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Placement of multiple mobile base stations in wireless sensor networks

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Abstract

Due to energy constraints in individual sensor nodes, extending the lifetime is an essential objective in Wireless Sensor Networks (WSN's). Several proposals have aimed at that objective by designing energy efficient protocols at the physical, medium access, and network layers. While the proposed protocols achieve significant energy savings for individual sensor nodes, they fail to solve topology-related problems; an example of such problems is that sensor nodes around the base station become bottlenecks and deplete their battery energy much faster than other nodes. A natural solution to such a problem is to have multiple mobile base stations so that the load is distributed evenly among all nodes. Only few proposals have followed that direction.

In this paper we propose a mobile base station placement scheme for extending the lifetime of the network. In our scheme the life of the network is divided into rounds and base stations are moved to new locations at the beginning of each round. While previous work has focused on placing the base stations at predefined spots (e.g., the work in [1]) or at the boundary of the network (e.g., the work in [2]), we define and solve a more general problem in which a base station can be placed anywhere in the sensing field. We formulate the problem as an Integer Linear Program (ILP) and use an ILP solver (with a constant time limit) to find a near-optimal placement of the base stations and to find routing patterns to deliver collected data to base stations. Our experiments show that our scheme makes significant extension to the lifetime of the network.

1 Introduction

Advances in wireless communication and embedded microprocessors have brought about the development of small, low-cost sensor devices, which are able to collect data from the surrounding environment and communicate in short distances. These tiny devices are battery-operated and, hence, untethered in terms of both power and communication. This enabled a new generation of large-scale networks of untethered, unattended sensor devices suitable for a wide range of commercial, scientific, health, surveillance, and military applications. This rapidly evolving technology promises to revolutionize the way we interact with the physical

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environment and to facilitate collecting data which has never been available before [3]. However, as a result of the limited energy supply for sensor nodes, extending the lifetime of WSN's has been a primary target for a significant amount of research during the last couple of years.

A sensor node has a wireless communication interface through which it can communicate with other devices in its vicinity. Due to the scarcity of the energy reservoir and due to the fact that communication is the dominant power consumer in a sensor node, the transmission range of these nodes is limited for energy-efficiency purposes. Sensor nodes which are spatially distant from the base station use multi-hop communication to deliver data to the base station. The multi-hop communication results in an unbalanced energy expenditure over different parts of the network; nodes around the base station deplete their energy reserve much faster than distant nodes [4] [1] [5]. This will not only stop those nodes around the base station from functioning, but will also make the base station unreachable by other nodes. Some proposals tried to solve the problem by placing more sensor nodes around the base station [6] [7]. However, this may result in an unbalanced sensing coverage over different parts of the field.

In this paper, we argue for using multiple mobile base stations and propose a scheme for placing these base stations in a way that balances the energy expenditure and increases the lifetime of the network. Some recently proposed schemes (see below) have addressed the issue of mobile base stations. However, they are either limited to a given set of base station locations, or incur high complexity. To this end, the novel contribution of this paper is twofold:

1. We define and solve the general placement problem in which a base station can be placed anywhere in the sensing field. Previous work has focused on placing the base stations at predefined spots (i.e., points) [1], or placing them at the boundaries of the field [2].

2. We devise an algorithm to construct a finite set of relatively small number of points, and we prove the existence of an optimal placement in which each base station is placed at a point in that set. Since the problem is modeled as an ILP, making the cardinality of this set as small as possible would significantly improve the efficiency and the solution quality. This makes our approach more efficient than earlier schemes, viz [8], which is based on solving a number of linear programming instances which is exponential in the number of base stations.

By formulating the problem as an ILP, an optimal solution can be found. However, that may require exponential run-time in the worst case [9]. Therefore, we impose a time limit on a branch-and-bound solver in order to find near-optimal solutions in reasonable time.

