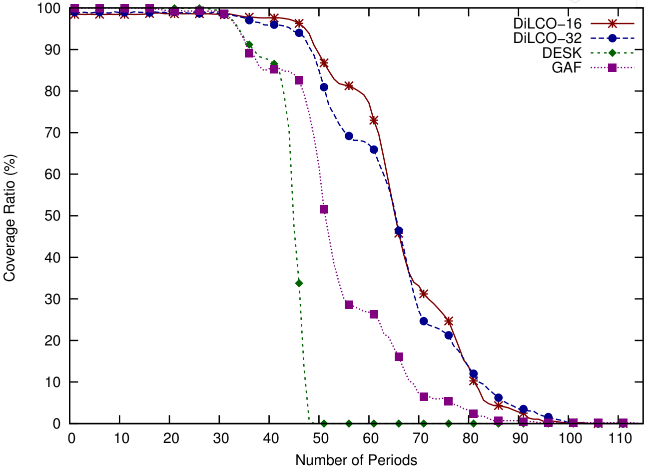


FIGURE: Coverage ratio for 150 deployed nodes

# DiLCO Protocol ▶ Performance Comparison

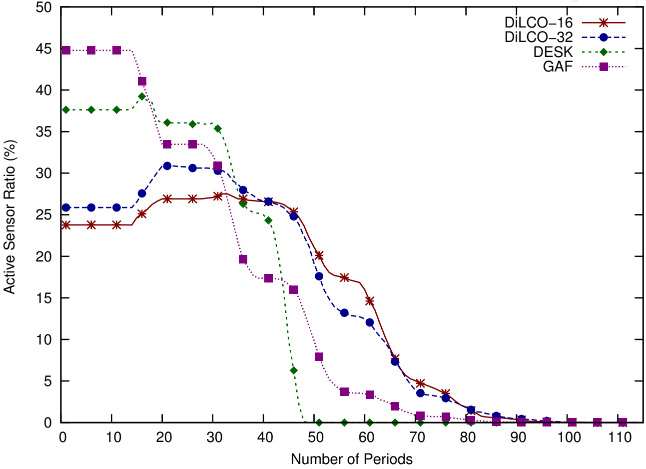


FIGURE: Active sensors ratio for 150 deployed nodes

# DiLCO Protocol ▶ Performance Comparison

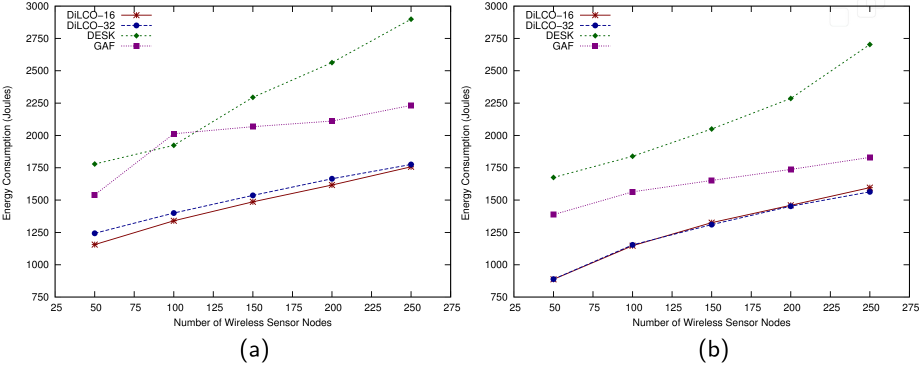


FIGURE: Energy consumption for (a) *Lifetime*$_{95}$ and (b) *Lifetime*$_{50}$

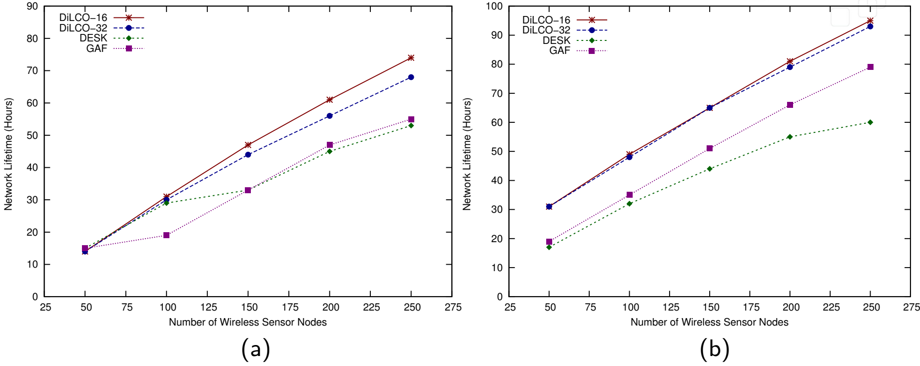


FIGURE: Network lifetime for (a) $\textit{Lifetime}_{95}$ and (b) $\textit{Lifetime}_{50}$

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# MuDiLCO Protocol ▶ Main Idea

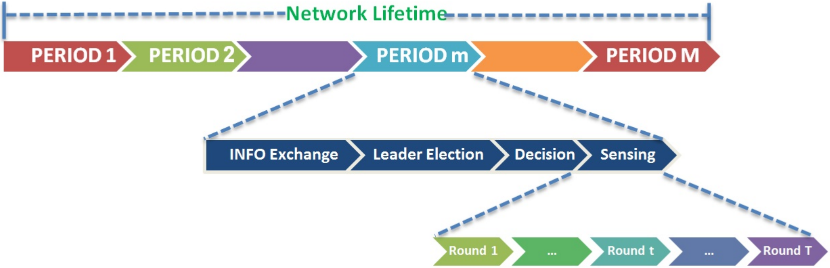



FIGURE: MuDiLCO protocol.

$$\min \sum_{t=1}^{T} \sum_{p=1}^{P} (W_{\theta} * \Theta_{t,p} + W_{U} * U_{t,p})$$

Number of rounds ($T$) — Number of primary points ($P$) — Nonnegative weights ($W_{\theta}$, $W_{U}$)

Subject to

$$\sum_{j=1}^{|J|} \alpha_{j,p} * X_{t,j} = \Theta_{t,p} - U_{t,p} + 1 \qquad \forall p \in P, t = 1, \ldots, T$$

Coverage Constraint

$$\sum_{t=1}^{T} X_{t,j} \leq \lfloor RE_j / E_{th} \rfloor \qquad \forall j \in J, t = 1, \ldots, T$$

Energy Constraint

Remaining energy of sensor **j**. ($RE_j$)

Amount of energy required to be alive during one round. ($E_{th}$)

$$X_{t,j} \in \{0,1\}, \qquad \forall j \in J, t = 1, \ldots, T$$

determine the activation of sensor **j** in the sensing round **t**.

$$U_{t,p} \in \{0,1\}, \qquad \forall p \in P, t = 1, \ldots, T$$

Undercoverage variable of the primary point **p** during round **t**.

$$\Theta_{t,p} \geq 0 \qquad \forall p \in P, t = 1, \ldots, T$$

Overcoverage variable of the primary point **p** during round **t**.

