Distributed Coverage Optimization Techniques for Improving Lifetime of Wireless Sensor Networks

PhD Dissertation Defense

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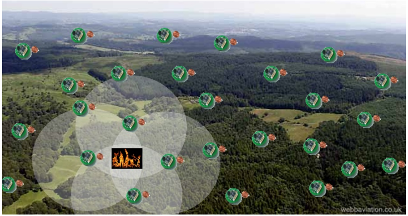
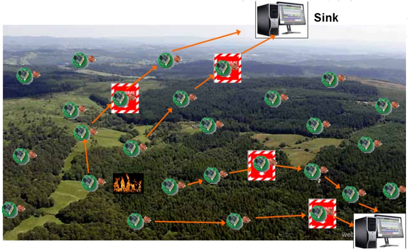
Problem Definition, Solution, and Objectives





MAIN QUESTION ?

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

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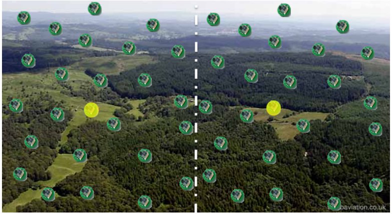
Problem Definition, Solution, and Objectives

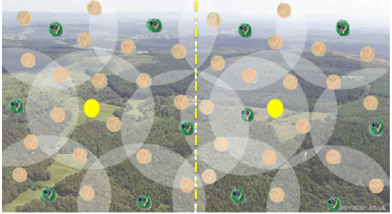
OUR SOLUTION : distributed optimization process

Division into subregions

For each subregion :

- **Leader election**
- **Activity Scheduling based optimization**

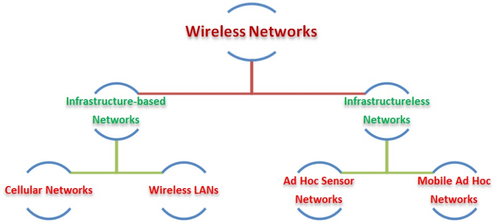




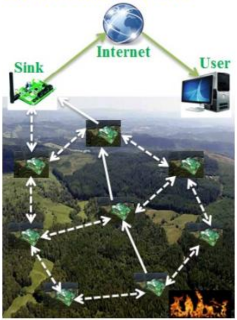
Presentation Outline

Presentation Outline

Wireless Sensor Networks (WSNs)