The rest of this paper is organized as follows. Section 2 describes the model of the system and gives a formal problem definition. In Section 3, we present our placement scheme. Section 4 shows the experimental results. Finally, In Section 5, we conclude this paper by summarizing the contributions and pointing out some related future research directions.

2 System model and problem definition

We consider a WSN consisting of N sensor nodes and R base stations. Each sensor node collects data from the surrounding environment and sends the collected data to one of the base stations. The transmission range of all sensor nodes is fixed to r m. The topology of the network is modeled as a graph $G = (V, E)$, where $V = \{n_0, n_1, ..., n_N\}$ is the set of N sensor nodes, and $(i, j) \in E$, if sensor nodes n_i and n_j are within the transmission range of each other. Each sensor node n_i has a data generation rate g_i; g_i is the number of data packets generated by node n_i per time unit.

Without loss of generality, we define the lifetime of the network as the time until the first sensor node dies. Yet other definitions (e.g., the time until a particular proportion of the sensors die) can be equally used in our approach.

Assumptions

1. For each sensor node n_i, the location loc_i, the residual energy E_i, and the data generation rate g_i are known.

2. Base stations are not energy constrained.

3. Every generated packet is sent to one base station.

Problem definition

The problem can be described as follows:
The lifetime of the network is divided into equal length rounds. At the beginning of each round, find the optimal locations of R base stations together with the routing patterns to deliver the generated data to base stations, which maximizes the minimum residual energy at the end of the round. Base stations can be placed anywhere in the field.

3 Base station placement scheme

The first challenge in this placement problem is the infinite search space for base station locations; the search space involves every single point in the field. The first step in our approach is to make the search space finite without affecting the quality of the solution. To explain our method of finding such a finite search space, we make the following definitions.

Definition A finite set of points K is *complete iff* it satisfies the following property:
There is an optimal placement of base stations where each base station is located at a point in K.

Finding a complete set would make the placement problem a discrete optimization problem rather than a continuous one.

Definition An *overlapping region* is a region where the transmission disks of a nonempty subset of sensor nodes overlap. For an overlapping region α, let $S(\alpha)$ denote the subset of sensor nodes whose transmission disks overlap at α.

Definition An overlapping region α is *maximal* if there is no overlapping region β where $S(\alpha) \subset S(\beta)$.

Fig. 1 shows six sensor nodes and their maximal overlapping regions (MOR's).
We next show that a complete set can be derived from the set of MOR's. We first state the following lemma without proof.

Lemma 1 *For every overlapping region β, there exists a MOR α, such that $S(\beta) \subseteq S(\alpha)$.*

Then, we deduce the following theorem.

Theorem 1 *A set K that contains one point from every MOR is complete.*

Proof To prove this theorem, it suffices to show that for any arbitrary placement $\aleph$ we can construct an equivalent placement $\aleph^*$ in which every base station is located at a point in K. Let us say that in $\aleph$, a base station B is placed such that it is within the transmission range of a subset of sensor nodes H. It is obvious that there exists an overlapping region β, such that $H \subseteq S(\beta)$. From the previous lemma, there exists a MOR α, such that $S(\beta) \subseteq S(\alpha)$. In $\aleph^*$, we place B at the point in K that belongs to α, so that B is placed at a point in K and is still within the transmission range of all sensor nodes in H. Repeating for all base stations, we construct a placement $\aleph^*$ which is equivalent to the placement $\aleph$. $\square$

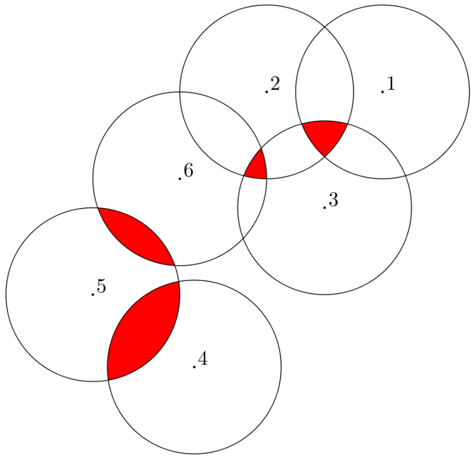

Figure 1: Maximal overlapping regions.

