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Mihiro Sasaki [a], Takehiro Furuta [b], Fumio Ishizaki [c], Atsuo Suzuki [a]

Abstract

One of the important issues in wireless sensor networks is how to save power consumption and extend the network lifetime. For this purpose, various network topology construction algorithms have been studied. However, most of them are based on a myopic method, where the topology construction is carried out round-by-round. To address this issue, we take the energy dissipation of sensor nodes over multiple rounds into account, and we consider the problem as a multi-dimensional knapsack problem, which enable us to find optimal network topologies until at least one sensor node exhausts its battery power. We also propose a solution method to maximize the network lifetime. The computational experiments show that the proposed approach provides efficient topology construction in the wireless sensor network in terms of network lifetime compared to the cluster-based approach.

1 Introduction

Wireless sensor networks have been paid much attention due to recent rapid advances of wireless technology combined with prospects of their future progress in scientific, medical, commercial, military area and so on. A wireless sensor network is formed by tens to thousands sensor nodes randomly deployed in a target area, which is called a sensor field. Using wireless sensor networks, we can easily collect information monitored by sensor nodes at the remote base station (BS) without checking each sensor node one by one. In addition, wireless sensor networks make it possible to monitor events even in a field where people cannot get in.

Various network architectures and protocols have been studied so far. (e.g., see [6] and references therein). These network architectures can be classified into two classes. One is based on a distributed network, where each sensor node makes decisions for itself with locally collected information. The other is based on a centralized network, where the BS organizes the network and controls all sensors' activities.

Throughout this paper, we focus on a topology construction problem arise in the centralized sensor networks. Main advantage of the centralized network is that the BS can collect global information about whole network and sensor nodes, which implies the BS may find better topology construction in order to save power consumption of sensor nodes. Moreover, sensor nodes do not expend their power for topology construction under the centralized network because the BS which has no power limitation is charged with doing all computing. From these reasons, the centralized network can be regarded as a good alternative if a good topology construction can be established.

[a]Department of Information Systems and Mathematical Sciences, Nanzan University
[b]Department of Management Science, Tokyo University of Science
[c]Department of Information and Telecommunication Engineering, Nanzan University

One of crucial challenges in the organization of sensor networks is energy efficiency, because battery capacities of sensor nodes are severely limited and replacing the batteries is not practical. Once all sensor nodes drain their batteries, the sensor network doesn't work anymore. Since sensor nodes expend a large amount of energy during the data transmission, the transmission distance is a critical factor to save power consumption. The transmission distance is largely depends on network topology. Therefore, an efficient network topology is required to save power consumption.

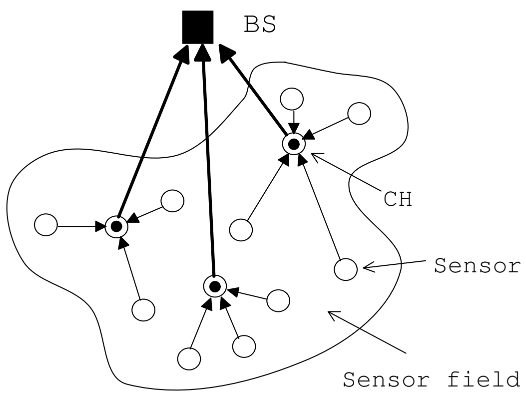
Various topology construction in sensor networks have been studied in order to save power consumption and extend the network lifetime [5, 6]. Among them, cluster-based network organization (see Figure 1(a)) is considered as the most favorable approach in terms of energy efficiency. In this approach, sensor nodes are organized into clusters, and one sensor node in each cluster is selected as cluster head (CH) to play a special role as transfer point. Moreover, each CH creates a schedule for the sensor nodes within the cluster, which allows the radio components of each non-CH-node to be turned off all times except during its transmit time. The rotation of CHs is also important factor in the cluster-based sensor networks. Since the BS is generally far away from the sensor field, CHs expend much amount of power for data transmission. Hence, CHs will die quickly if the same node continuously works as a CH. As a result, it is required to introduce the rotation of CHs among sensor nodes to find efficient clustering or topology construction in order not to drain the battery power of a single sensor.