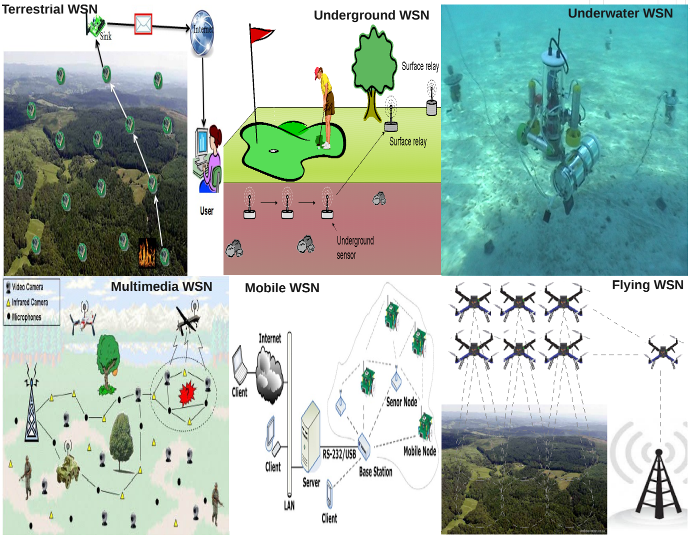
Architecture of WSNs



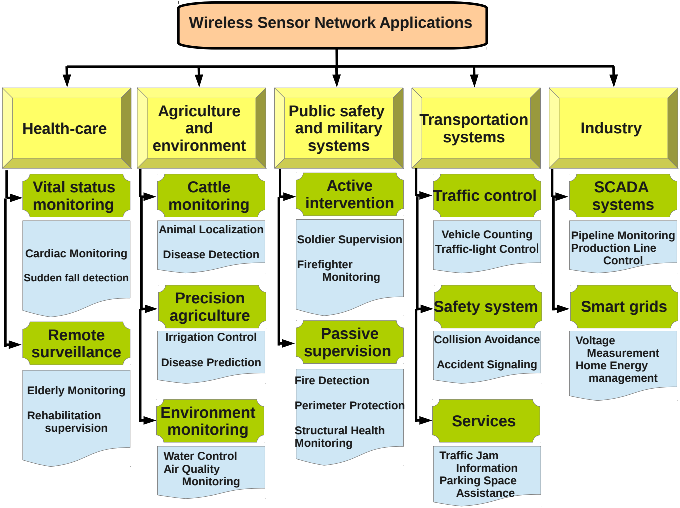
Sensor

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

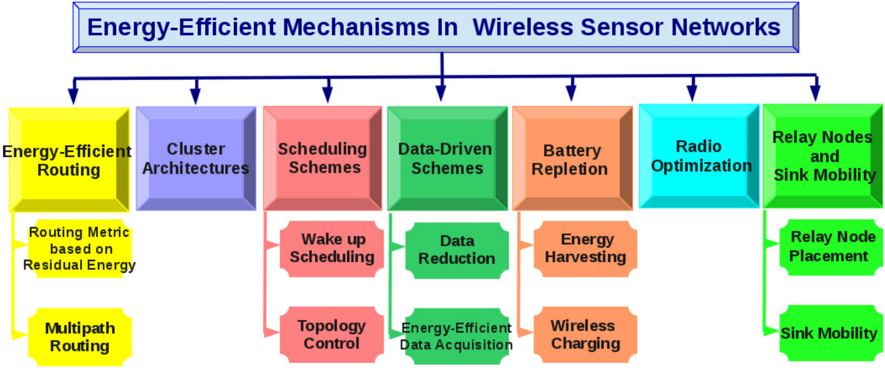
Types of Wireless Sensor Networks



Applications



Energy-Efficient Mechanisms of a working WSN



Our approach : includes cluster architecture and scheduling schemes

Network lifetime

Some 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.

vi) **Time elapsed until the coverage ratio becomes less than a predetermined threshold α.**

Coverage in Wireless Sensor Networks

Coverage definition :

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

Coverage in Wireless Sensor Networks

Coverage definition :

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

Coverage types :

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

Existing works

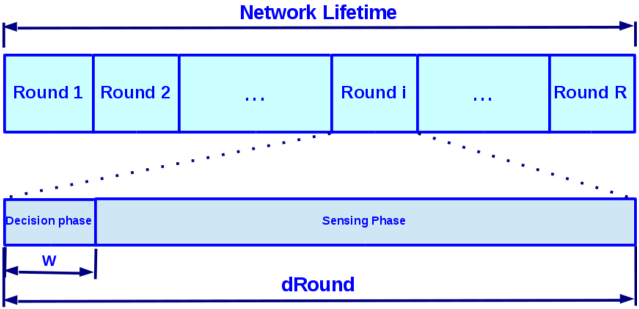
Coverage approaches :

i) 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

ii) Full distributed coverage algorithms
   - Lower quality solution
   - Less energy consumption for communication in large WSN
   - Reliable and scalable for large WSNs

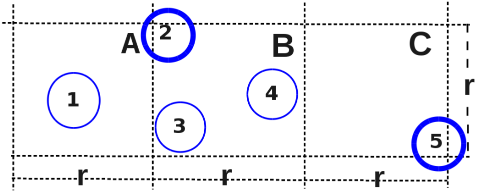
iii) Hybrid approaches
   - Globally distributed and locally centralized

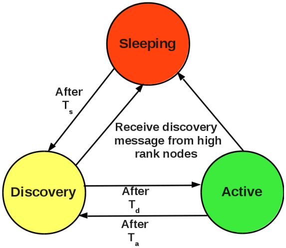
Existing works : DESK algorithm (Vu et al.)



- Requires only one-hop neighbor information (fully distributed)
- Each sensor decides its status (Active or Sleep) based on the perimeter coverage model without optimization

Existing works : GAF algorithm (Xu et al.)





