Distributed Coverage Optimization Techniques for Improving Lifetime of Wireless Sensor Networks

PhD Dissertation Defense

Ali Kadhum IDREES

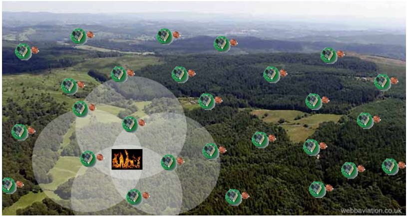
Under Supervision:

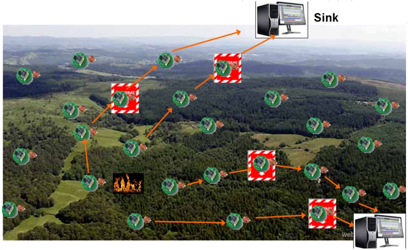
Raphaël COUTURIER, Karine DESCHINKEL & Michel SALOMON

University of Franche-Comté - FEMTO-ST - DISC Dept. - AND Team

1 October 2015

Problem definition and solution





MAIN QUESTION

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

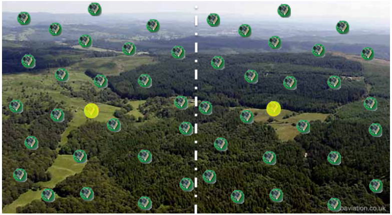
Problem definition and solution

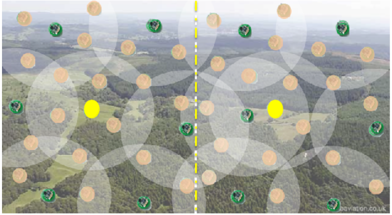
OUR SOLUTION ▶ Distributed optimization process

i) **Division into subregions**

ii) **For each subregion**

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





Presentation Outline

Presentation Outline

1. State of the Art

2. The main scheme for our protocols

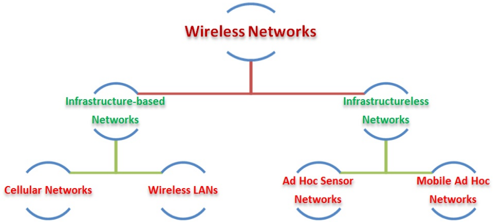
3. Distributed Lifetime Coverage Optimization Protocol (DiLCO)

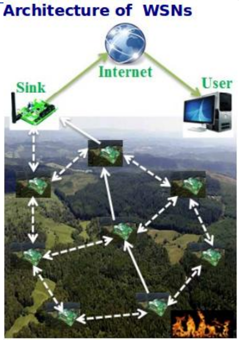
4. Multiround Distributed Lifetime Coverage Optimization Protocol (MuDiLCO)

5. Perimeter-based Coverage Optimization (PeCO)

6. Conclusion and perspectives

Wireless Sensor Networks (WSNs)