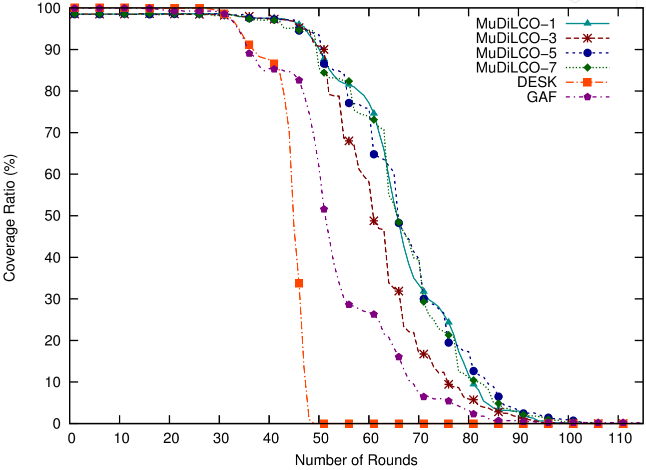



FIGURE: Average coverage ratio for 150 deployed nodes

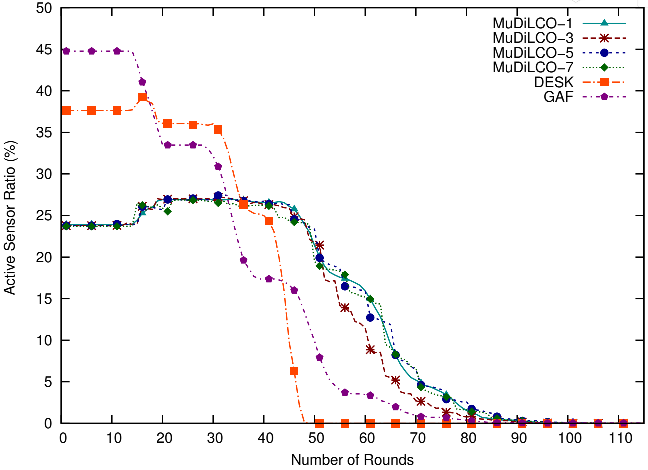
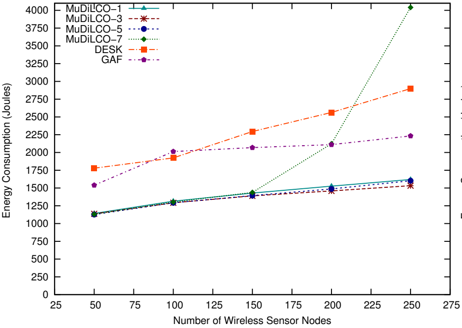
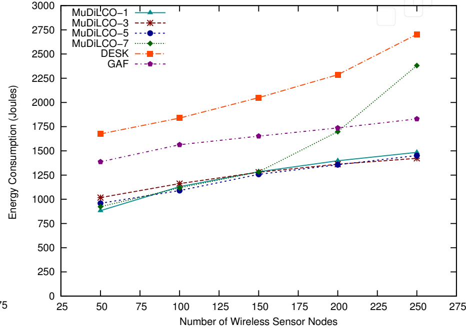



Figure: Active sensors ratio for 150 deployed nodes




(a)




(b)

FIGURE: Energy consumption for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

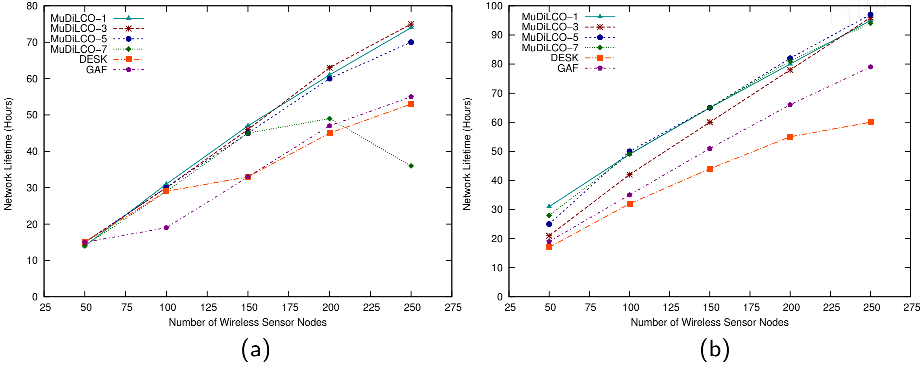



FIGURE: Network lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

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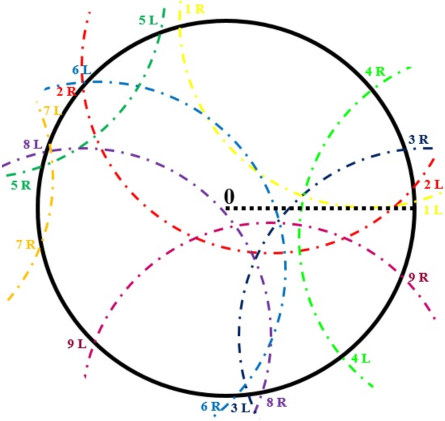
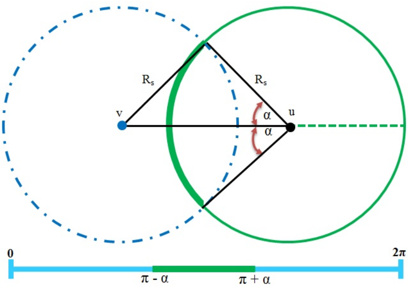
$$\alpha = \arccos\left(\frac{Dist(u,v)}{2R_s}\right).$$

