Distributed Coverage Optimization Techniques for Improving Lifetime of Wireless Sensor Networks

PhD Dissertation Defense

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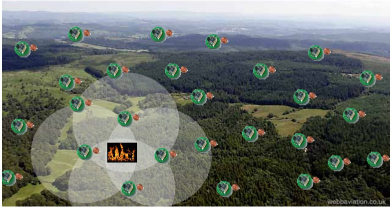
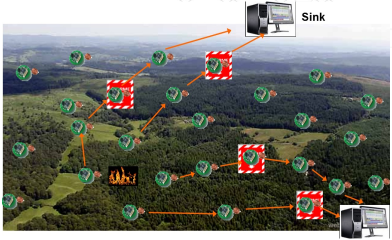
Problem Definition, Solution, and Objectives





MAIN QUESTION ?

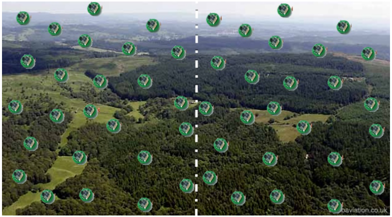
How to reduce the redundancy while coverage preservation for prolong the network lifetime continuously and effectively when monitoring a certain area of interest ?

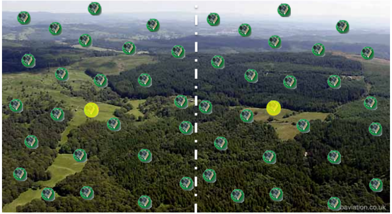
Problem Definition, Solution, and Objectives

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.

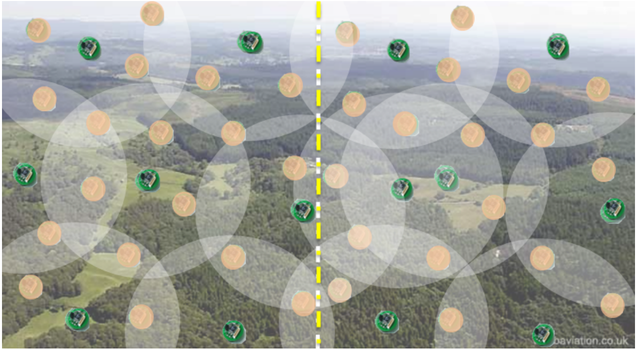




Problem Definition, Solution, and Objectives

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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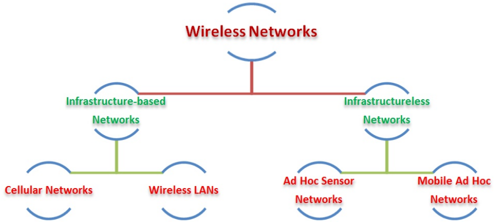
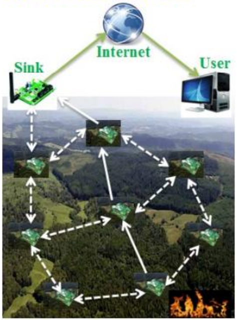
Wireless Sensor Networks (WSNs)



