Sensor Placement for Lifetime Maximization in Monitoring Oil Pipelines*

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ABSTRACT

Wireless sensor networks (WSNs) have been widely deployed and it is crucial to properly control the energy consumption of the sensor nodes to achieve the maximum WSNs' operation time (i.e., *lifetime*) as they are normally battery powered. In this paper, for sensor nodes that are utilized to monitor oil pipelines, we study the *linear sensor placement problem* with the goal of maximizing their lifetime. For a simple *equal-distance* placement scheme, we first illustrate that the result based on the widely used ideal power model can be misleading (i.e., adding more sensor nodes can improve WSN's lifetime) when compared to that of a realistic power model derived from Tmote Sky sensors. Then, we study *equal-power* placement schemes and formulate the problem as a MILP (mixed integer linear programming) problem. In addition, two efficient placement heuristics are proposed. The evaluation results show that, even with the Tmote power model, the equal-power placement schemes can improve the WSN's lifetime by up to 29% with properly selected number of sensor nodes, the distance between them and the corresponding transmission power levels. Moreover, one heuristic scheme actually obtains almost the same results as that of MILP, which is optimal. The real deployment in one oil field is also discussed.

Categories and Subject Descriptors

D.4.8 [**Operating Systems**]: Performance—*Modeling and prediction, Operational analysis*; I.6.4 [**Simulation and Modeling**]: Model Validation and Analysis

General Terms

Algorithms; Performance

Keywords

WSN, linear sensor placement, energy management, operation lifetime, oil pipeline;

1. INTRODUCTION

The advancements in wireless sensor networks (WSNs) in recent years make it possible to deploy them in many real-life applications, such as animal habitat study [11], environment/ecology monitoring [18] and railway bridge monitoring [3]. Moreover, with close integration of such WSNs into surrounding physical systems, we have reached an era with various *cyber-physical systems* (such as smart energy efficient buildings [16] and intelligent cars [21]).

The main problem in WSNs is how to efficiently collect and deliver the sensor (and/or pre-processed) data to a base-station, which normally has more computation power for further analysis. Note that, wireless sensor nodes are generally small in size with limited communication range that depends on the transmission power. In addition, sensor nodes normally operate on a small capacity battery. Considering the difficulty (if not impossible) of replacing the battery after deploying the sensor nodes, it is crucial to properly manage their energy consumption to achieve the maximum operation time (i.e., *lifetime*) for WSNs.

In general, the data collection/aggregation in WSNs is achieved through *multi-hop data forwarding* schemes [1]. In these schemes, for the sensor nodes that are far away and can not reach the base station in a single hop, their data will be relayed by their neighbors that are closer to the base station. However, the increased transmission activities could quickly deplete the energy of such near-by sensor nodes and limit the lifetime of WSNs [13]. To address this problem, we can deploy more sensors close to the base-station and make them transmit at lower power levels [13] or adopt duty cycle scheduling approaches [19] to extend their operation time. In addition, the mobility of base stations can also be exploited, where the base station moves around in the field to collect data from sensor nodes [2, 5]. For the cases where the base station are not moveable, energy efficient

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data collection schemes that exploit mobile elements, which can move around the deployed field and convey the data from each sensor node to the base station, have been studied as well [7, 10, 20, 22, 23, 24].

In this paper, focusing on WSNs that are used to monitor oil pipelines [8, 12], we study the *linear sensor placement problem* with the goal of maximizing the lifetime of WSNs. As a cost effective approach for oil delivery, oil pipelines have been built in many places. However, to ensure oil flow through the pipelines freely, the pressure and temperature along the pipelines need to be maintained within a certain range. If the temperature is too low, oil could clot and even cause pipeline broken, which can be a disaster for the environment. For oil pipelines in cold regions, *heat stations* are built along the pipelines (as shown in Figure 1) to ensure the required temperature for oil flowing through pipelines. In such a case, it is essential to monitor the temperature and pressure along the oil pipelines for the heat stations to provide *proper* heating (and thus reduce heating cost).

Wireless sensor nodes have be exploited to collect the required temperature and pressure data and, in general, such data will be delivered through multi-hop forwarding schemes [8]. The linear sensor deployment problem has been addressed in several recent studies [6, 12, 14], and the solutions could be applied to other real-life applications as well, such as railway bridge monitoring [3], highway traffic monitoring and border control. In one recent study [9], for a given number of available sensor nodes, Liu and Mohapatra investigated the problem of how to optimally deploy the sensor nodes along a linear segment with given length to maximize the WSN's lifetime. Based on an ideal continuous power model for sensor nodes, their results show that a greedy *equal-power* heuristic can improve the lifetime of WSNs around 2.4 times, when compared to that of the *equal-distance* scheme.