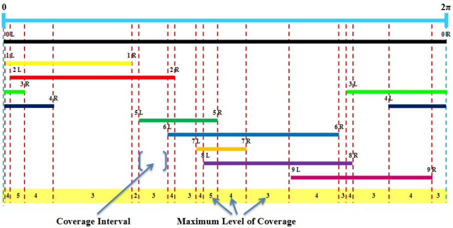



(a)




(b)

FIGURE: (a) Perimeter coverage of sensor node 0 and (b) finding the arc of $u$'s perimeter covered by $v$.




(a)

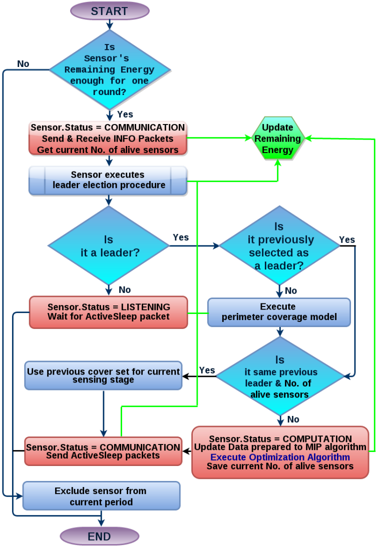
Table 6.1: Coverage intervals and contributing sensors for sensor node 0

| Left point angle $\alpha$ | Interval left point | Interval right point | Maximum coverage level | Set of sensors involved in coverage interval | | | | |
|---|---|---|---|---|---|---|---|---|
| 0.0291 | 1L | 2L | 4 | 0 | 1 | 3 | 4 | |
| 0.104 | 2L | 3R | 5 | 0 | 1 | 3 | 4 | 2 |
| 0.3168 | 3R | 4R | 4 | 0 | 1 | 4 | 2 | |
| 0.6752 | 4R | 1R | 3 | 0 | 1 | 2 | | |
| 1.8127 | 1R | 5L | 2 | 0 | 2 | | | |
| 1.9228 | 5L | 6L | 3 | 0 | 2 | 5 | | |
| 2.3959 | 6L | 2R | 4 | 0 | 2 | 5 | 6 | |
| 2.4258 | 2R | 7L | 3 | 0 | 5 | 6 | | |
| 2.7868 | 7L | 8L | 4 | 0 | 5 | 6 | 7 | |
| 2.8358 | 8L | 5R | 5 | 0 | 5 | 6 | 7 | 8 |
| 2.9184 | 5R | 7R | 4 | 0 | 6 | 7 | 8 | |
| 3.3301 | 7R | 9R | 3 | 0 | 6 | 8 | | |
| 3.9464 | 9R | 6R | 4 | 0 | 6 | 8 | 9 | |
| 4.767 | 6R | 3L | 3 | 0 | 8 | 9 | | |
| 4.8425 | 3L | 8R | 4 | 0 | 3 | 8 | 9 | |
| 4.9072 | 8R | 4L | 3 | 0 | 3 | 9 | | |
| 5.3804 | 4L | 9R | 4 | 0 | 3 | 4 | 9 | |
| 5.9157 | 9R | 1L | 3 | 0 | 3 | 4 | | |

(b)

FIGURE: (a) Maximum coverage levels for perimeter of sensor node 0. and (b) Coverage intervals and contributing sensors for sensor node 0.

# PeCO Protocol ▶ PeCO Protocol Algorithm



$$\text{Minimize} \sum_{j \in S} \sum_{i \in I_j} (\alpha_i^j M_i^j + \beta_i^j V_i^j)$$

Subject to:

$$\sum_{k \in A} (a_{ik}^j X_k) + M_i^j \geq l \quad \forall i \in I_j, \forall j \in S$$

$$\sum_{k \in A} (a_{ik}^j X_k) - V_i^j \leq l \quad \forall i \in I_j, \forall j \in S$$

$$X_k \in \{0, 1\}, \forall k \in A$$

$$M_i^j, V_i^j \in \mathbb{R}^+$$

Number of active sensors in the coverage interval i for sensor j.

measure of undercoverage.