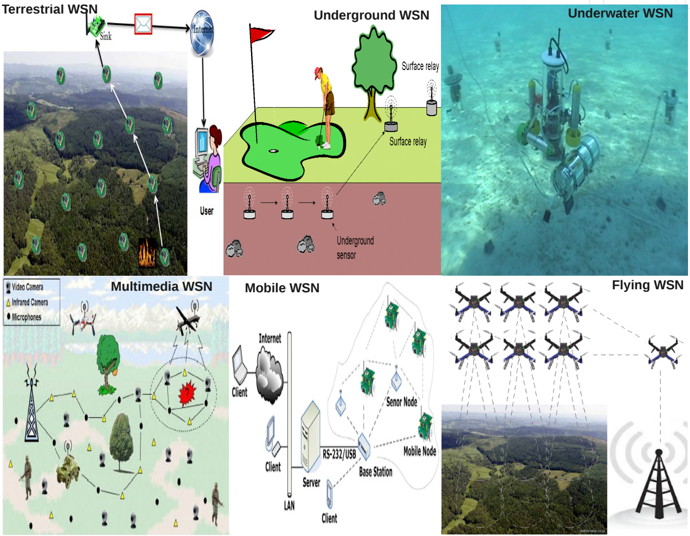
Architecture of WSNs



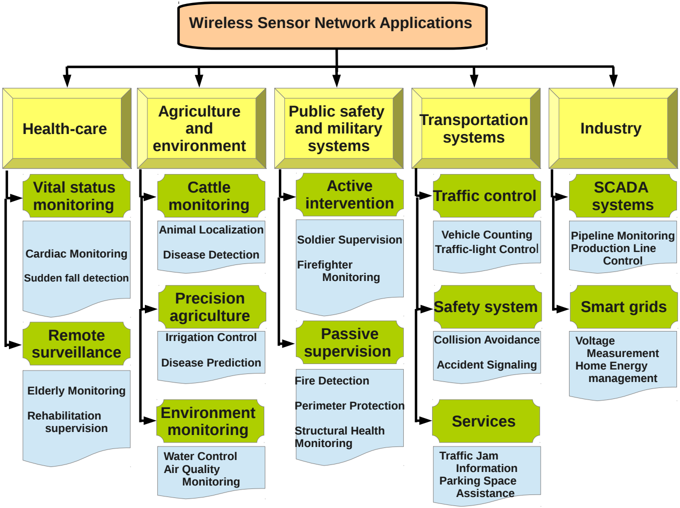
Sensor

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

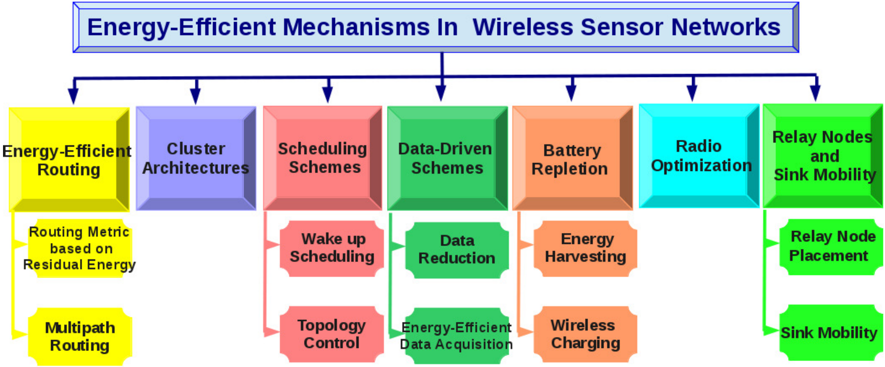
Types of Wireless Sensor Networks



Applications



Energy-Efficient Mechanisms of a working WSN



Network Lifetime

Some network lifetime defintions :

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 α.

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 : is to cover only a finite number of discrete points called targets.
3. Barrier coverage : is to detect 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).
- High communication overhead.
- Not scalable for large WSNs.

B) Full distributed coverage algorithms.

- Lower quality solution.
- High communication overhead especially for dense WSNs.
- Reliable and scalable for large WSNs.

Coverage protocols in this dissertation :

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

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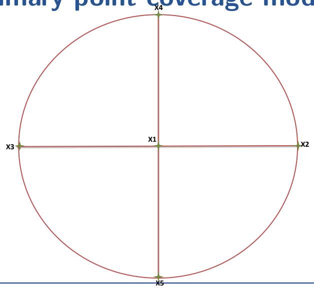
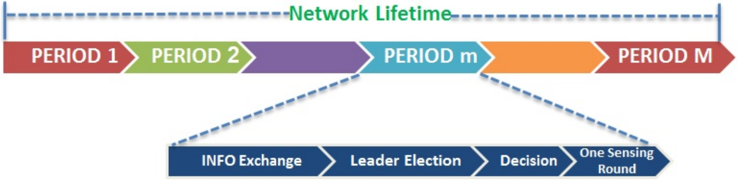
5. Conclusion and Perspectives

- 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.
- Know Its 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.

Our coverage optimization problem can then be formulated as follows :

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

- X_j : indicates whether or not the sensor j is actively sensing (1 if yes and 0 if not) ;
- Θ_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).