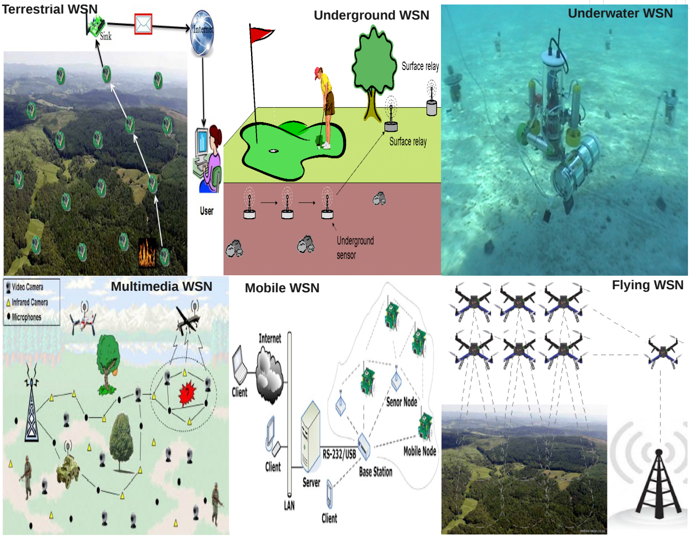




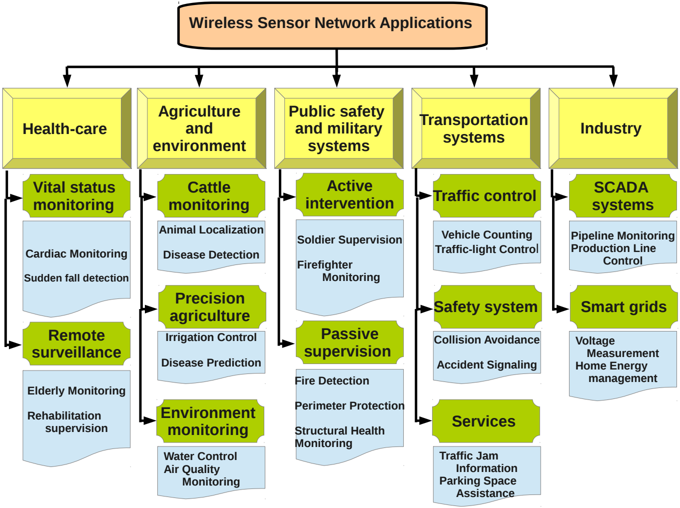
Sensor

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

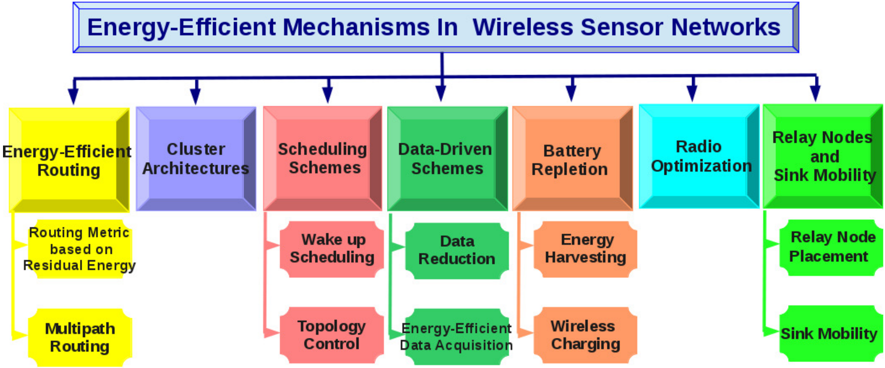
Types of Wireless Sensor Networks



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

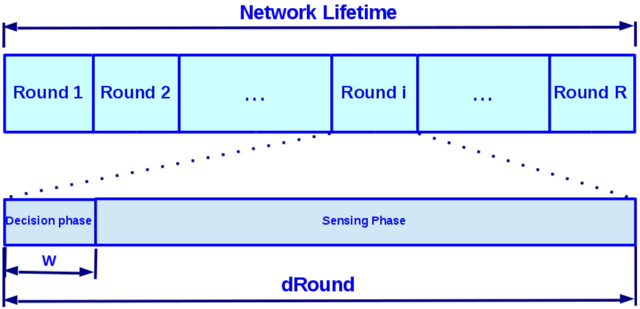
Coverage approaches

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

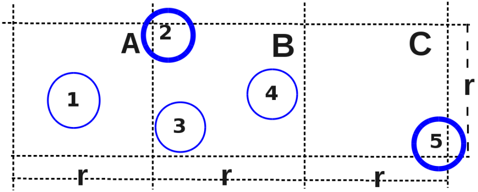
iii) Hybrid approaches
- Globally distributed and locally centralized

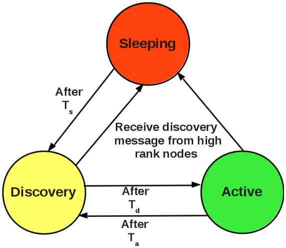
Existing works ▶ DESK algorithm (Vu et al.)