Desired level of coverage.

measure of overcoverage.

determine the activation of sensor k in the sensing phase.

$S$ represents the set of sensor nodes.

$A \subseteq S$ is the subset of alive sensors.

$I_j$ designates the set of coverage intervals (CI) obtained for sensor j.

$a_{ik}^j$ is indicator function of whether sensor k is involved in coverage interval i of sensor j.

$\alpha_i^j$ and $\beta_i^j$ are nonnegative weights.

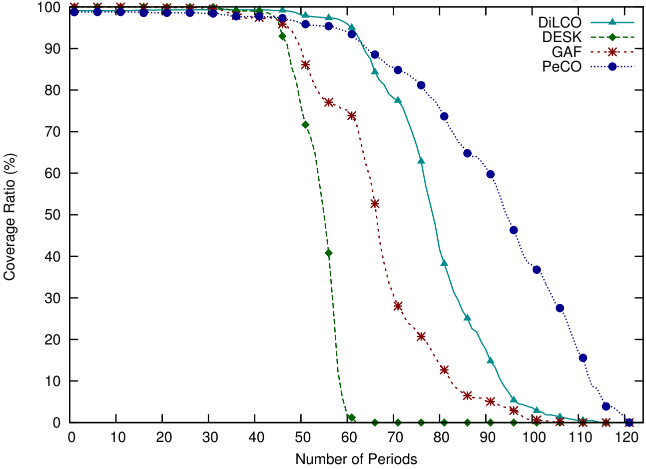



FIGURE: Coverage ratio for 200 deployed nodes.

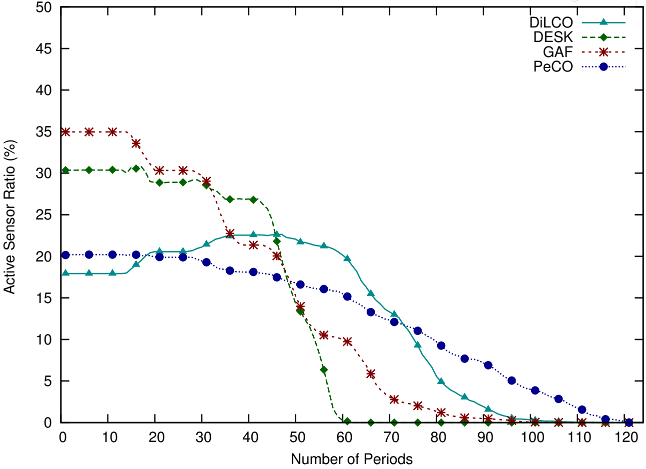



FIGURE: Active sensors ratio for 200 deployed nodes.

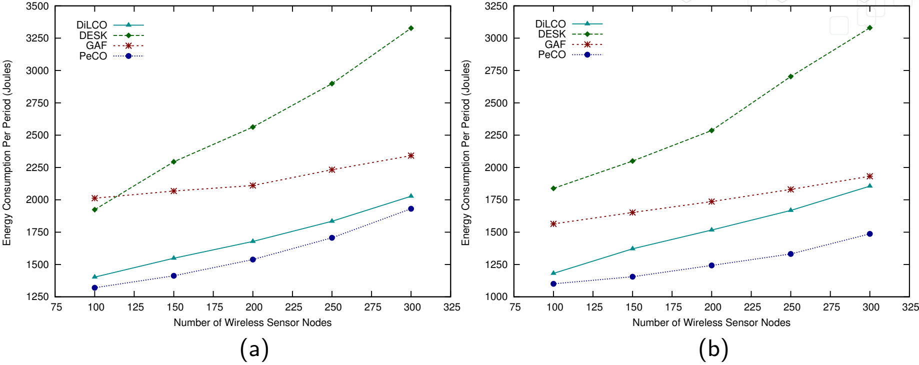



FIGURE: Energy consumption per period for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$.