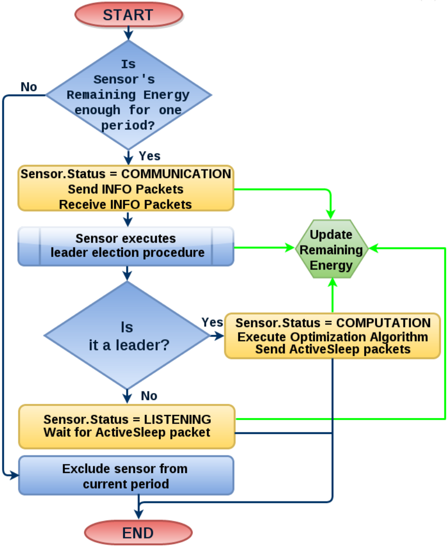

START
Is Sensor's Remaining Energy enough for one period?
No
Yes
Sensor.Status = COMMUNICATION
Send INFO Packets
Receive INFO Packets
Sensor executes leader election procedure
Update Remaining Energy
Is it a leader?
Yes
Sensor.Status = COMPUTATION
Execute Optimization Algorithm
Send ActiveSleep packets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

TABLE: Relevant parameters for network initializing.

Parameter	Value
Sensing Field	(50×25) 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

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

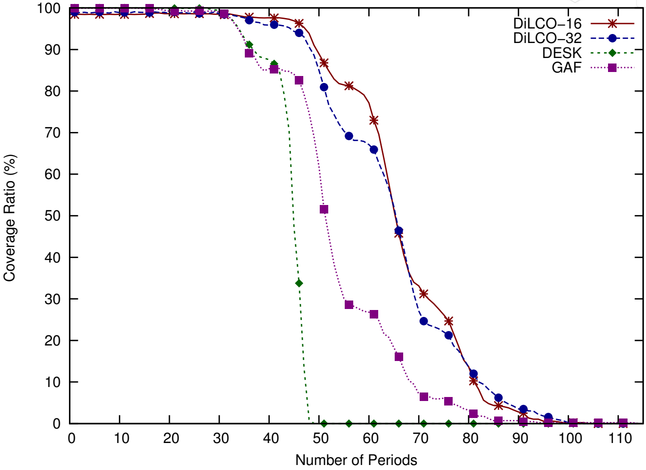


FIGURE: Coverage ratio for 150 deployed nodes

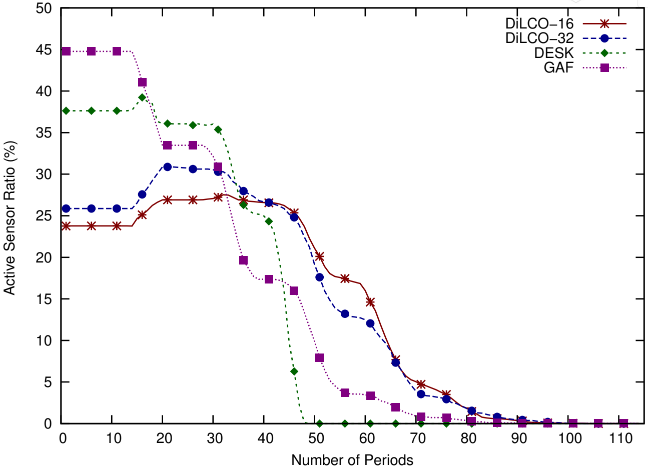


FIGURE: Active sensors ratio for 150 deployed nodes

DiLCO Protocol ▶ Performance Comparison

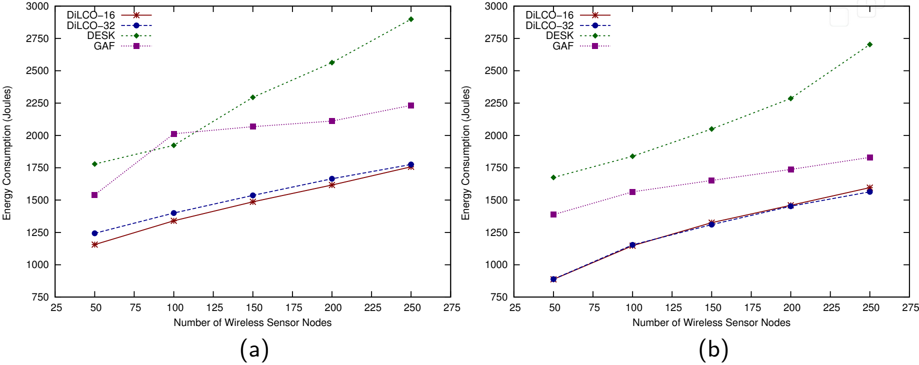


FIGURE: Energy consumption for (a) $\textit{Lifetime}_{95}$ and (b) $\textit{Lifetime}_{50}$