Different from most of the existing work that builds on the widely used ideal power model, which can lead to misleading results, in this paper, we study the effects of a realistic power-distance model derived from Tmote Sky sensors. When sensor nodes are uniformly distributed (i.e., with the equal-distance scheme), we first show that the maximum lifetime is obtained with the smallest number of sensor nodes that are needed to cover the desired pipeline length (where all nodes operate at the highest power level). Adding more sensor nodes actually leads to reduced lifetime as the most energy hungry node (i.e., the one next to the base station) consumes more power to forward the additional data packets even when it can operate at lower power levels.

Then, following the same idea as in [9], we study *equal-power* placement schemes, which intend to balance the energy consumption among the sensor nodes to improve the WSN's lifetime. We formulate the problem with discrete power model of sensor nodes as a *mixed integer linear programming (MILP)* problem. In addition, for a given number of sensor nodes and a desired length of a pipeline to cover, we propose two efficient heuristic schemes to find the power level for each sensor node to maximize the WSN's lifetime. The evaluation results show that the proposed equal-power schemes can improve the WSN's lifetime significantly (up to 29%) with properly selected number of sensor nodes, the distance between them and corresponding transmission power levels, even with the realistic Tmote power model.

The remainder of the paper is organized as follows. Section 2 presents the system model and our assumptions. The equal-distance placement scheme is presented and evaluated with both an ideal power model and the Tmote power model in Section 3. Section 4 presents the equal-power MILP formulation and two heuristic schemes. Evaluation results are presented and one real deployment in an oil field is discussed in Section 5. Section 6 concludes the paper and points out our future work.

2. SYSTEM MODEL AND PROBLEM DESCRIPTION

For oil pipeline monitoring with WSNs, We assume that each heat station will have a base station to collect the sensor temperature and pressure data. The temperature information can be used by the controller of the heater for proper heating and pressure data can be further transmitted to a control center through other network means (such as linked infrastructure or cellular communication). Therefore, in this paper, we focus on a pipeline segment between two adjacent heat stations, which runs from a few kilometers to tens of kilometers. For simplicity, we assume that sensor nodes on a pipeline segment only need to transmit their sensor data to one base station (e.g., the one located in the upstream heat station as shown in Figure 1) and the sensor data is collected through a multi-hop forwarding scheme.

That is, we consider a WSN consisting of n sensor nodes $\{N_1, ..., N_n\}$, which is used to monitor an oil pipeline segment of length L. Here, the oil pipeline segment is assumed to be a straight line. The closest sensor node to the base station is N_n and node N_1 is the furthest one. We further assume that sensor nodes forward the sensor data one by one to the base station as shown in Figure 1. That is, node N_1 sends its data to node N_2, and N_2 sends its own data as well as the relayed data to node N_3 and so on without interweaving transmission among the nodes.

Note that, in WSNs, the transmission range of a sensor node directly depends on its transmission power. Suppose that the distance between two sensor nodes is d, the required transmission power can be modeled as [15]:

$$P(d) = \gamma + \alpha d^{\beta} \tag{1}$$

where γ and α are system dependent parameters and $2 \leq \beta \leq 4$. In general, γ is a small constant. This *ideal power model* (represented by Equation 1) has been widely adopted to study various theoretical aspects of WSNs [9, 13, 20, 22].

Note that most modern sensor nodes cannot adjust their transmission power continuously and normally have only a few discrete power levels, which enable them to transmit data for different distances [4, 17]. In this paper, we assume that the sensor nodes under consideration have m different power levels, which are represented as m couples: (P_1, R_1), ..., (P_m, R_m), where R_i is the transmission range[1] when sensor nodes transmit at power level P_i. Here, the maximum transmission power level $P^{max} = P_m$ limits the maximum transmission range to be $R^{max} = R_m$. Similarly, at the minimum power level $P^{min} = P_1$, the sensor nodes can transmit data up to the range of $R^{min} = R_1$.

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[1] Instead of using the maximum transmission range under a given power level, which may lead to excessive packet drops, we can adopt R_i to be the range that can ensure reliable packet delivery under the power level P_i.