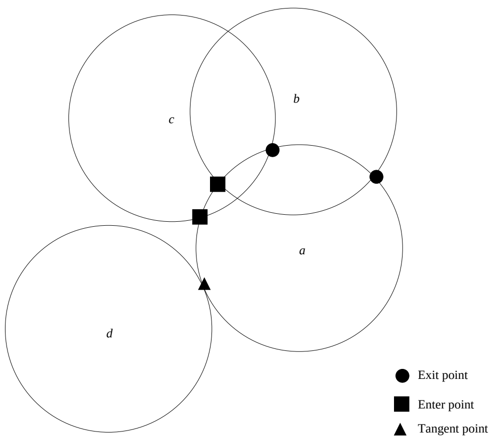

Figure 2: Enter points and exit points.

3.1 Finding MOR's

We need to find the arrangement of transmission disks. Let $D(i)$ denote the transmission disk of sensor node n_i, and if p is an intersection point of the boundaries of $D(i)$ and $D(j)$, let $succ_i(p)$ ($succ_j(p)$) denote the intersection point incident to $D(i)$ ($D(j)$) that comes right after p according to a clockwise order, and let $other_i(p) = j$ and $other_j(p) = i$. The arrangement of disks is a data structure by which for any intersection point p of $D(i)$ and $D(j)$, we can get $succ_i(p)$ and $succ_j(p)$ in $O(1)$ time. Such a data structure can be constructed by Algorithm 1.

Algorithm 1: Arrangement of transmission disks.

```
Procedure FindArrangement()
Find all intersection points;
foreach sensor node n_i do
    sort all intersection points incident to D(i) in a clockwise order;
end
```

[H] Algorithm 1 runs in $O(n^2 \log n)$ time.
By walking over the boundary of a transmission disk $D(i)$ in a clockwise direction, intersection points incident to $D(i)$ can be classified into three groups: *enter points*, *exit points*, and *tangent points*. Enter point is one at which we enter the transmission disk of another sensor node. Exit point is one at which we leave the transmission disk of another sensor node. Tangent point occurs if two transmission disks intersect at exactly one point. Fig. 2 gives an example of four sensor nodes (a,b, c, and d) where the intersection points incident to $D(a)$ are classified.
Now, it is straightforward to realize the following observation.

Observation An overlapping region β is maximal *iff* it satisfies one of the following properties:

1. β is a tangent point.

2. By walking on the boundary of β in a clockwise direction, all intersection points are exit points.

This observation allows us to check whether an overlapping region is maximal. Algorithm 2 uses this observation to test whether an overlapping region is maximal or not. Algorithm 3 uses Algorithms 1 and 2 to find all MORs. Note that the Boolean array $Flag(p, i)$ is used to guarantee that we do not check the same overlapping region more than once.
The overall complexity of Algorithm 3 is $O(n^2 \log n)$.

3.2 ILP formulation

Once we obtain the set $K = \{k_0, k_1, ..., k_M\}$, which contains a point from each MOR, the problem of finding the optimal locations of R base stations and the flow patterns from sensor nodes to base stations can be formulated as an ILP. We define the following constants and variables.
Constants:
g_i is the data generation rate of sensor node n_i.
$j \in N(i)$ if n_j is withing the transmission range of n_i (i.e., n_j is a neighbor of n_i).
$j \in M(i)$ if k_j is withing the transmission range of n_i.
N is the number of sensor nodes.
R is the number of base stations.
M is the number of MOR's.
E_i is the residual energy of sensor node n_i.
E_{Tr} is the energy consumed to send one packet.
E_{Rc} is the energy consumed to receive one packet.