DiLCO Protocol ▶ Performance Comparison

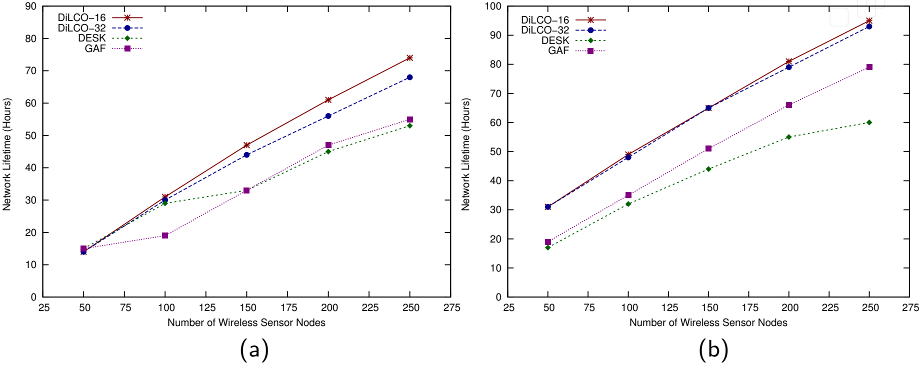


FIGURE: Network lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

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MuDiLCO Protocol ▶ Main Idia

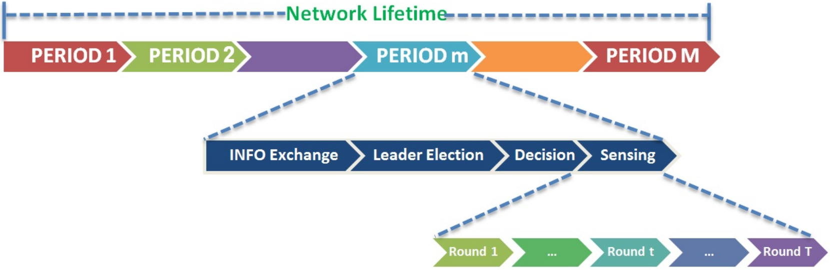


FIGURE: MuDiLCO protocol.

Our coverage optimization problem can then be formulated as follows

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

Subject to

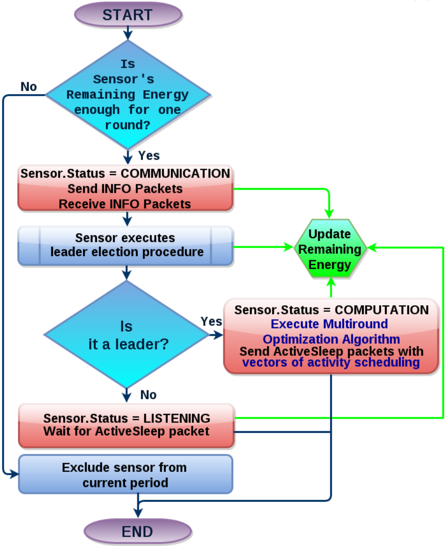
$$\sum_{j=1}^{|J|} \alpha_{j,p} * X_{t,j} = \Theta_{t,p} - U_{t,p} + 1 \qquad \forall p \in P, t = 1, \dots, T$$

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

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

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

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


START
Is Sensor's Remaining Energy enough for one round?
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 Multiround Optimization Algorithm
Send ActiveSleep packets with vectors of activity scheduling
No
Sensor.Status = LISTENING
Wait for ActiveSleep packet
Exclude sensor from current period
END