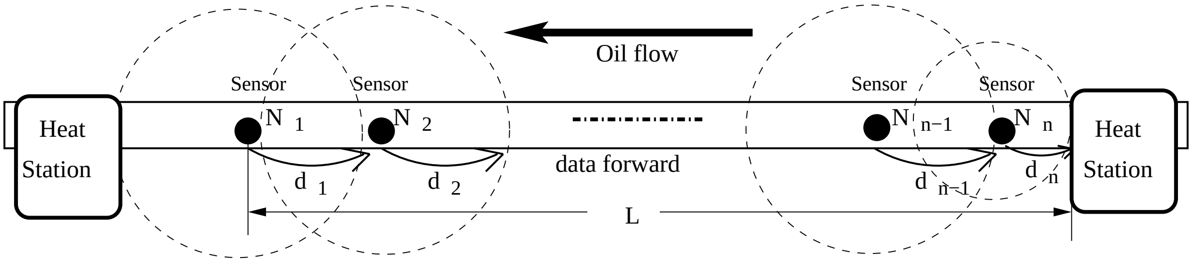


Figure 1: Monitor oil pipelines with sensors.

Therefore, to cover the oil pipeline segment of length L, the minimum number of sensor nodes needed in the WSN is $n_{min} = \lceil L/R^{max} \rceil$, where all sensor nodes need to transmit the data at the highest power level $P^{max} = P_m$. Intuitively, when more sensor nodes are available, the distance between adjacent nodes becomes smaller, which may allow some sensor nodes transmit data at lower power levels and thus increase the WSN's lifetime.

However, adding more sensor nodes also results in additional data to be transmitted, which in turns consumes more energy in the sensor nodes, especially for the ones that are close to the base station. Moreover, when all sensor nodes can transmit at the lowest power level $P^{min} = P_1$, the maximum number of sensor nodes should be deployed in the WSN will be $n_{max} = \lceil L/R^{min} \rceil$. We should not deploy more than n_{max} sensor nodes as doing so will only impair the WSN's lifetime.

The sensor nodes are assumed to have the same sensoring rate and, for each round of data collection, the amount of sensor data at each sensor node is the same, which needs time t to transmit. That is, for the node N_i that also needs to relay the data from all its predecessors, it will take time $i \cdot t$ to transmit all data to the next node N_{i+1}. Suppose that the distance between nodes N_i and N_{i+1} is d_i ($i = n, ..., 1$ and N_{n+1} is assumed to be the base station) and the required corresponding transmission power for the node N_i is $P(d_i)$. That is, the amount energy needed for the node N_i to relay and transmit all the data will be $E_i = P(d_i) \cdot i \cdot t$.

Define the *critical sensor node* as the one consumes the most energy during one round of data collection. The lifetime of a WSN will be determined by its critical sensor node. To obtain the maximum lifetime of the WSN, we need to find out the optimal number of sensor nodes n ($\geq n_{min}$), the transmission distance d_i and corresponding power level $P(d_i)$ for each sensor node N_i ($i = 1, \ldots, n$), such that the energy consumption of the critical sensor node is minimized. That is, our objective is to find n and d_i to

$$minimize\{\max\{E_i | i = 1, \ldots, n\}\}$$

subject to

$$d_i \leq R^{max} \tag{2}$$

$$\sum_{i}^{n} d_i \geq L \tag{3}$$

where the first condition states the transmission constraint of each node and the second one ensures the WSN can cover the oil pipeline segment under consideration.

3. EQUAL-DISTANCE SENSOR PLACEMENT

The simplest scheme is to distribute the sensor nodes along the oil pipeline uniformly with equal distance between adjacent nodes, where $d_i = d = L/n$. Note that, under equal-distance placement scheme, all nodes will transmit data at the same power level. However, as the node N_n that is the closest to the base station needs to forward all data to the base station, it will always consume the most energy and become the *critical sensor node*.

As mentioned early, when there are only $n = n_{min}$ sensor nodes, every sensor node needs to transmit data at the highest power level P^{max} and the energy consumption at node N_n will be $E_n = P^{max} \cdot n \cdot t$ for one round of data collection. Suppose that sensor data is collected every T time units (e.g., 5 minutes in our real deployment as discussed in Section 5), the *baseline* lifetime can be calculated as $LT_{based} = \frac{E_{budget}}{E_n} T$, where E_{budget} is the initial energy capacity of the battery that is assumed to be the same for all sensor nodes.

Table 1: Transmission Power and Range for Tmote Sky Sensors [17].