Algorithm 2: Testing whether an overlapping region is maximal or not.

```
Function Maximal(i: sensor node, p: intersection point)
Input: A sensor node n_i and an intersection point p incident to D(i).
Output: True if a MOR is found, and False otherwise.
if p is a tangent point then
    return True ;
end
if Flag(p,i) = 1 OR p is an enter point with respect to i then
    return False ;
end
q:=p;
j:=other_i(p);
p:=succ_j(p);
i:=j;
while p ≠ q do
    if Flag(p,i) = 1 OR p is an enter point with respect to i then
        return False ;
    end
    Flag(p,i) := 1;
    j:=other_i(p);
    p:=succ_j(p);
    i:=j;
end
return True ;
```

Algorithm 3: Finding all MORs.

```
Procedure FindMORs()
Output: A set K that contains one point from every MOR.
K:=∅ ;
FindArrangement();
foreach intersection point p which is incident to two transmission disks D(i) and D(j) do
    Flag(p,i):=0;
    Flag(p,j):=0;
end
foreach sensor node i do
    foreach point p incident to D(i) do
        if Maximal(i,p) then
            K:=K + {p};
        end
    end
end
```

Variables:

$l_i = 1$ if a base station is located at k_i, and $l_i = 0$ otherwise.

If $j \in N(i)$, f_{ij} is the flow from sensor node n_i to sensor node n_j (i.e., the number of packets to be sent from n_i to n_j per time unit).

If $j \in M(i)$, h_{ij} is the flow from sensor node n_i to the base station at k_j (if no base station is located at k_j, h_{ij} will be set to 0).

E_{min} is the minimum residual energy over all sensor nodes at the end of the round.

Our policy of maximizing the lifetime is to maximize E_{min} at the end of each round. An ILP that reflects

this policy is supposed to be solved at the beginning of each round in order to move base stations to new locations.
The ILP is shown in Fig. 3. Equation (1) guarantees the flow balance. Equation (2) makes E_{min} the minimum residual energy over all sensor nodes (note that we maximize E_{min}). Equation (3) guarantees that the energy expenditure of any sensor node is not more than its current residual energy. Equation (4) guarantees that if no base station is located at k_j (i.e., l_j=0), no flow is sent to k_j. Equation (5) satisfies the constraint that only R base stations are available.

Maximize E_{min}
s.t.,

$$\sum_{j \in N(i)} f_{ij} + \sum_{j \in M(i)} h_{ij} - \sum_{j \in N(i)} f_{ji} = g_i, 0 \leq i < N \tag{1}$$

$$\begin{aligned} E_i \quad &- \quad E_{Tr}(\sum_{j \in N(i)} f_{ij} + \sum_{j \in M(i)} h_{ij}) \\ &- \quad E_{Rc} \sum_{j \in N(i)} f_{ji} \geq E_{min} \quad , 0 \leq i < N \end{aligned} \tag{2}$$

$$E_{min} \geq 0 \tag{3}$$

$$\sum_{0 \leq i < N} h_{ij} \leq l_j \sum_{0 \leq i < N} g_i, 0 \leq j < M \tag{4}$$

$$\sum_{0 \leq j < M} l_j = R \tag{5}$$

f_{ij} is Integer, $0 \leq i < N, j \in N(i)$
h_{ij} is Integer, $0 \leq i < N, j \in M(i)$
$l_i \in \{0, 1\}$, $0 \leq i < M$

Figure 3: ILP formulation.

4 Simulation results

We compare our approach with another approach in which base stations are static and are located randomely in the sensing field. In the static approach, we use a similar ILP to find near-optimal flow patterns for a given placement.
We use the energy consumption model in [4] which can be described as follows.