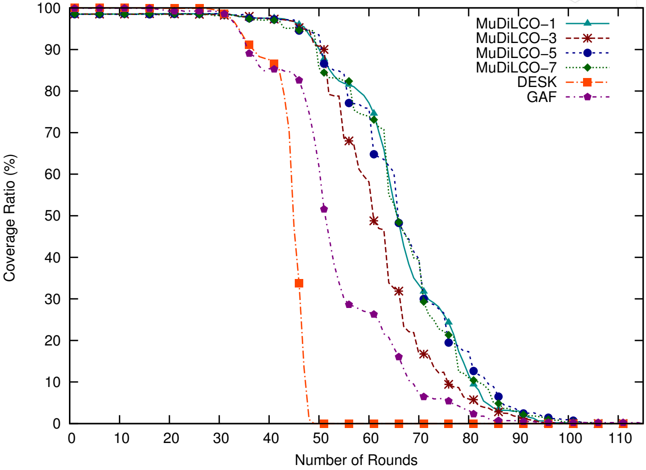


FIGURE: Average coverage ratio for 150 deployed nodes

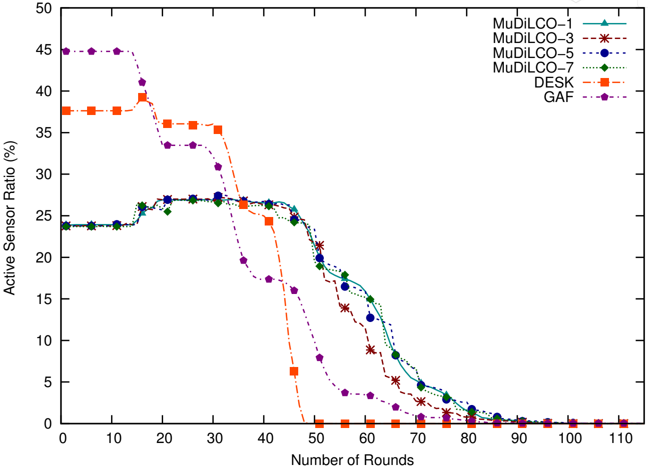


FIGURE: Active sensors ratio for 150 deployed nodes

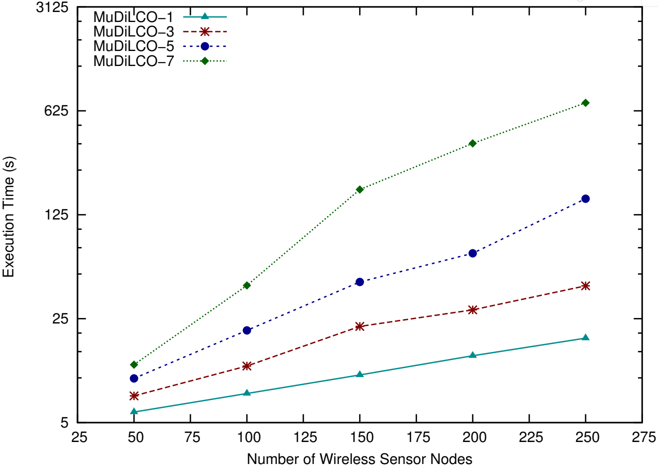


FIGURE: Execution Time (in seconds)

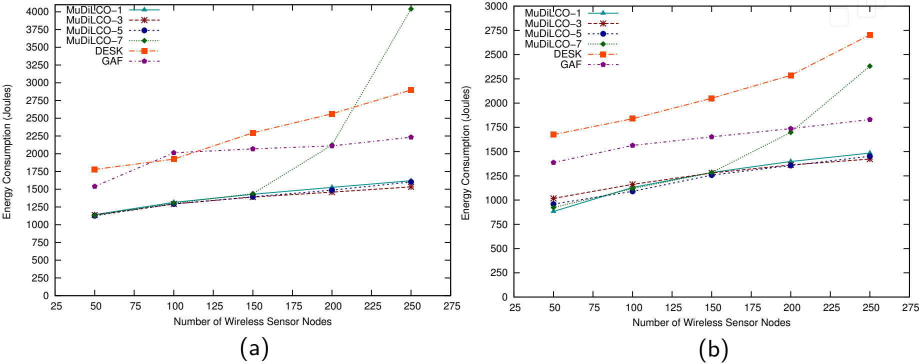
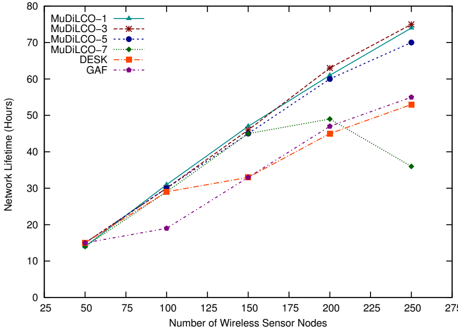