Levels	1	2	3	4	5	6
R_i (meters)	5.49	15.85	39.01	60.96	71.02	87.48
P_i (mW)	33.1	39.6	45.0	51.1	57.2	61.9

3.1 Ideal Power Model

In what follows, we illustrate how the WSN's lifetime is affected by the number of sensor nodes with different power models under the equal-power placement scheme. First, we consider the ideal power model with 6 different power levels. For comparison, we assume the same transmission ranges as those of the Tmote power model as shown in Table 1 and the transmission power at each level is given by Equation 1 with $\gamma = 0, \alpha = 0.0081$ and $\beta = 2$.

For the cases with $L = 5000m$ and $L = 15000m$, Figure 2 shows the normalized lifetime (with LT_{base} being used as the baseline) when different number of sensor nodes are utilized. Note that, with $R^{max} = R_6 = 87.48m$, the values of n_{min} are different for $L = 5000m$ and $L = 15000m$, which are 58 and 172, respectively. From the figure, we can see that as the number of sensor nodes increases and sensor nodes can transmit at the next lower power level, the WSN's lifetime can be improved significantly (the spikes in the figure). However, if the increased number of sensor nodes are not enough for them to transmit at a lower power level, the WSN's lifetime decreases gradually (between two spikes) as

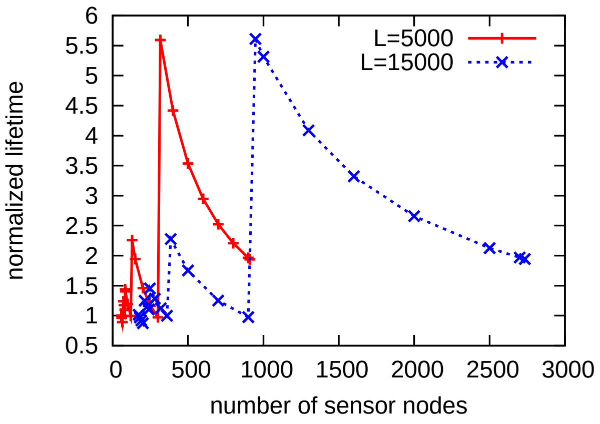


Figure 2: Normalized WSN lifetime under equal-distance placement with the ideal power model.

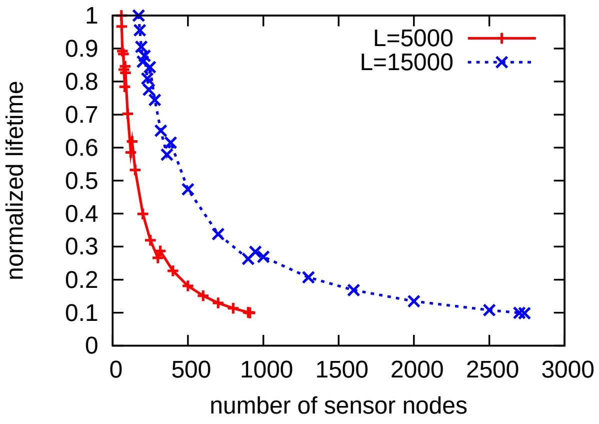


Figure 3: Normalized WSN lifetime under equal distance placement with Tmote power model.

expected. When the number of sensor nodes is just enough for them to operate at the second lowest power level, the WSN's lifetime can be improved to 5.5 times of the baseline. When n_{max} sensor nodes are deployed, the lifetime can be improved by more than 16 times, which is not shown in the figure.

3.2 Tmote Power Model

In this section, we examine the equal-distance placement scheme with a more realistic Tmote power model. It has been reported that there are 32 different power levels for Tmote Sky sensors, however, we found that some power levels are not really useful (e.g., with indistinguishable transmission distance). In this paper, we consider only 6 levels as shown in Table 1. Here, the transmission range R_i are measured values, and the corresponding power values are obtained from the datasheet of Tmote Sky sensors [17].

For the same cases with $L = 5000m$ and $L = 15000m$, Figure 3 shows the normalized lifetime with different number of sensor nodes. **Surprisingly, the results show that, when compared to that of the baseline, the WSN's lifetime becomes shorter as more sensor nodes are available even if the sensor nodes can transmit at lower power levels.** The reasons come from the fact that the relation between transmission power and distance for Tmote power model is sub-linear instead of being quadratically/cubically related as in the ideal power model (represented by Equation 1). Hence, the energy saving obtained for the critical sensor node N_n operating at lower power levels is overshadowed by the additional energy consumption needed to transmit more sensor data.

Therefore, different from the conclusion obtained with the ideal power model, for the more realistic Tmote power model, the maximum lifetime is obtained when the minimum number of sensor nodes are deployed and adding more sensor nodes can not improve the WSN's lifetime under the equal-distance placement scheme.