- 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

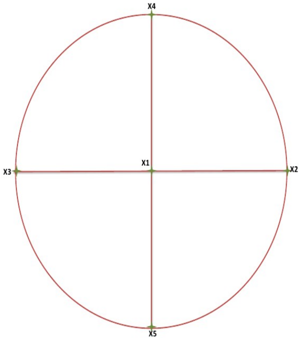
Presentation Outline

Assumptions for our protocols

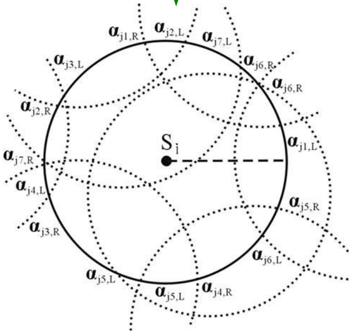
- Static wireless sensor, homogeneous in terms of
  - Sensing, communication, and processing capabilities
- Heterogeneous initial energy
- High density uniform deployment
- $R_c \geq 2R_s$ complete coverage $\Rightarrow$ connectivity (proved by Zhang and Zhou)
- Multi-hop communication
- Known location 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

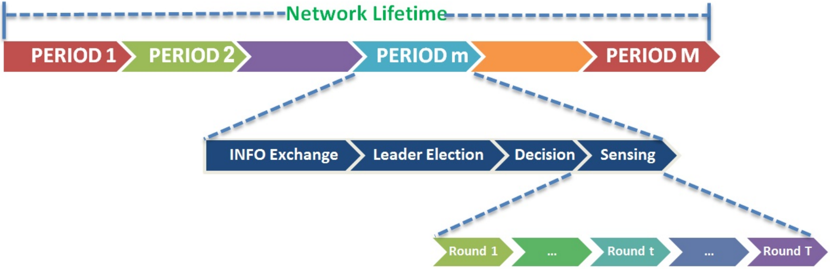
DiLCO and MuDiLCO are based on primary points model



PeCO is based on perimeter coverage model



General scheme



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

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

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

subject to :

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

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

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

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

Set of primary points

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

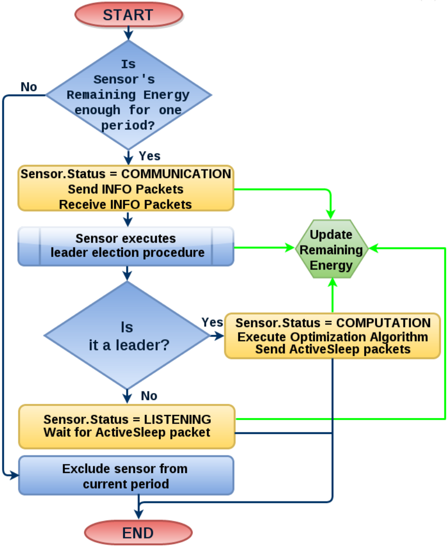

START
Is Sensor's Remaining Energy enough for one period?
No
Yes
Sensor.Status = COMMUNICATION
Send INFO Packets
Receive INFO Packets
Update Remaining Energy
Sensor executes leader election procedure
Is it a leader?
Yes
Sensor.Status = COMPUTATION
Execute Optimization Algorithm
Send ActiveSleep packets
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_{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**