FIGURE: Energy consumption for (a) *Lifetime*$_{95}$ and (b) *Lifetime*$_{50}$



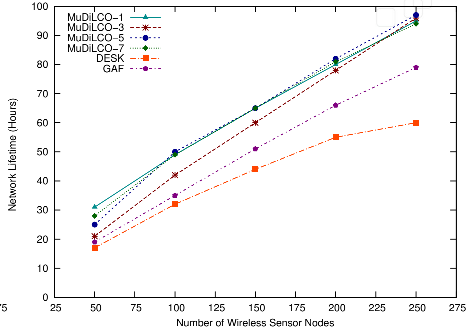
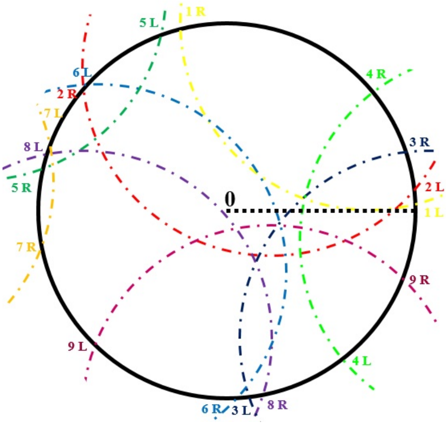


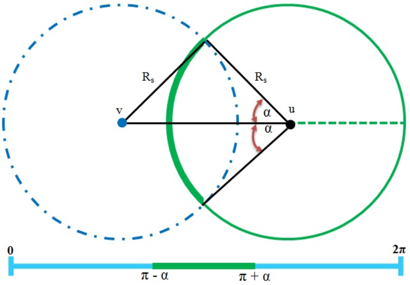
FIGURE: Network lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$

Presentation Outline



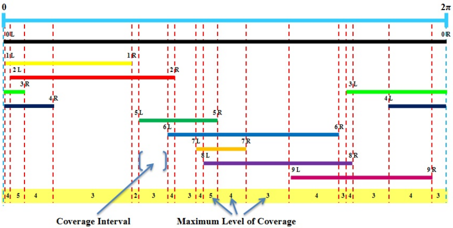
(a)

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



(b)

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



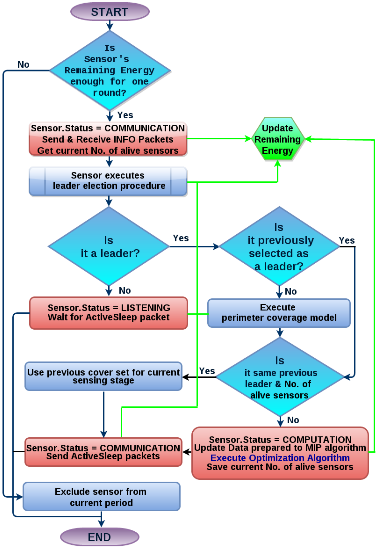
(a)

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

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

Subject to :

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

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

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

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

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 ;
α_i^j and β_i^j are nonnegative weights ;
l is the level of coverage required for one sensor ;
l^i the number of active sensors for covering the coverage interval i ;
If the sensor j is undercovered $\Rightarrow M_i^j = l - l^i$, $V_i^j = 0$;
If the sensor j is overcovered $\Rightarrow M_i^j = 0$, $V_i^j = l^i - l$.