4. EQUAL-POWER SENSOR PLACEMENT

Instead of having all sensor nodes transmit the same distance, better WSN lifetime can be obtained if the energy consumption at each sensor node is balanced [13]. Following this idea, an equal-power greedy heuristic scheme has been studied by Liu and Mohapatra in [9], where the sensor nodes are *unevenly* distributed along the oil pipeline. That is, for sensor nodes that are closer to the base station and need to relay/transmit more data, a shorter transmission distance is assigned which allows the sensor nodes to transmit at a lower power level, while the sensor nodes that are far away from the base station can transmit longer distance to cover the same length of oil pipeline. Assuming the continuous ideal power model, [9] concludes that the equal-power scheme can improve the WSN lifetime around 2.4 times when compared to that of the equal-distance scheme.

In this section, focusing on a *discrete and more realistic* Tmote power model, we first formulate the problem with a given number of sensor node as a MILP (mixed integer linear programming) problem. Then, based on the energy consumption characteristics of the sensor nodes in the optimal solution, we propose two efficient heuristic schemes to obtain the approximate solutions, which turn out to be very close to the optimal solution obtained from MILP.

4.1 MILP Formulation

For each sensor node N_i, define m binary variables $\{x_{i1}$, ..., x_{ij}, ..., $x_{im}\}$, which denote the assignment of power level (and the corresponding transmission distance) for N_i. That is

$$\sum_{j=1}^{m} x_{ij} = 1 \tag{4}$$

$$d_i = \sum_{j=1}^{m} x_{ij} \cdot R_j \tag{5}$$

The energy consumption for node N_i can be expressed as

$$E_i = i \cdot t \cdot \left(\sum_{j=1}^{m} x_{ij} \cdot P_j \right) \tag{6}$$

In order to maximize the lifetime of the WSN, we need to minimize the energy consumption of the critical sensor node that consumes the most energy. Define $E^{max} = \max\{E_i | i =$

$1, \cdots, n\}$. That is, our object is to

$$\min\ \{E^{max}\} \tag{7}$$

subject to the following constraints:

$$\sum_{i=1}^{n} d_i \geq L \tag{8}$$

where L is the length of the oil pipeline to be covered and d_i is given in Equation (5).

With Equations (4) to (8), we have formulated a *MILP* problem with $n*m$ variables, which can be solved by existing MILP solver to obtain the optimal WSN's lifetime for a given number of sensor nodes. By varying the number of sensor nodes n, we can find out the optimal number of sensor nodes that give the maximum lifetime for the WSN.

4.2 Efficient Greedy Heuristic Schemes

As we mentioned before, to balance the energy consumption among the sensor nodes, the nodes closer to the base station should transmit data at lower power levels. Suppose that node N_i is assigned power level x_i $(1 \leq x_i \leq m)$ with transmission distance R_{x_i} in the optimal solution for a WSN with n sensor nodes. In what follows, we first formally show that, for two nodes N_i and N_j where $i < j$ (i.e., N_j is more close to the base station), there is $x_i \geq x_j$. Then, two efficient greedy heuristic schemes will be presented.

THEOREM 1. *To maximize the lifetime of the WSN, for the sensor nodes N_i and N_j, the power level assignment should satisfy $x_i \geq x_j$ for $i < j$.*

Proof: By contradiction. Assume that there is $x_i < x_j$ for nodes N_i and N_j $(i < j)$ as shown in Figure 4. The energy consumption of nodes N_i and N_j will be $E_i = i \cdot P_{x_i} \cdot t$ and $E_j = j \cdot P_{x_j} \cdot t$, respectively. We will have $\max\{E_i, E_j\} = E_j$. Suppose that N_j is the critical sensor node that consumes the most energy.

If we switch the power level assignment (and their transmission distance) for nodes N_i and N_j as shown in Figure 5, the covered length of oil pipeline does not change. The new energy consumption for these two nodes will be $E_i' = i \cdot P_{x_j} \cdot t$ and $E_j' = j \cdot P_{x_i} \cdot t$, respectively. Note that, there are $E_i' < E_j$ and $E_j' < E_j$. Since the energy consumption for other nodes does not change, the energy consumption for the critical sensor node after switching the assignment should be less than E_j. That is, better lifetime can be obtain, which contradicts with the assumption that the original assignment is optimal. This concludes the proof. ■

DEFINITION 1. *Let $V =< c_1, \ldots, c_m >$ denote the vector of the number of sensor nodes in each power level. That is, there are c_i sensor nodes with power level i.*

Therefore, from Theorem 1 and the above definition, a power and distance assignment solution to the equal-power problem can be represented by a vector V, where the first c_1 sensor nodes have the lowest power level P_1, and the next c_2 nodes take the next power level P_2 and so on. Moreover, there is $\sum_{i=1}^{m} c_i = n$.