- Distributed energy-based scheduling approach
- Uses geographic location information to divide the area into a fixed square grids
- Nodes are in one of three sates : discovery, active, or sleep
- Only one node staying active in grid
- The fixed grid is square with r units on a side
- Nodes cooperate within each grid to choose the active node

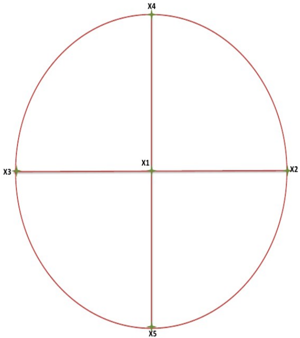
Presentation Outline

Assumptions for our protocols

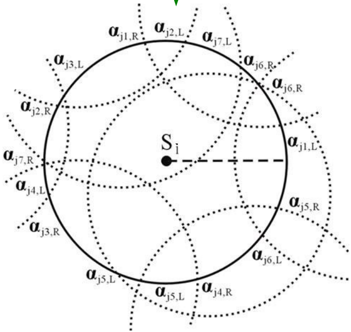
- Static wireless sensor, homogeneous in terms of :
  - Sensing, communication, and processing capabilities
- Heterogeneous initial energy
- High density uniform deployment
- Its $R_c \geq 2R_s$ for imply connectivity among active nodes during complete coverage (hypothesis proved by Zhang and Zhou)
- Multi-hop communication
- Known location by :
  - Embedded GPS or location discovery algorithm
- Using two kinds of packets :
  - INFO packet
  - ActiveSleep packet
- Five status for each node :
  - LISTENING, ACTIVE, SLEEP, COMPUTATION, and COMMUNICATION

Assumptions for our protocols

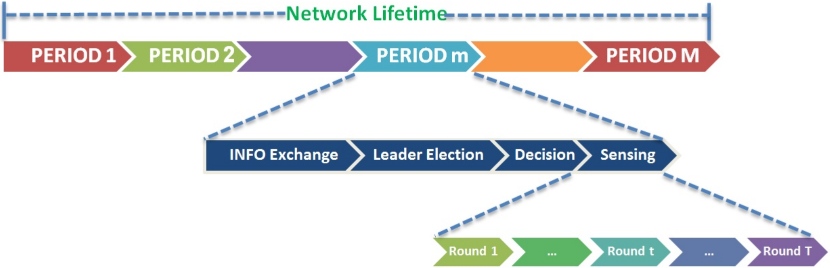
DiLCO and MuDiLCO are based on primary points model



PeCO is based on perimeter coverage model



Our general scheme



- DiLCO and PeCO ▶ use one round sensing ($T = 1$)
- MuDiLCO ▶ uses multiple rounds sensing ($T = 1 \cdots T$)

Our general scheme

i) **INFORMATION EXCHANGE** ▶ Sensors exchange through multi-hop communication, their
   - Position coordinates, current remaining energy, sensor node ID, and number of its one-hop live neighbors

ii) **LEADER ELECTION** ▶ The selection criteria are, in order
   - Larger number of neighbors
   - Larger remaining energy, and then in case of equality
   - Larger ID

iii) **DECISION** ▶ Leader solves an integer program to
   - Select which sensors will be activated in the sensing phase
   - Send Active-Sleep packet to each sensor in the subregion

iv) **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

Presentation Outline

Nonnegative weights

Coverage Constraint

Set of primary points

$$\min \sum_{p \in P} (w_{\theta}\Theta_p + w_U U_p)$$

subject to :

$$\sum_{j \in J} \alpha_{jp} X_j - \Theta_p + U_p = 1, \quad \forall p \in P$$

$$\Theta_p \in \mathbb{N}, \quad \forall p \in P$$

$$U_p \in \{0, 1\}, \quad \forall p \in P$$

$$X_j \in \{0, 1\}, \quad \forall j \in J$$

Overcoverage variable of the primary point p

Indicator function of whether the primary point p is covered by sensor j

Undercoverage variable of the primary point p

Determine the activation of sensor j during sensing round

Set of sensors

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DiLCO Protocol ▶ DiLCO Protocol Algorithm

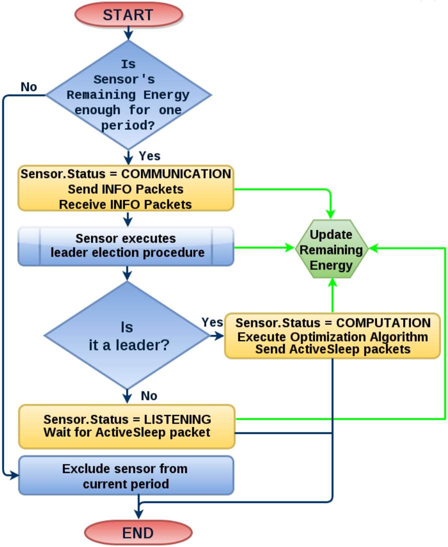


TABLE: Relevant parameters for simulation.