One of the primal studies on cluster-based network organization is LEACH-C (Low Energy Adaptive Clustering Hierarchy Centralized) [4], which is considered as a centralized version of LEACH [3]. LEACH-C is more efficient than LEACH in terms of energy efficiency as the computational results reported in [4] show. Moreover, Furuta et al [1, 2] pointed out the drawbacks of LEACH-C and proposed a new clustering approach in which they overcame the drawbacks and further extended the network lifetime.

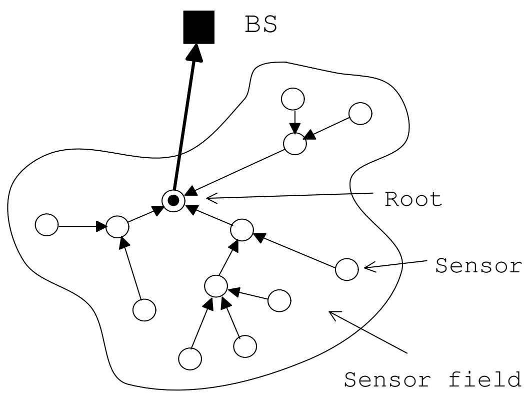
Topology construction algorithms proposed in LEACH-C [4] and its improved method [1] are designed based on a myopic view. More precisely, they construct a single topology using the information about current battery level distribution, and repeat the topology construction for every data transmission. The objective in each topology construction is to maximize the total amount of battery power of sensors to be remained after the next data transmission.

Repeating a myopic method may fail to find a good solution after all. To address this issue, we propose a multi-round topology construction method, where we take into account continual changing battery level distribution as well as current distribution in order to find better topologies over multiple data transmissions at a time.

The remainder of this paper is organized as follows. In Section 2, we briefly describe our model and explain a multi-round topology construction arises in the centralized wireless sensor networks. In Section 3, we formulate the multi-round topology construction problem as a multi-



(a) Cluster-based sensor network



(b) Tree-based sensor network

Figure 1: Wireless Sensor Networks

dimensional knapsack problem. We also address a problem to find topology construction to maximize the network lifetime, and propose a solution method. In Section 4, we show the computational results. Finally, we give concluding remarks and mention future works in Section 5.

2 Model description

We consider the following centralized sensor network. The BS is located far from the sensor field. Each sensor node monitors events and transmits the data to the BS through the network simultaneously. The data monitored by a sensor node is transmitted in a small packet of a fixed size. If a sensor node receives data from several sensor nodes, data aggregation process can be carried out by the sensor, then the resultant data is transmitted from the sensor. These operations are continued until all sensor nodes die, i.e. drain their own batteries. Each sensor node has a small battery, however, its capacity is severely limited and replacing the battery is not possible. Since the data monitored by sensor nodes located closely each other are often correlated or redundant, the BS does not require all data. Data aggregation process removes such redundant data and reduces the size of data to be sent to the BS, which consequently saves the power consumption. Here, we assume the perfect aggregation, where all packets received by a sensor node can be combined into one packet. Hence, each sensor node transmits the same size of data. Sensor nodes expend their own battery power by data reception, data aggregation and data transmission.

The operation of wireless sensor network can be divided into *rounds*. Each round has two phases, which are a set up phase and a data transmission phase. In the set up phase, network topology is constructed. In the data transmission phase, each sensor node monitors events and transmit the data using predetermined network topology. Rounds are repeated to monitor events continuously.

Once a sensor drains its battery, it never monitor events and transmit data. In addition, all sensor nodes drain their batteries, the sensor network doesn't work anymore. As a measure for evaluation of wireless sensor networks, we introduce a network lifetime, which is defined as the number of rounds repeated before all sensor nodes die. An energy efficient network topology will be a strong tool for the centralized wireless sensor networks in terms of network lifetime.

In most of the cluster-based networks, data is transmitted from each sensor node to the BS via a CH (see Figure 1(a)). Thus, the number of hops between each sensor and the BS is at most two. In other words, every data can be transmitted to the BS on a two-level tree. Another possibility is a multi-level tree, where more than two hops may be required to transmit data to the BS (see Figure 1(b)). We call this sensor network as a tree-based sensor network.