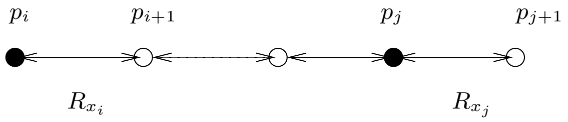


Figure 4: Original power level assignment

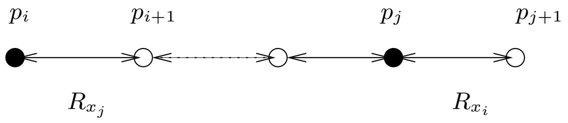


Figure 5: Switched power level assignment

THEOREM 2. *For a power level assignment of the sensor nodes represented by a vector $V =< c_1, \ldots, c_m >$, the maximum energy consumption by the critical sensor node can be found as*

$$E^{max} = \max_{j, c_j \neq 0} \left\{ P_j \cdot t \cdot \sum_{i=j}^{m} c_i \right\}$$

Similarly, the minimum energy consumption of any sensor nodes with power level less than m can be found as

$$E^{min} = \min_{j, c_j \neq 0} \left\{ P_j \cdot t \cdot (1 + \sum_{i=j+1}^{m} c_i) \right\}$$

Basically, Theorem 2 says that: a) among the sensor nodes that have the same power level, the one that is nearest to the base station consumes the most energy and the critical sensor node should be the one of such nodes; and b) when looking for the node consumes the least amount of energy, we should focus on, for those having the same power levels, the one that is the most far away from the base station. Based on the above theorem, we propose in what follows two efficient heuristics for equal-power placement with a given number of sensor nodes.

4.2.1 Expansion: From Low to High Power Levels

For the first heuristic scheme, we begin with assigning all sensor nodes to transmit at the lowest power level P_1. That is, the initial assignment vector is $V =< n, 0, \ldots, 0 >$. If $n \cdot R_1 \geq L$, there are enough sensor nodes and the initial assignment will be the optimal one. Otherwise, if $n \cdot R_1 < L$, we need to expand the coverage and increase the transmission range and power level for some nodes. For such purpose, we will iteratively search for the sensor node that consumes the minimum amount of energy and increase its power level by one, until the coverage length is no less than L. We denote this approach as the *expansion (from low to high: L-to-H)* heuristic scheme.

Note that it may happen that, during the iteration, the node which has the minimum energy consumption is already in power level m and cannot increase its power level anymore. Therefore, when finding the node consumes the minimum amount of energy to increase its power level, we consider only the sensor nodes with power level being less than m. The outline for this scheme is shown in Algorithm 1.

First, if the sensor nodes are not enough to cover the desired length L, the algorithm fails and exits (lines 3 to 5). Otherwise, we initialize the power level assignment vector V such that all sensor nodes transmit at the lowest power

Algorithm 1 : Expansion L-to-H Heuristic Algorithm

```
1:  Input: $n$, $L$, and $(P_j, R_j)$ with $j = 1, \ldots, m$;
2:  Output: power level assignment vector $V$;
3:  if $(n \cdot R_m < L)$ then
4:      exit: the input parameters are not feasible;
5:  end if
6:  Initialize $V =< n, 0, \ldots, 0 >$;
7:  while $(\sum_{i=1}^{m}(c_i \cdot R_i) < L)$ do
8:      $E^{min} = n \cdot t \cdot P^{max}$;
9:      for $(i = 1$ to $m - 1)$ do
10:         $E_{tmp} = P_i \cdot t \cdot (1 + \sum_{j=i+1}^{m} c_j)$;
11:         if $(c_i \neq 0$ and $E_{tmp} \leq E^{min})$ then
12:             $E^{min} = E_{tmp}$; $x = i$;
13:         end if
14:     end for
15:     Update assignment vector: $c_x - = 1$; $c_{x+1} + = 1$;
16: end while
```

level P_1 (line 6). If the current power level assignment cannot cover the desired length L, appropriate sensor node will be selected to increase its power level (lines 8 to 15). Note that, to find the sensor node that consumes the minimum amount of energy, for the nodes with the same power level, only the one that is the most far away from the base station is considered (line 10; based on Theorem 2), which makes the algorithm more efficient. When the while-loop exits, the vector V will contain the power level assignment information.