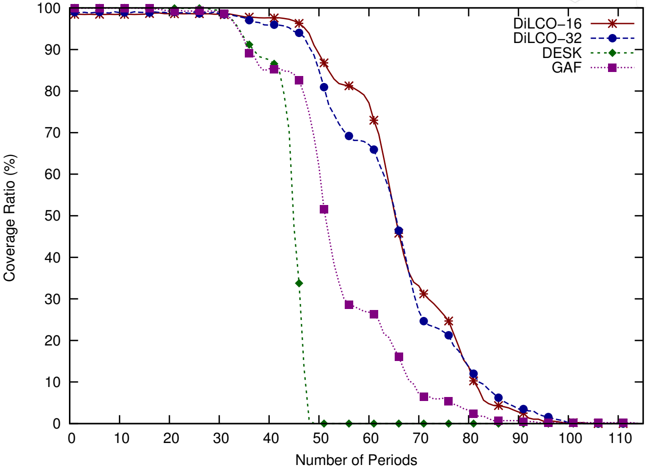


FIGURE: Coverage ratio for 150 deployed nodes

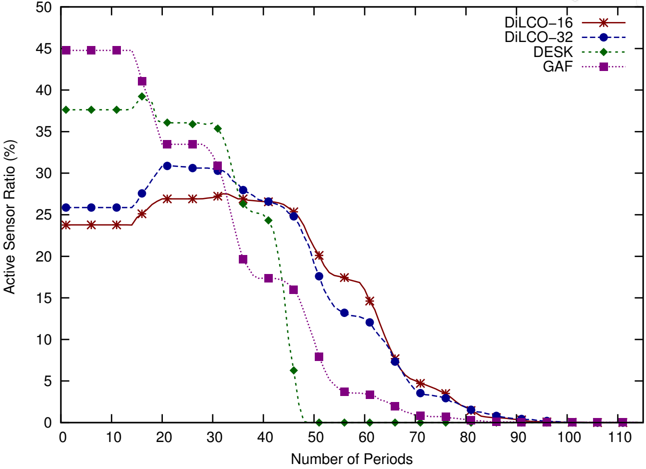


FIGURE: Active sensors ratio for 150 deployed nodes

DiLCO protocol ▶ Performance comparison

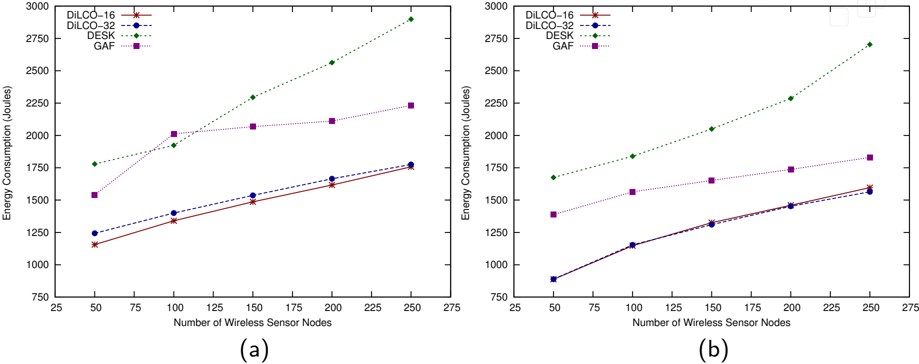


FIGURE: Energy consumption for (a) $\mathit{Lifetime}_{95}$ and (b) $\mathit{Lifetime}_{50}$

DiLCO protocol ▶ Performance comparison

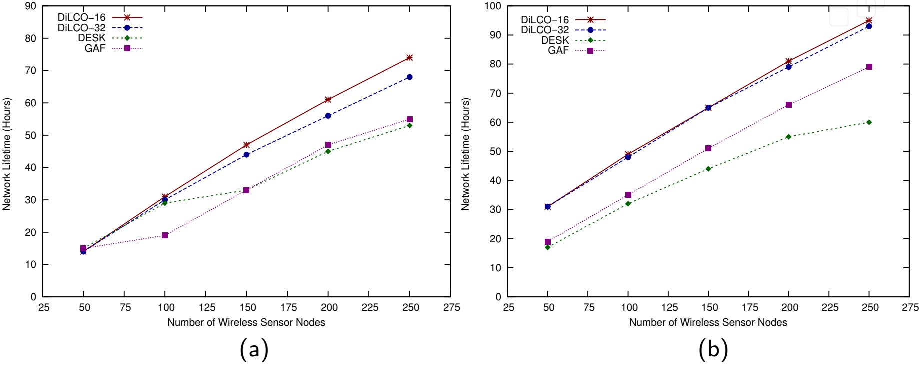


FIGURE: Network lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

Presentation Outline

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

Nonnegative weights

subject to :

Number of primary points

Coverage Constraint

Set of sensors

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

Energy Constraint

Remaining energy of sensor j

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

Amount of energy required to be alive during one round.

