On the Planning of Wireless Sensor Networks: Energy-Efficient Clustering under the Joint Routing and Coverage Constraint

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Introduction and related work

- In surveillance applications, sensors are deployed in a certain field to detect and report events like presence, movement, or intrusion in the monitored area.

- Generally, energy conservation is dealt with on five different levels:
  - 1. efficient scheduling of sensor states to alternate between sleep and active modes;
  - 2. energy-efficient routing, clustering, and data aggregation;
  - 3. efficient control of transmission power to ensure an optimal trade-off between energy consumption and connectivity;
  - 4. data compression (source coding) to reduce the amount of uselessly transmitted data;
  - 5. efficient channel access and packet retransmission protocols on the Data Link Layer.

- The scope of this paper includes both the first and the second levels.
- We address the global problem of maximizing network lifetime under the joint clustering, routing, and coverage constraint.
- We consider a sensor network that is deployed in a certain area A to monitor some given events.
- To save network energy and increase its lifetime, we propose to switch on only a subset of sensors that covers A while all other sensors are turned off.

- On the other hand, clustering has been proven energy efficient in WSN.
To the best of our knowledge, the problem of maximizing sensor network lifetime under the integrated constraint of clustering, coverage, and routing has not been addressed within the same global optimization process.

In this paper, we address the optimal planning of cluster-based WSN under the joint routing and coverage constraint.

In our architecture, any sensor can be active, switched off, or upraised as CH, and only CHs can route data.

We seek an optimal allocation of states to sensors, which maximizes network lifetime, while ensuring simultaneously full area coverage, connectivity of every sensor to a CH, and connectivity of the overlay network composed of CHs.

The problem of maintaining both area coverage and network connectivity under energy constraint in WSN has been extensively addressed in the literature and many protocols were proposed to alternate sensor states between active and sleep in order to maximize network lifetime.

However, all the works cited above do not address cluster-based architectures.

Hwang et al. [9] propose a cluster-based coverage-preserved node scheduling scheme. This mechanism assumes a dense network and assigns states (Active, Sleep, Cluster head) to sensors in a distributed and self-organized manner.

They assume that sensed data are routed to the sink in one hop.

In this paper, we consider a WSN deployed in an area A to monitor certain critical activities or events.

we propose to dynamically designate the set of CHs according to their residual energies, their distance to their neighboring non-CH active nodes, and their position within the graph formed by CHs.

we will consider, without loss of generality, that each sensor can be in one of the three states: Sleep, Active, and Cluster Head (CH) having, respectively, power consumptions $E_{\text{Sleep}}$, $E_{\text{Active}}$, and $E_{\text{CH}}$ per time unit, where $E_{\text{Sleep}} < E_{\text{Active}} < E_{\text{CH}}$.

In our problem modeling, we propose that any admissible configuration must exhibit a spanning tree connecting all CHs, as shown in Fig. 4.

On the other hand, we assume that all sensors have the same sensing range $R_s$ and that their detection model follows a binary probability function.

In critical surveillance applications, it is important to guarantee that the monitored area is fully covered by sensors at every instant of the network lifetime.

− contain a full-covering set of active sensors;
− contain a set of CHs so that every sensor is connected to a CH;
− ensure that all CHs belong to a spanning tree over which data will be routed toward the PN.
**Problem statement and assumptions**

- Our objective is to find the network-lifetime-optimal allocation of sensors’ states (Active, Sleep, CH) that meets these three conditions.
- Before modeling our problem, we make the following assumptions:
  1. Each sensor has a unique ID known to the PN and to the sensor itself.
  2. The position of each sensor is fixed and known to the PN.
  3. Active sensors capture events occurring in their sensing range and transmit data associated with these events straightaway, without any buffering.
  4. All sensors have the same sensing range $R_s$ and the same transmission range $R_t$. All CHs have the same transmission range $R_{CH} > R_t$.
  5. Only the CHs can perform data routing.
  6. Each sensor has an initial energy $E_0$. The PN has no energy limitation.
  7. The network is dense enough so that when all the sensors are Active, the monitored area is fully covered.
  8. Network lifetime is defined as the time separating the instant the network starts operating and the instant at which the network cannot be covered anymore because of the expiration of some nodes.
  9. We assume ideal MAC layer conditions, i.e., perfect transmission of data on a node-to-node wireless link.
  10. We assume that sensors have ideal sensing capabilities, i.e., inside the sensing range, the quality of sensing does not depend on the distance from the sensor.