When the number of sensor nodes $n = n_{min}$, all sensor nodes need to increase their power level to P_m in the worst case. As sensor nodes increase their power level by only one at a time and only one node will increase its power level during one iteration, the maximum number of iterations for the while-loop will be $n \cdot m$. Together with the inner for-loop (which takes m steps), we can see that the overall complexity of Algorithm 1 will be $\mathbf{O}(nm^2)$.

4.2.2 Contraction: From High-to-Low Power Levels

Instead of assigning all sensor nodes the lowest power level P_1 at the very beginning, following an opposite direction, the second heuristic scheme starts with assigning the highest power level P_m for all sensor nodes. That is, the initial assignment vector is $V =< 0, \ldots, 0, n >$.

While the coverage of the sensor nodes is larger than the length of pipeline L, we can decrease the power level of the critical sensor node that consumes the most energy until no further improvement to the lifetime can be obtained. That is, decreasing the power level for the critical sensor node will lead to a coverage being less than L, or all sensor nodes already operate at the lowest power level. This approach is denoted as the *contraction (from high to low: H-to-L)* heuristic scheme.

The outline for the contraction heuristic scheme is shown in Algorithm 2. The steps are similar to those in Algorithm 1 except that we try to find the critical sensor node (lines 8 to 13) and reduce its power level. Note that, it is possible that the critical sensor node already has the lowest power level and no more contraction can help to improve the WSN's lifetime. Similarly, where there are n_{max} sensor nodes, it is possible that all sensor nodes can go down the lowest power level and the complexity of the algorithm is the same as Algorithm 1.

Algorithm 2 : Contraction: H-to-L Heuristic Algorithm

```
1:  Input: $n$, $L$, and $(P_j, R_j)$ with $j = 1, \ldots, m$;
2:  Output: power level assignment vector $V$;
3:  if $(n \cdot R_m < L)$ then
4:      exit: the input parameters are not feasible;
5:  end if
6:  Initialize $V =< 0, \ldots, 0, n >$;
7:  while $(\sum_{i=1}^{m}(c_i \cdot R_i) > L)$ do
8:      $E^{max} = n \cdot t \cdot P^{min}$;
9:      for $(i = 1$ to $m)$ do
10:         $E_{tmp} = P_i \cdot t \cdot (\sum_{j=i}^{m} c_j)$;
11:         if $(c_i \neq 0$ and $E_{tmp} \geq E^{max})$ then
12:             $E^{max} = E_{tmp}$; $x = i$;
13:         end if
14:     end for
15:     if $(x == 1$ or $\sum_{i=1}^{m}(c_i \cdot R_i) < L + (R_x - R_{x-1}))$ then
16:         break; //no more contraction is needed;
17:     else
18:         Update assignment vector: $c_x - = 1$; $c_{x-1} + = 1$;
19:     end if
20: end while
```

5. EVALUATIONS AND DISCUSSIONS

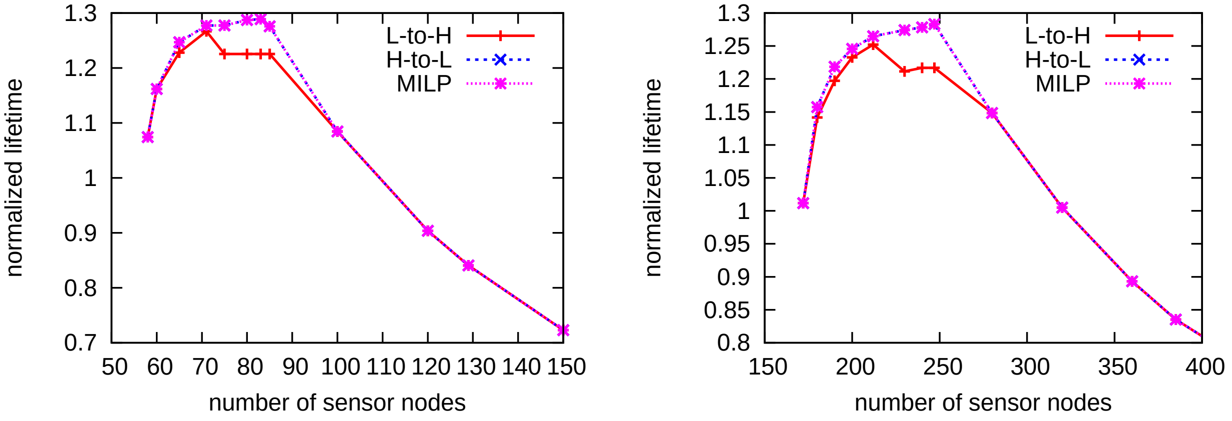
A MILP solver has been exploited to obtain the optimal solution for the equal-power placement problem. In what follows, compared to the optimal solution, we first evaluate the performance of the proposed equal-power placement heuristic schemes on improving the WSN's lifetime. Then, we describe one sensor that has been implemented for monitoring oil pipelines and the real deployment of the sensors in one oil field.