Determine the activation of sensor j in the sensing round t

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

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

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

Number of rounds

Undercoverage variable of the primary point p during round t

Overcoverage variable of the primary point p during round t

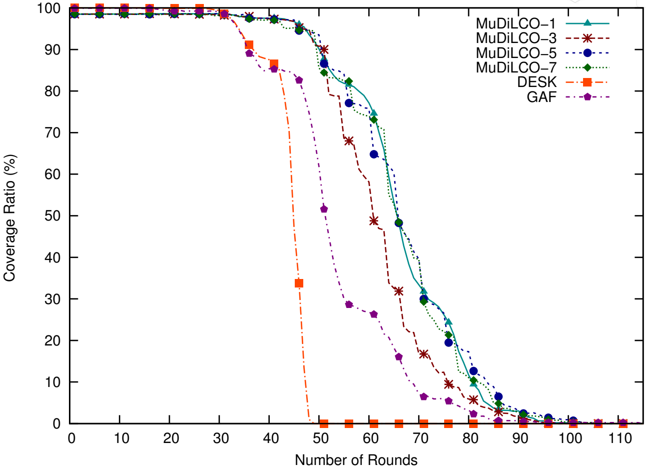


FIGURE: Average coverage ratio for 150 deployed nodes

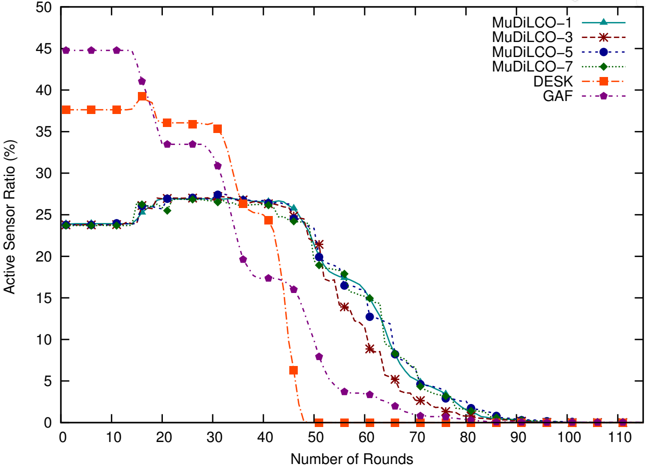
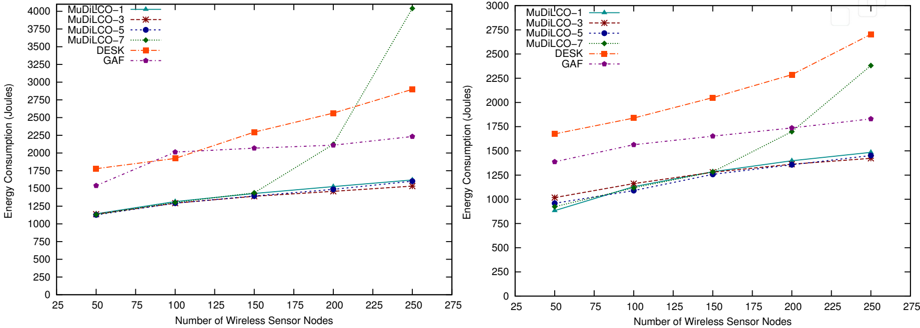


FIGURE: Active sensors ratio for 150 deployed nodes



(a) (b)