**Problem modeling**

- OPT-ALL-RCC
- Our problem consists in finding the optimal allocation of states to sensors, which maximizes network lifetime under the integrated constraint of coverage, clustering, and routing.
- To maximize network lifetime, we need a trade-off between total energy consumption and energy balancing among sensors.
- On the other hand, any admissible solution of our model has to ensure full coverage of the monitored area and the existence of a spanning tree connecting all CHs.
- To balance energy consumption among nodes, we choose to minimize an objective function that is a linear combination of sensors scores. The score of a sensor $i$ is defined by

\[
\text{Score}(i) = \log \left( 1 + \frac{E_{Act}}{E_i} \right),
\]

where

\[
E_{Act} = \begin{cases} 
E_{Act} & \text{if sensor } i \text{ is Active but not CH} \\
E_{CR} & \text{if sensor } i \text{ is CH} \\
E_{Sleep} = 0 & \text{else}.
\end{cases}
\]

- The residual energy is low, sensors will be selected essentially according to their residual energies, favoring the activation of sensors having relatively high residual energy and when the residual energy is relatively high, the optimal solution will tend to activate as less sensors as possible.
We can model our problem by the following optimization system:

Minimize:

\[ \sum_{i=1}^{|S|} Y_i \log \left( 1 + \frac{E_{\text{radio}}}{E_{\text{link}}} \right) + X_i \log \left( 1 + \frac{E_{\text{sensor}}}{E_{\text{link}}} \right) \]  \hspace{1cm} (3a)

\[ E_{\text{link}} = \begin{cases} E_{\text{sensor}} & \text{if sensor } i \text{ is Active but not CH} \\ E_{\text{radio}} & \text{if sensor } i \text{ is CH} \\ E_{\text{sensor}} & \text{otherwise} \end{cases} \]

\[ X_i = \begin{cases} 1 & \text{if sensor } i \text{ is Active} \\ 0 & \text{else} \end{cases} \]

\[ Y_i = \begin{cases} 1 & \text{if sensor } i \text{ is a CH} \\ 0 & \text{else} \end{cases} \]

Let \( S = \{1..N\} \) be the set of sensors. Let \( i = 1..|S| \).

**Problem modeling**

**Subject to:**

\[ \forall \ c = 1..|C|, \ 1 - \prod_{i=1}^{|S|} (1 - X_i \cdot P_{\text{ic}}) \geq \text{const.} \]  \hspace{1cm} (4)

**Problem modeling**

**Subject to:**

\[ \forall \ i = 1..|S|, \ 1 - \prod_{i=1}^{|S|} (1 - X_i \cdot P_{\text{ic}}) \geq \text{const.} \]  \hspace{1cm} (4)

**Problem modeling**

**Subject to:**

\[ \sum_{j=1}^{|S|} Z_{ij} \leq \rho_{\text{max}}, \quad (5) \]

*Constraint (5) gives an upper bound on clusters’ sizes.*

\[ Z_{ij} = \begin{cases} 1 & \text{if sensor } i \text{ is connected to CH } j \\ 0 & \text{else} \end{cases} \]

**Problem modeling**

\[ \forall \ i = 1..|S|, \ \forall \ j = 1..|S|, \ j \neq i, \ \forall \ k, \ Z_{ij} \leq X_k - Y_k. \quad (6) \]

**Problem modeling**

\[ \forall \ i = 1..|S|, \ \forall \ j = 1..|S|, \ j \neq i, \ \forall \ k, \ Z_{ij} \leq Y_k - X_k. \quad (7) \]

**Problem modeling**

\[ \forall \ i = 1..|S|, \ \forall \ j = 1..|S|, \ j \neq i, \ Z_{ij} \leq d_{ij}. \quad (8) \]

**Problem modeling**

\[ \forall \ i = 1..|S|, \ \forall \ j = 1..|S|, \ j \neq i, \ Z_{ij} \leq d_{ij}. \quad (9) \]

**Problem modeling**

**Subject to:**

\[ \forall \ i = 1..|S|, \ \forall \ j = 1..|S|, \ j \neq i, \ W_{ij} \leq Y_k. \quad (10) \]

**Problem modeling**

\[ \forall \ i = 1..|S|, \ \forall \ j = 1..|S|, \ j \neq i, \ W_{ij} \leq Y_k. \quad (11) \]

**Problem modeling**

\[ \forall \ i = 1..|S|, \ \forall \ j = 1..|S|, \ j \neq i, \ W_{ij} \leq d_{ij}. \quad (12) \]