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_{Θ}	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**

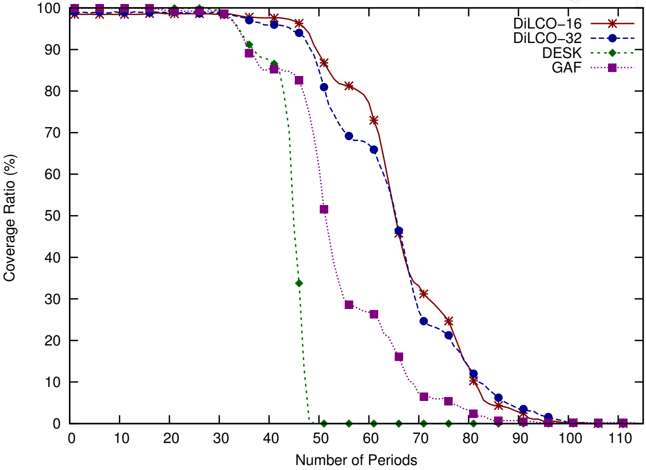


FIGURE: Coverage ratio for 150 deployed nodes

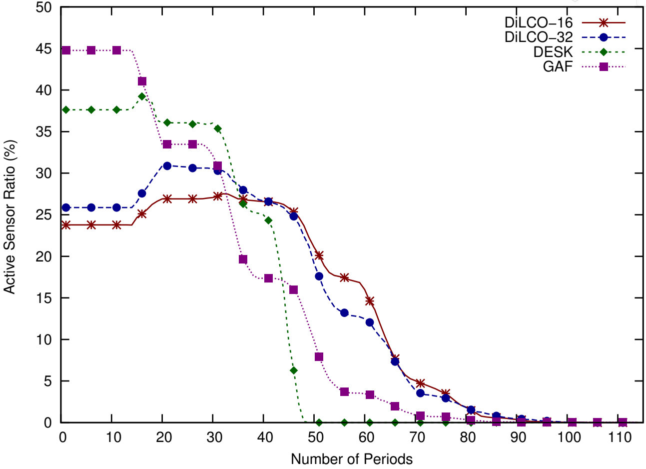


FIGURE: Active sensors ratio for 150 deployed nodes

DiLCO Protocol ▶ Performance Comparison

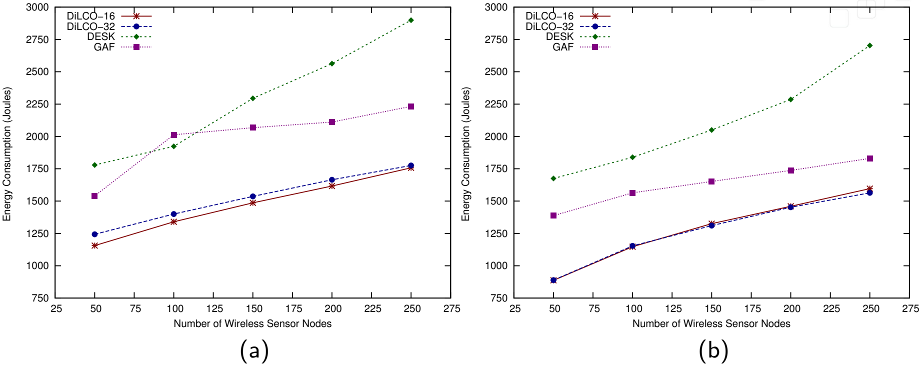


FIGURE: Energy consumption for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

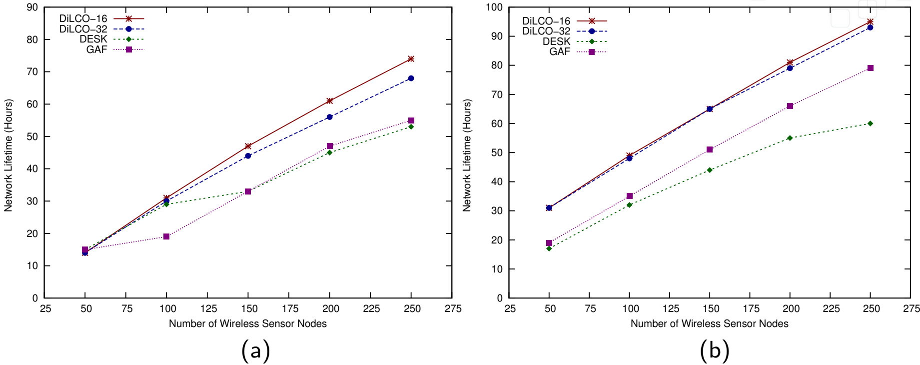


FIGURE: Network lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

Presentation Outline

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

Nonnegative weights

subject to :

Coverage Constraint — Set of sensors — Number of primary points

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

Energy Constraint — Remaining energy of sensor j

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

Amount of energy required to be alive during one round.