$$E_{Tr}(d, k) = k \times (e_{elec} + e_{amp} \times d^{\alpha}) \tag{6}$$

$$E_{Rc}(k) = k \times e_{elec} \tag{7}$$

where $E_{Tr}(d, k)$ is the energy consumed to send k bits over d m, $E_{Rc}(k)$ is the energy consumed to receive k bits, e_{elec} is the energy consumed by the transmitter (receiver) to send (receive) one bit, e_{amp} is the energy consumed by the transmission amplifier for one bit, and α is the path-loss exponent. In our simulation, d is set to 10 m, e_{elec} is set to 50 nJ/bit, e_{amp} is set to 0.1 nJ/bit/m^2, and α is set to 2. The packet size is 512 bits. Every sensor node has an initial energy of 0.1 J. Data generation rates are uniformly distributed between 50 and 300 packets/round.
Our simulations involve networks of size 50 sensors and 100 sensors. In each network, we tested different

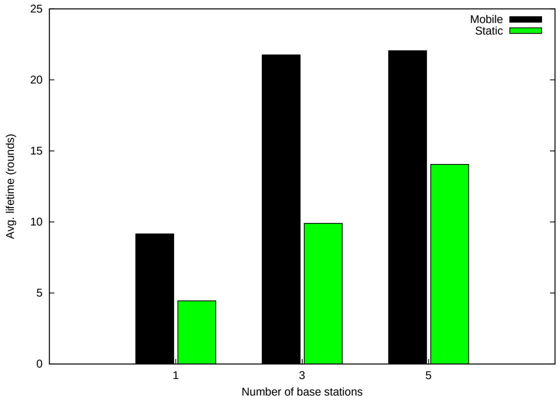

Figure 4: Comparison results in a network of 50 sensor nodes.

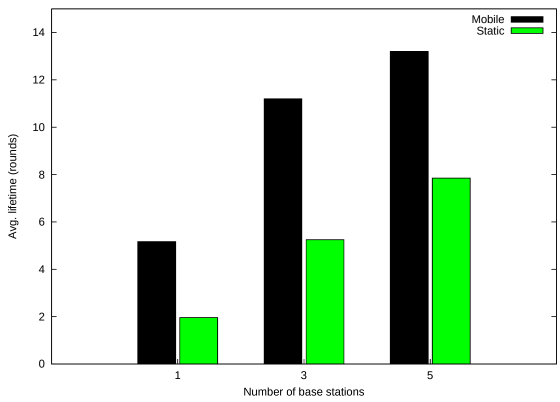

Figure 5: Comparison results in a network of 100 sensor nodes.

scenarios of one, three, and five base stations. To solve the ILP, we use *lp_solve* 5.5 [10] with a timeout of 20 minutes. Fig. 4 shows the simulation results in a network of 50 sensor nodes randomly deployed in a 1000 m^2 field. Fig. 5 shows the simulation results in a network of 100 sensor nodes randomly deployed in a 2000 m^2 field. Both figures show a comparison between our approach (i.e, Mobile) and the random, static approach (i.e., Static) in terms of the number of rounds until the first node dies. It is obvious that the lifetime of our approach is almost twice as long as that of the static approach. Using different values for the ILP solver timeout, different sensor densities, and different number of base stations have shown similar trends.

In an extended version of this paper [11], we compare these approaches in terms of the number of rounds until a particular proportion (e.g., 50%) of the sensor nodes die, and we study the behavior of different objective functions (e.g., minimizing the maximum energy consumption over all nodes).

5 Conclusion

In this paper, we address the problem of unbalanced energy expenditure in WSN's resulting from multi-hop communication. To alleviate the effect of this problem, we argue for using multiple, mobile base stations, and propose a scheme for finding near-optimal placement of mobile base stations together with the routing patterns to deliver data to base stations. The novelty of our approach stems from solving a general problem in which a base station can be located anywhere in the sensing field and from finding a complete, discrete search space for base station locations. We use a novel objective function that takes into account both the current residual energy and future energy expenditure of each sensor node. Simulation results show that our approach has the potential to double the lifetime of a WSN as compared to a static approach.

We are currently extending our approach to a WSN where base stations can be placed along tracks (i.e., roads) spanning the sensing field [11]. This would be practical in a situation where base stations are carried on unmanned vehicles or robots that move along paved roads only.

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