In the tree-based sensor network, we assume that there is one special node which is connected to the BS. We call this sensor node as a root. Data monitored by each sensor node should be transmitted to the root through the given tree, then the root finally transmits the data to the BS. A forest composed of several trees can be a candidate. In this case, more than one sensor node should be connected to the BS. However, from our preliminary test to evaluate energy efficiency of both trees and forests, we confirm that trees are more efficient. This may be caused by a large amount of power consumption during the data transmission from the roots to the remote BS. The perfect aggregation may also help trees be more efficient than forests. Thus, we eliminate forests from the candidates.

As we see, more than two hops are required from some sensor nodes to the BS in the tree-based sensor network. As the number of hops increases, power consumption caused by the data reception and aggregation increases while that caused by data transmission decreases. However, since power consumption caused by data transmission is most critical, shorter transmission distances would afford to save power consumption. From these observations, we consider a topology construction problem arise in a tree-based sensor network.

As mentioned in the previous section, wireless sensor networks have been applied in many different settings. One of the common objectives among them is to extend the network lifetime, or perhaps maximize the number of rounds repeated while a certain percentage of sensor nodes is alive. With these objectives, various methods for topology construction have been addressed [5]. Most of them are based on a myopic algorithm, where one topology established by the current battery level distribution. After the current optimal topology is found, battery level distribution is updated in order to find an optimal topology for the next round. Repeating these operations until certain criterion is satisfied, the network lifetime or the number of rounds can be obtained. However, repeating myopic method does not necessarily provide optimal topologies throughout the rounds. On the other hand, in the multi-round topology construction, we take into account continual changing battery level distribution. We may expect to find better topologies over multiple rounds at a time.

Note that a tree should be a spanning tree of all sensor nodes to ensure network connectivity. Once a tree to be used in a round is given, the transmission routes from each sensor node to the BS are uniquely established. Hence, we can compute the power consumption of each sensor node in the round. From these observations, we consider an approach, where we first prepare some candidate trees which consists of a spanning tree and a root, then find out which candidate tree should be used how many rounds in order to maximize the number of rounds. This approach enables to construct optimal topologies for multiple rounds at a time.

3 Formulation and solution method

In the following, we show a mathematical programming formulation of the multi-round topology construction problem. First, we employ the following notations.

N: the index set of sensor nodes,

T: the index set of candidate trees,

b_j: the battery level of sensor node $j \in N$,

c_{ij}: energy dissipation of sensor $j \in N$ when tree $i \in T$ is used.

We further introduce $x_i (i \in T)$ as integer variables, which express the number of rounds using candidate tree $i \in T$. Hence, the multi-round topology construction problem MRTC(N, T) can be formulated as the following multi-dimensional knapsack problem.

[MRTC(N, T)]

$$\text{maximize} \quad \sum_{i \in T} x_i \tag{1}$$

$$\text{s.t.} \quad \sum_{i \in T} c_{ij} x_i \leq b_j, \quad j \in N, \tag{2}$$

$$x_i \in \mathbb{Z}, \quad i \in T.$$

The objective (1) is to maximize the number of rounds. Constraints (2) show that sensor node $j \in N$ cannot expend energy over the battery level b_j.

We further propose a simple algorithm to maximize the network lifetime using MRTC. Note that the optimal objective value of MRTC(N, T) denotes the maximum number of rounds until at least one sensor node among N drains its battery. Some wireless sensor network systems are rather interested in maximizing the network lifetime. In this case, the network lifetime can be computed in the following manner. First, we solve MRTC(N, T) with all sensor nodes set N and associated T, After that, we reconstruct the sensor node set N by removing the dead sensor nodes and remake candidate trees set T to be adjusted to the updated N. With the updated N and T, we solve a MRTC(N, T) again. Repeating these operations until all sensor nodes die, i.e. $N = \emptyset$, we can obtain the network lifetime of the sensor network. We summarize the algorithm to compute the network lifetime as follows.

[**Algorithm for computing the network lifetime**]

(Input) N: the index set of all sensor nodes.