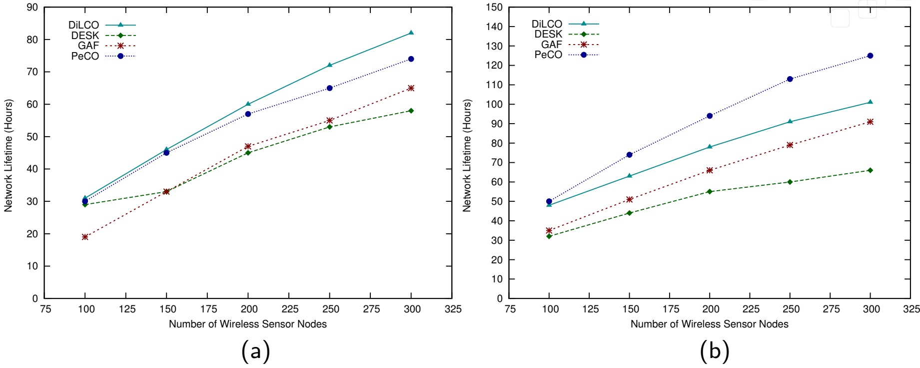



FIGURE: Network Lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$.

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3. Multiround Distributed Lifetime Coverage Optimization Protocol (MuDiLCO)

4. Perimeter-based Coverage Optimization (PeCO) to Improve Lifetime in WSNs

5. Conclusion and Perspectives

# Conclusion

- Two-step approaches are proposed to optimize both coverage and lifetime performances, where :
  - Sensing field is divided into smaller subregions using divide-and-conquer method.
  - One of the proposed optimization protocols is applied in each subregion in a distributed parallel way.
- The proposed protocols (DiLCO, MuDiLCO, PeCO) combine two efficient mechanisms :
  - Network leader election, and
  - Sensor activity scheduling based optimization.
- Our protocols are periodic where each period consists of 4 phases :
  - Information exchange,
  - Network leader election,
  - Decision based optimization,
  - Sensing.

# Conclusion

- DiLCO and PeCO provide a schedule for one round per period.
- MuDiLCO provides a schedule for multiple rounds per period.
- Comparison results show that DiLCO, MuDiLCO, and PeCO protocols :
  - maintain the coverage for a larger number of rounds.
  - use less active nodes to save energy efficiently during sensing.
  - are more powerful against network disconnections.
  - perform the optimization with suitable execution times.
  - consume less energy.
  - prolong the network lifetime.

# Conclusion

## Journal Articles

[1] Ali Kadhum Idrees, Karine Deschinkel, Michel Salomon, and Raphaël Couturier. Perimeter-based Coverage Optimization to Improve Lifetime in Wireless Sensor Networks. *Engineering Optimization, 2015, (Submitted)*.

[2] Ali Kadhum Idrees, Karine Deschinkel, Michel Salomon, and Raphaël Couturier. Multiround Distributed Lifetime Coverage Optimization Protocol in Wireless Sensor Networks. *Ad Hoc Networks, 2015, (Submitted)*.

[3] Ali Kadhum Idrees, Karine Deschinkel, Michel Salomon, and Raphaël Couturier. Distributed Lifetime Coverage Optimization Protocol in Wireless Sensor Networks. *Journal of Supercomputing , 2015, (Submitted)*.

## Technical Reports

[1] Ali Kadhum Idrees, Karine Deschinkel, Michel Salomon, and Raphaël Distributed lifetime coverage optimization protocol in wireless sensor networks. Technical Report DISC2014-X, University of Franche-Comte - FEMTO-ST Institute, DISC Research Department, Octobre 2014.

## Conference Articles

[1] Ali Kadhum Idrees, Karine Deschinkel, Michel Salomon, and Raphaël Coverage and lifetime optimization in heterogeneous energy wireless sensor networks. In ICN 2014, The Thirteenth International Conference on Networks, pages 49–54, 2014.

# Perspectives

- Investigate the optimal number of subregions.
- Design a heterogeneous integrated optimization protocol to integrate coverage, routing, and data aggregation protocols.
- Extend PeCO protocol so that the schedules are planned for multiple sensing periods.
- Consider particle swarm optimization or evolutionary algorithms to obtain quickly near optimal solutions.
- Improve our mathematical models to take into account heterogeneous sensors from both energy and node characteristics point of views.

# Fin

Thank You for Your Attention !

Questions ?