Determine the activation of sensor j in the sensing round t

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

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

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

Number of rounds

Undercoverage variable of the primary point p during round t

Overcoverage variable of the primary point p during round t

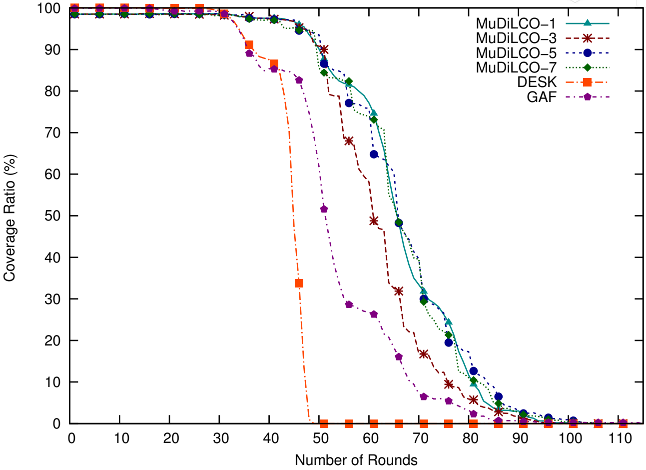


FIGURE: Average coverage ratio for 150 deployed nodes

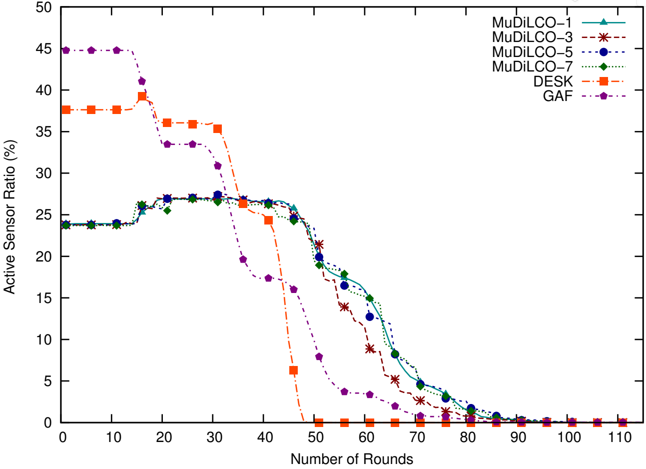


FIGURE: Active sensors ratio for 150 deployed nodes

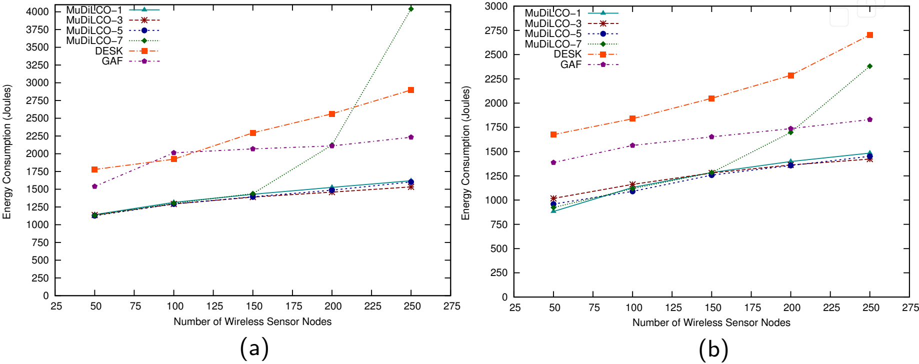


FIGURE: Energy consumption for (a) *Lifetime*$_{95}$ and (b) *Lifetime*$_{50}$

MuDiLCO Protocol ▶ Results Analysis and Comparison

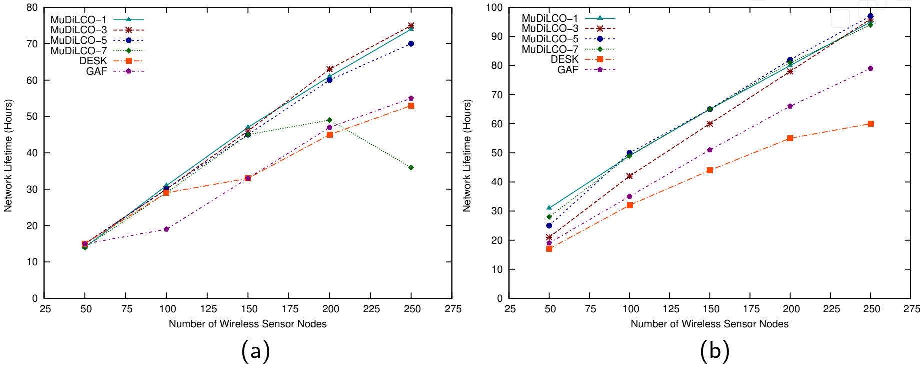
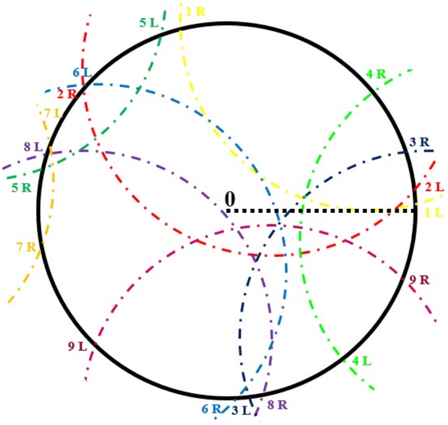


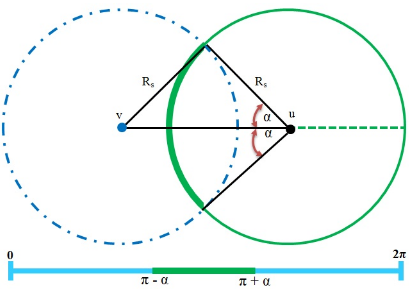
FIGURE: Network lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

Presentation Outline



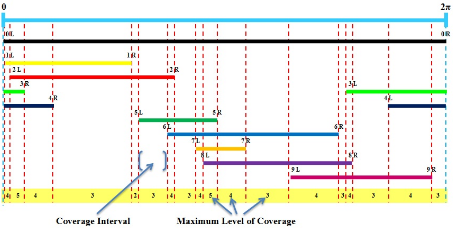
(a)

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



(b)

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



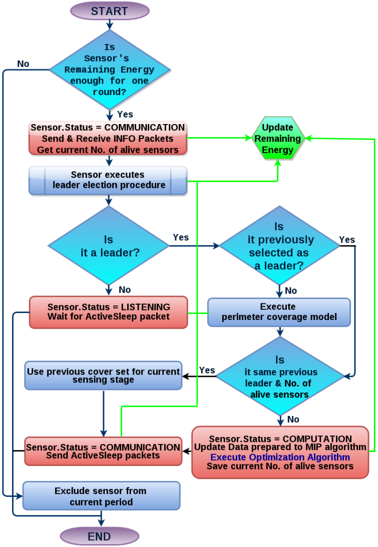
(a)

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

Left point angle α	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.


START
Is Sensor's Remaining Energy enough for one round?
No
Yes
Sensor.Status = COMMUNICATION
Send & Receive INFO Packets
Get current No. of alive sensors
Update Remaining Energy
Sensor executes leader election procedure
Is it a leader?
Yes
Is it previously selected as a leader?
Yes
No
No
Sensor.Status = LISTENING
Wait for ActiveSleep packet
Execute perimeter coverage model
Use previous cover set for current sensing stage
Yes
Is it same previous leader & No. of alive sensors
No
Sensor.Status = COMMUNICATION
Send ActiveSleep packets
Sensor.Status = COMPUTATION
Update Data prepared to MIP algorithm
Execute Optimization Algorithm
Save current No. of alive sensors
Exclude sensor from current period
END

PeCO Protocol ▶ Perimeter-based Coverage Problem Formulation

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

Subject to :

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

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

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

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

Nonnegative weights

Measure of undercoverage

Set of coverage intervals obtained for sensor j

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

Desired level of coverage

Set of sensors

Indicator function of whether sensor k is involved in coverage interval i of sensor j