(Output) L: the total number of rounds.

T^*: the set of used trees.

f_i: the number of rounds using tree $t_i^* \in T^*$.

Step 0: (Initialize) Set $k := 1, N_k := N, L := 0$ and $T^* = \emptyset$.

Step 1: (Tree set-up) Create the set of candidate trees T_k for sensor node set N_k. Set $M := |T_k|$. Let $t_k^i (i = 1, \cdots, M)$ denote an element of T_k.

Step 2: (Solve) Find an optimal solution x of MRTC(N_k, T_k) with the optimal value z_k.

Step 3: (Update)

(a) Set $L := L + z_k$ and $i := 1$.

(b) If $x_i > 0$, then update $T^* := T^* \cup t_k^i$ and set $f_i := x_i$. If $i < M$, then set $i := i + 1$. Goto Step 3(b).

(c) Let D be the index set of the dead sensor nodes. Set $k := k + 1$, and $N_k := N_{k-1} \backslash D$. If N_k is not empty, then go to Step 1.

Step 4: (Terminate) L is the network lifetime which is established by using tree $t_i \in T^*$ for f_i rounds $(i = 1, \cdots, |T^*|)$.

This algorithm also can be regarded as a kind of myopic method, because it doesn't necessarily take into account continual change of battery level distribution throughout the network lifetime. However, as far as the authors know, topology construction considering multiple rounds at a time has never addressed. It may be possible to provide better topologies compared to those provided by the algorithm based on round-by-round optimization such as proposed in [1].

4 Computational experiments

We made computational experiments to see how long our approach can extend the network lifetime compared to that achieved by the cluster-based approach proposed in [1]. We adopted the same physical constants and parameters as used in [1, 4]. That is, we assume that initial battery level of each sensor node is 0.5 J, i.e. $b_i = 0.5$ for all $i \in N$; energy dissipation c_{ij} is computed under the conditions that the data amount transmitted by each sensor node is 4200 bits; the electronics energy is 50 nJ/bit; the amplifier energy is 10 pJ/bit/m^2 if the transmission distance is less than 87 m and 0.0013 pJ/bit/m^4 otherwise; the energy dissipation for data aggregation is set as 5 nJ/bit.

We used an optimization software Xpress-MP (2005B) to solve the problems. All experiments were run on a PC with Intel Pentium 4 processor (2.53GHz) and 512MB RAM.

We prepared three test data sets (data1, $\cdots$, data3), where 100 sensor nodes are randomly deployed in a 100-meter-square. For convenience, we define the lower left of the square as ($x = 0$, $y = 0$) and the upper right of the square as ($x = 100$, $y = 100$). We assume that the BS is located at ($x = 50$, $y = 175$). These settings are also the same as those used in [1, 4].

We selected the minimum spanning tree (MST) and shortest path trees (SPT) as the candidates of the sensor network topology. They should be suitable to save power consumption because they connect the sensor nodes so as to minimize distance measures. Hence, the set of candidate trees consists of a hundred SPT-based trees and a hundred MST-based trees. For SPT-based trees, we select a sensor node as a root and find the shortest path form the root to all sensor nodes, where the distance is measured by the squared distance. For MST-based trees, we first constructed the MST of the sensor node set, where the distance is also measured by squared distance. Then, we created the hundred MST-based trees so that each has a different root. Note that topology of all MST-based trees is the same and each MST-based candidate tree has the different energy dissipation because the root is different.

The objective of the problem is to select the trees from the candidate trees and decide how many rounds we should use the trees so as to maximize the number of rounds until at least one sensor node dies. After that, at least one sensor node can not send data using any given candidate trees. To continue the monitoring, we need to decide new candidate trees without the dead sensor nodes. To remove the dead senor nodes, we need to know whether a sensor node still have enough battery power. In our experiments, we use two criteria for it. The first is whether a sensor node has enough power to receive data from at least two sensor nodes and transmit the aggregated data to the nearest sensor node. We use this criterion in the first experiment (ex1). The second is whether a sensor node has power to receive data from at least three sensor nodes and transmit the aggregated data to the nearest sensor node. We use this criterion in the second experiment (ex2). Note that the power consumption of receiving and aggregating data is dependent on only the amount of data.