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

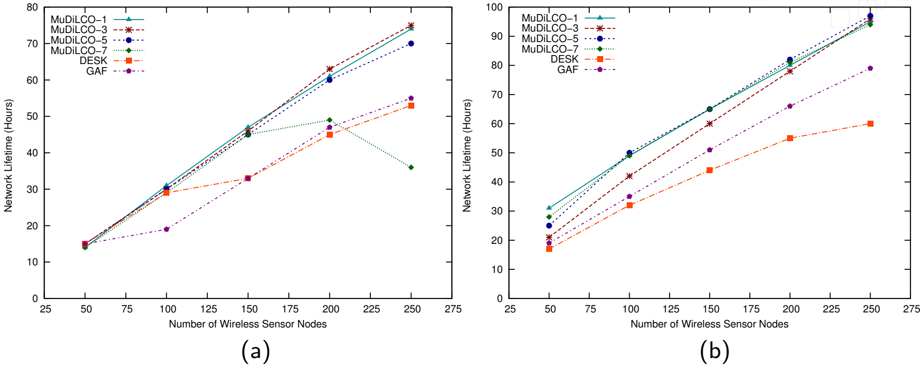
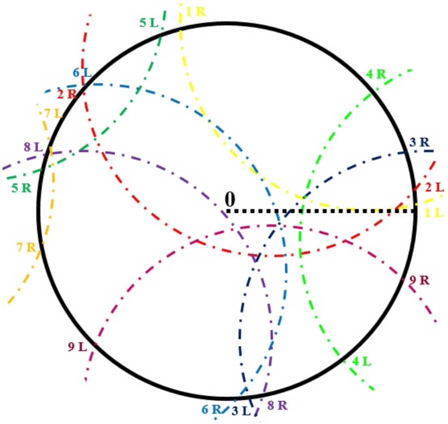


FIGURE: Network lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

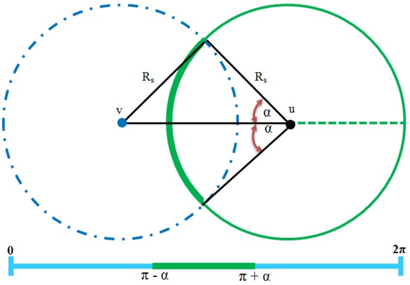
Presentation Outline

PeCO protocol ▶ Assumptions and models



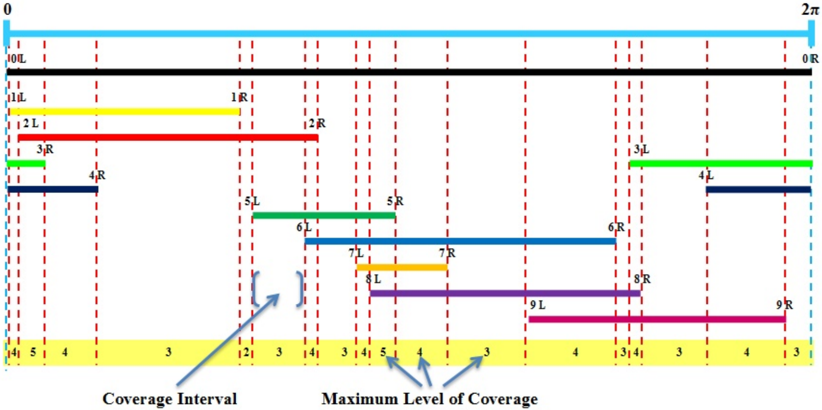
(a)

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



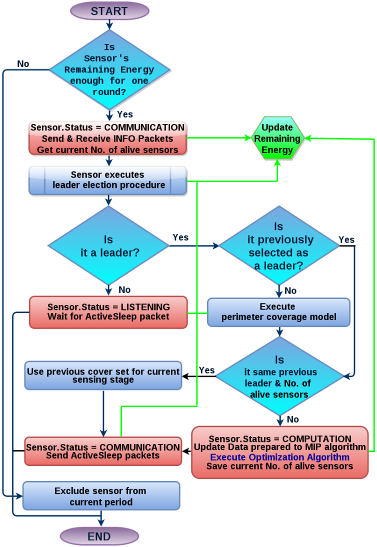
(b)

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



Set of sensors involved in coverage interval of sensor 0 between 3R to 4R ⇒ [0,1,2,4]

Maximum coverage level : 4



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
No
Is it previously selected as a leader?
Yes
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

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

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

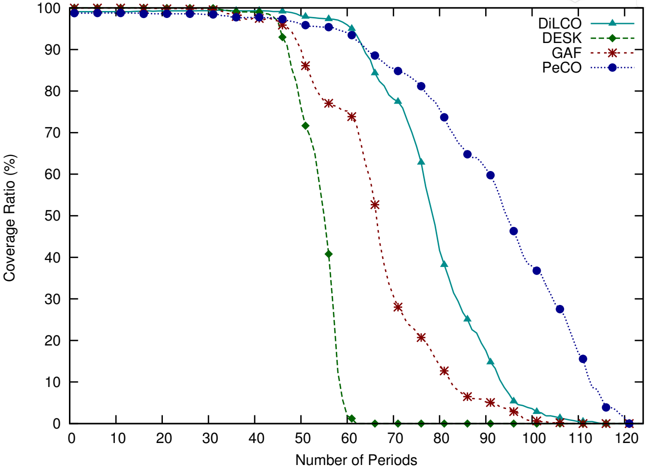


FIGURE: Coverage ratio for 200 deployed nodes.