5.1 Performance of Equal-Power Schemes

Based on the Tmote power model as shown in Table 1, Figure 6 shows the normalized lifetime of the WSN under the equal-power schemes for different number of sensor nodes. Similar to Section 3, the lifetime for the WSN with n_{min} sensor nodes is used as the baseline. From the results, we can see that, the equal-power heuristic schemes can improve the WSN's lifetime with more than n_{min} sensor nodes, even with the Tmote power model. When appropriate number of sensor nodes are adopted, the WSN's lifetime can be improved by up to 29%.

However, if excessive number of sensor nodes are deployed (more than 100 nodes for $L = 5000m$ and 300 nodes for $L = 15000m$), the WSN's lifetime reduces significantly even with the equal-power placement schemes due to more energy being consumed in the critical sensor node to transmit the additional data. Therefore, more sensor nodes may not always be able to help improve WSN's lifetime and it is important to choose the appropriate number of sensor nodes to achieve the maximum lifetime of the WSN. For the cases considered, the best number of sensor nodes is about $1.5n_{min}$, which depends directly on the power model and the pipeline length considered.

Moreover, the results also show that the contraction heuristic scheme (denoted as H-to-L) performs almost the same as the optimal MILP solution, while the expansion heuristic scheme (denoted as L-to-H) performs slightly worse. This can be explained that the contraction scheme aims at minimizing the energy consumption for the node that consumes



(a) $L = 5000m$ (b) $L = 15000m$

Figure 6: Normalized lifetime for equal-power heuristic schemes and MILP.

the most energy. However, instead of minimizing the energy consumption of the most energy hungry node, the expansion scheme follows a different direction by choosing the node that consumes the minimum energy and increasing its power level. Such power level increase may lead to energy consumption jump and make the node to be the critical sensor node, where such conversion is not revertible in the expansion scheme.

5.2 Implementations and Real Deployment

Figure 7: The real implemented sensor.

We have designed and implemented one sensor for monitoring oil pipelines as shown in Figure 7. The sensor adopts a low power MCU MSP430 and the TI CC1101 transceiver chip, which is different from the one (CC2420) on Tmote sensors but has similar relation between its transmission power and range. With the added amplifier and external antenna, the maximum transmission distance of this sensor can reach 2.5 kilometers. Currently, a set of such sensor nodes have been installed on one pipeline following the uniform distribution (i.e., the equal-distance approach) in Liaohe oil field in China.

All sensor nodes are set to transmit at the highest power level. The temperature and pressure data is collected every 5 minutes and nodes go to sleep mode for energy conservation after each round of data collection. The sensor is powered by a battery with capacity of $2000mAh$. For a set of 10 sensors, we have performed accelerated experiments (i.e., with much smaller time interval for each round of data collection), which imply that the WSN can operate for up to 2 years under normal situation.

6. CONCLUSIONS AND FUTURE WORK

In this paper, we study the sensor placement problem to maximize the WSN's lifetime when the sensor nodes are utilized to monitor oil pipelines. We first illustrate that the widely used ideal power model for sensor nodes can lead to *misleading* results for a simple *equal-distance* placement scheme. Based on a power model derived from Tmote Sky sensors, we show that the best lifetime can be achieved when only the minimum number of sensor nodes are deployed and adding more sensor nodes will actually result in reduced lifetime under the equal-distance placement scheme.

Then, we study *equal-power* placement schemes, which intend to balance the energy consumption among the sensor nodes through uneven distribution of them along the pipeline. We formulate the problem as a MILP (mixed integer linear programming) problem and propose two efficient equal-power placement heuristics based on energy characteristics of the optimal solution. The evaluation results show that, even with the Tmote power model, the equal-power placement schemes can improve the WSN's lifetime by up to 29% with properly selected number of sensor nodes. Moreover, the contraction heuristic scheme actually obtains almost the same results as that of MILP, which is optimal.

For our future work, we plan to adopt the equal-power placement for sensor nodes in real deployment and measure the actual improvement for the WSN's lifetime. Moreover, instead of sequentially forwarding the data, we will study the multi-hop scheme with interleaved data forwarding.

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