Table 1 and Figure 2 show the comparisons of the number of rounds in the two experiments mentioned above and "UFLP" using data1. The column labeled "UFLP" denotes the results of Furuta et al. [1] which is one of the cluster-based approach. The number of total rounds in our proposed method is about twice of the number of rounds displayed in "UFLP". The ex1 provides better results compared to those achieved by the ex2. This can be caused by the different criteria introduced to determine the dead sensor nodes. The criterion introduced in the ex2 is more strict than that of the ex1. Regardless of the strict criterion, the number of dead sensor nodes is the same in both the ex1 and the ex2 at the beginning. However, as the rounds are repeated, more sensor nodes can be regarded as dead in the ex2. After all, the ex1 which has rather soft criterion tends to provide better results. In our experiments using the other two data sets, we observed similar results (see Tables 2 and 3, Figures 3 and 4). These results show that our algorithm provides energy-efficient selection of the spanning trees throughout the network lifetime. As a result, the network lifetime is drastically extended.

Table 1: The number of rounds (data1)

#Sensors	UFLP	ex1	ex2
99	902	961	961
90	922	967	967
70	933	1171	1171
50	939	1327	1321
30	944	1456	1477
10	952	1645	1605
0	963	1857	1814

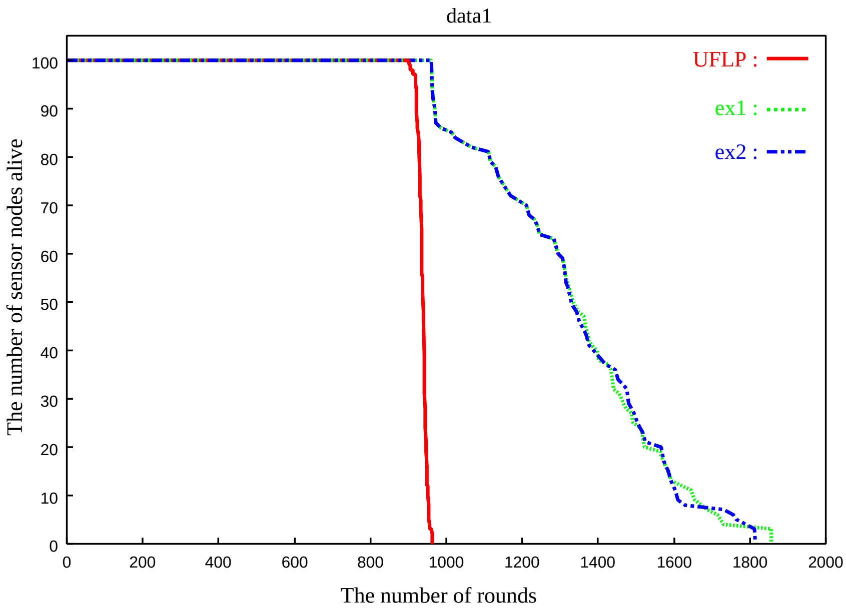


Figure 2: Relationship between the number of sensor nodes alive and the number of rounds : the case of data1

5 Conclusion

We consider a multi-round topology construction problem arises in the centralized wireless sensor networks, and formulated the problem as a multidimensional knapsack problem. We made computational experiments to compare our results with those provided by the previous approach using the cluster-based network. From the computational experiments, we showed that the number of rounds until at least one sensor node drains its battery is larger than those achieved in the previous study. Moreover, we showed that the network lifetime is also extended