**Problem modeling**

**Subject to:**

\[ \sum_{j=1}^{|S|} W_{ij} \leq \sum_{j=1}^{|S|} Y_j - 1. \quad (13) \]

**Problem modeling**

\[ \sum_{j=1}^{|S|} W_{ij} \leq \sum_{j=1}^{|S|} Y_j - 1. \quad (14) \]

**Problem modeling**

\[ W_{ij} = \begin{cases} 1 & \text{if CH } i \text{ is connected to CH } j \text{ within a spanning tree} \\ 0 & \text{else} \end{cases} \quad (15) \]

**Problem modeling**

\[ d_{ij} = \begin{cases} 1 & \text{if CH } i \text{ can reach CH } j \text{ in one hop} \\ 0 & \text{else} \end{cases} \quad (16) \]
**Problem modeling**

Subject to:

\[
X, Y \in \{0,1\}^{M}, Z, W \in \{0,1\}^{M}. \quad (10)
\]

Equations (10) are the integrality constraints.

\[
X_i = \begin{cases} 
1 & \text{if sensor } i \text{ is Active} \\
0 & \text{else} 
\end{cases}, \\
Y_i = \begin{cases} 
1 & \text{if sensor } i \text{ is a CH} \\
0 & \text{else} 
\end{cases}, \\
Z_{ij} = \begin{cases} 
1 & \text{if sensor } i \text{ is connected to CH } j \\
0 & \text{else} 
\end{cases}, \\
W_{ij} = \begin{cases} 
1 & \text{if CH } i \text{ is connected to CH } j \text{ within a spanning tree} \\
0 & \text{else} 
\end{cases}
\]

**Proposed heuristic**

- The problem is NP-Complete, we propose a Tabu search heuristic, called TABU-RCC.
- TABU-RCC will be run by the PN and starts with an admissible solution.
- The network will operate with this configuration for a predefined period \( T \) during which residual energies of active nodes and CHs will decrease, then TABU-RCC is run again.
- The requires sensors-related information (e.g., residual energies) to be transmitted periodically to the PN (upstream communication) and the newly computed sensor states to be transmitted to the sensors (downstream communication).

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**Proposed heuristic**

**Algorithm 1: TABU-RCC**

- **Initial solution**: the Tabu algorithm starts with a configuration where all sensors are activated as cluster heads. This configuration is obviously admissible;
- **Admissible configuration**: a configuration \( S \) is defined by the states of its sensors (Sleep, Active, or CH). Only feasible configurations (i.e., satisfying model constraints (1b) to (1i)) are considered;
- **Score function**: a configuration is evaluated using the score function given by (1a);
- **Neighborhood investigation**: a search movement \( M < i; u; v > \) consists in changing the state (Sleep, Active, or CH) of a single sensor \( i \) from state \( u \) to state \( v \) such that the model constraints (1b) to (1i) are satisfied;
- **Aspiration criterion**: Tabu movements are allowed when the score of the resulting configuration is lower than the score of the best solution \( s^* \) found so far over the whole search process;
- **Stop criterion**: The search algorithm stops after a predefined number of iterations.

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**Simulation results**

Comparative Performance Evaluation: TABU-RCC With Respect To Its Lower Bound (CPLEX)

![Graph showing performance evaluation](image1)

**Simulation results**

Comparative Performance Evaluation: TABU-RCC With Respect To Its Lower Bound (CPLEX)

![Graph showing performance evaluation](image2)
**Simulation results**

Performance Evaluation of TABU-RCC: Impact of the Sensing Range

![Graph showing network lifetime with varying sensing range](image)

**Simulation results**

Performance Evaluation of TABU-RCC: Impact of the Maximum Cluster Size

![Graph showing network lifetime with maximum cluster size](image)

**Simulation results**

Comparative Performance Evaluation: TABU-RCC versus EESH

![Graph comparing network lifetime](image)

**Conclusion**

- Proposed a novel centralized mechanism for near-optimal state assignment to sensors in large-scale cluster-based monitoring wireless sensor networks.
- It is based on a tabu algorithm.
- Our mechanism maximizes network lifetime while ensuring the full coverage of the monitored area and the connectivity of the obtained configuration.
- Connectivity is fulfilled through an optimally computed spanning tree connecting all the cluster heads.
- As future research directions: more sophisticated heuristic to improve the network lifetime; distance-dependent probabilistic event detection; distributed algorithms.

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Thank you very much!