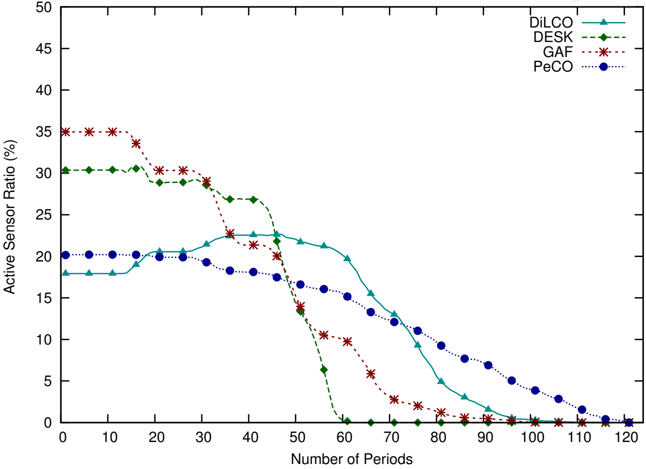
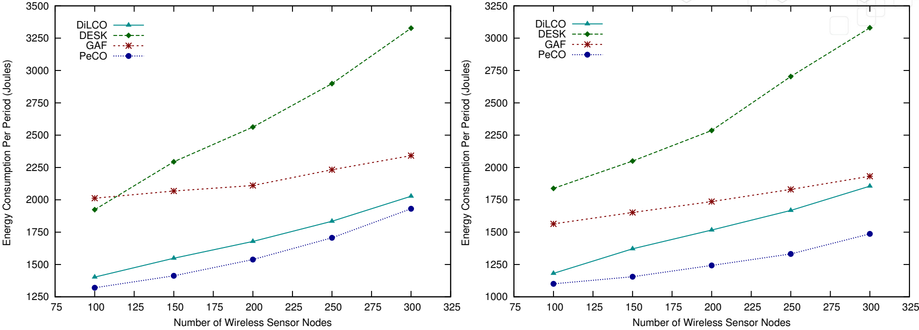


FIGURE: Active sensors ratio for 200 deployed nodes.

PeCO protocol ▶ Performance evaluation and analysis



(a) (b)

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

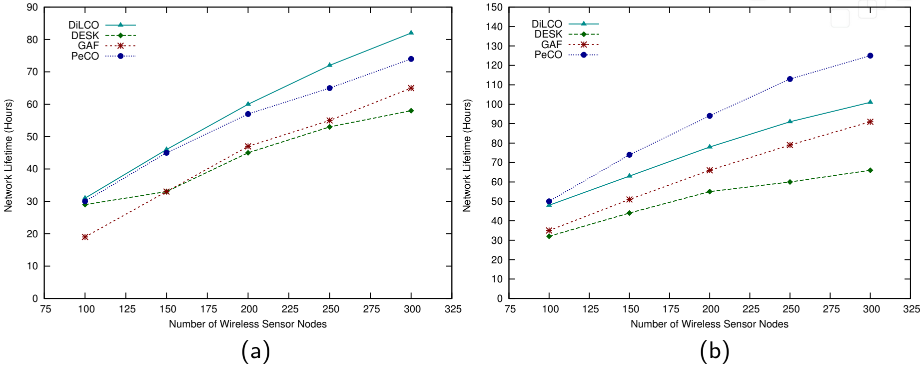


FIGURE: Network lifetime for (a) *Lifetime*$_{95}$ and (b) *Lifetime*$_{50}$.

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 ?