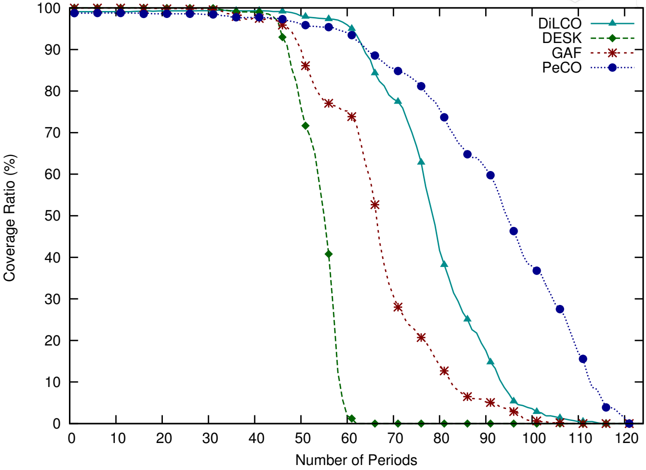


FIGURE: Coverage ratio for 200 deployed nodes.

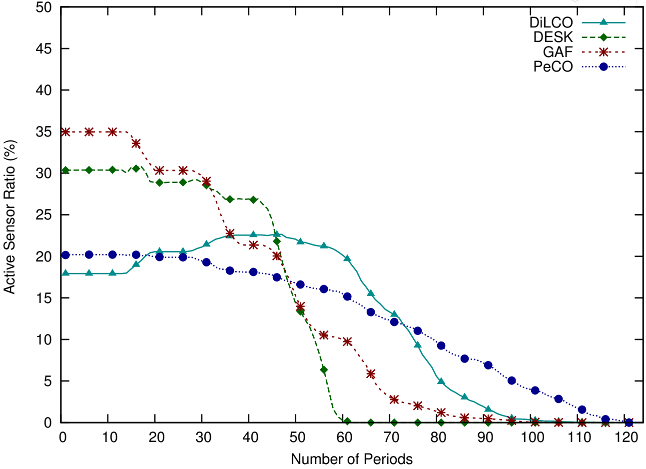


FIGURE: Active sensors ratio for 200 deployed nodes.

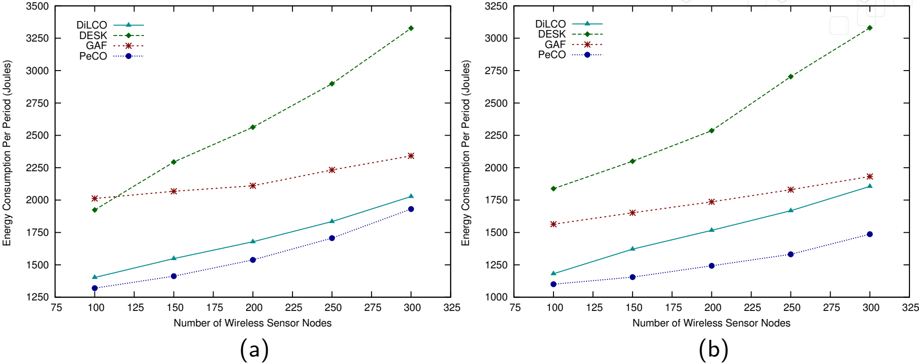


FIGURE: Energy consumption per period for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$.

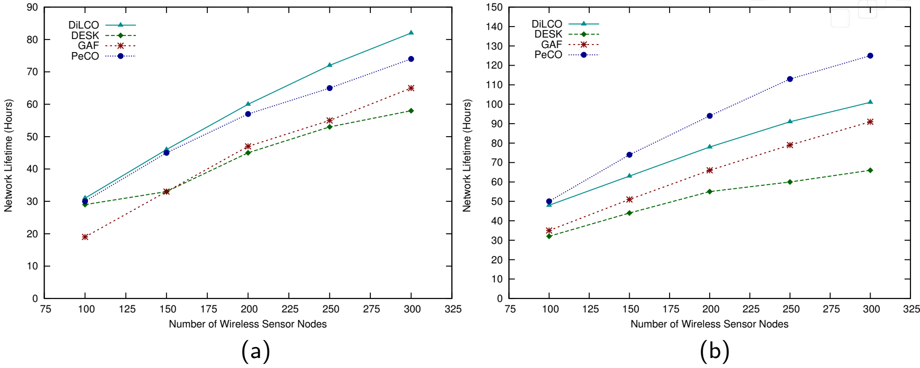


FIGURE: Network Lifetime for (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$.

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, and
  - 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.

Perspectives

- The optimal number of subregions will be investigated.
- 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.
- We plan to 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.
- The cluster head will be selected in a distributed way and based on local information.

Fin

Thank You for Your Attention !

Questions ?