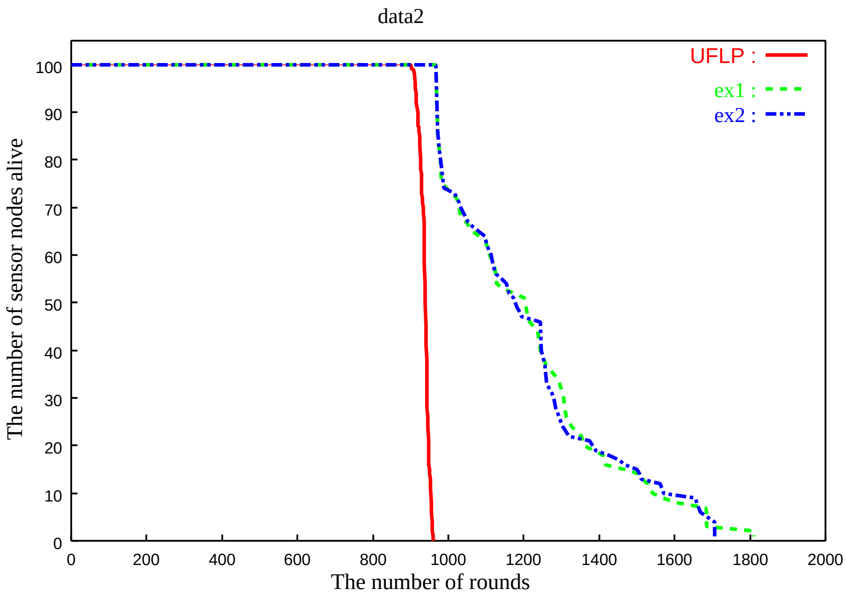


Figure 3: Relationship between the number of sensor nodes alive and the number of rounds : the case of data2

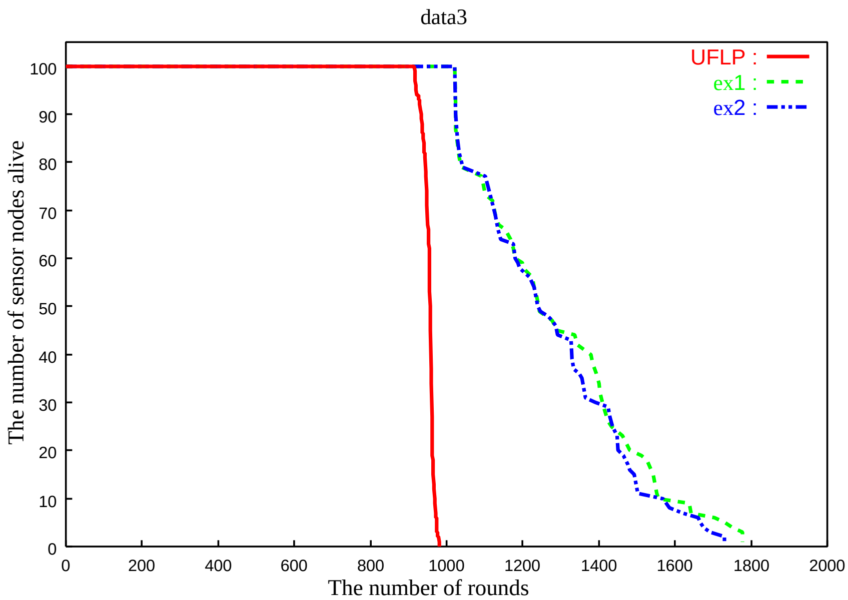


Figure 4: Relationship between the number of sensor nodes alive and the number of rounds : the case of data3

Table 2: The number of rounds (data2)

# Sensors	UFLP	ex1	ex2
99	902	969	969
90	919	969	969
70	933	1028	1035
50	939	1203	1175
30	944	1307	1281
10	954	1543	1573
0	960	1811	1708

Table 3: The number of rounds (data3)

# Sensors	UFLP	ex1	ex2
99	916	1022	1022
90	933	1024	1025
70	950	1123	1120
50	957	1241	1240
30	961	1405	1391
10	969	1559	1570
0	981	1778	1730

about two times of the previous results. Our solution method is primitive, however it still provides better results in a reasonable time.

In this paper, in order to extend the network lifetime of wireless sensor networks, we focus on the topology construction which is energy efficient. However, although the delivery rate of data to the BS is an important factor in the topology construction of wireless sensor networks as well as energy efficiency, we do not consider the delivery rate of data. As a future work, we will develop a topology construction method considering both the delivery rate and energy efficiency. Since the failure of data transmission randomly occurs in wireless networks, we may need the analysis of a mathematical model incorporating the stochastic characteristics of the failure process.

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