Measure of overcoverage

Subset of alive sensors

Determine the activation of sensor k in the sensing phase

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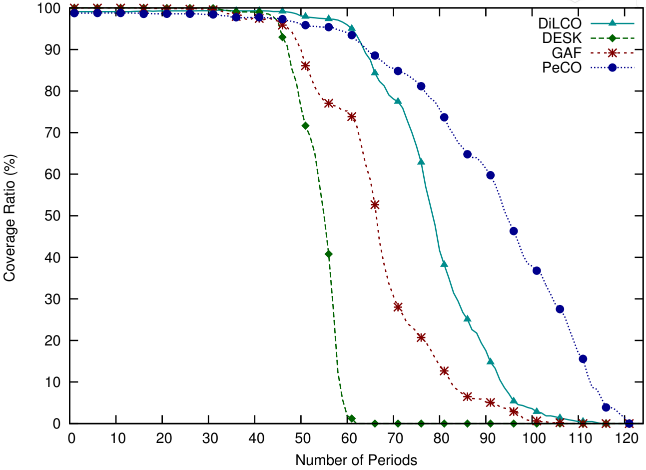


FIGURE: Coverage ratio for 200 deployed nodes.

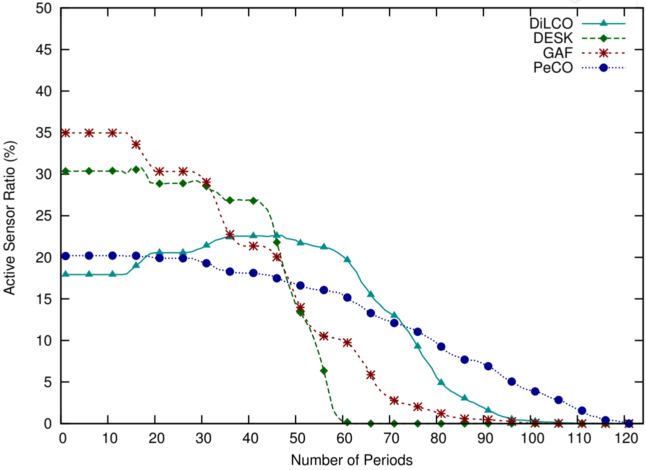


FIGURE: Active sensors ratio for 200 deployed nodes.

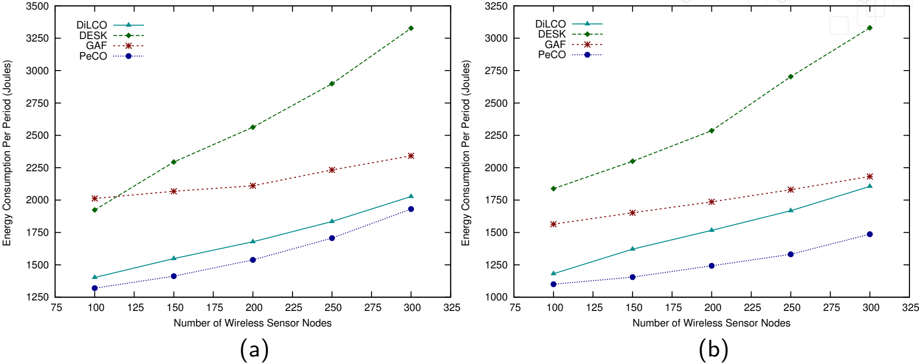
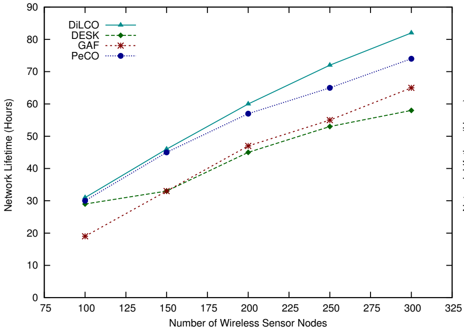
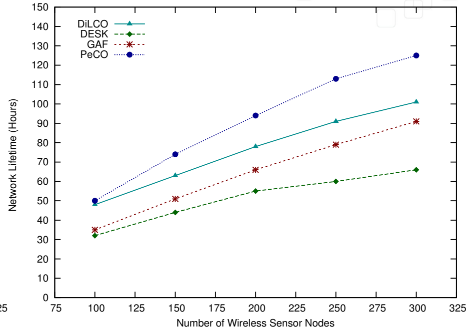


FIGURE: Energy consumption per period for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$.



(a)



(b)

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

Presentation Outline

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 ?