Optimal Multi-sink Positioning and Energy-Efficient Routing in Wireless Sensor Networks*

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Abstract. In wireless sensor networks, the sensors collect data and deliver it to a sink node. Most of the existing proposals deal with the traffic flow problem to deliver data to the sink node in an energy-efficient manner. In this paper, we extend this problem into a multi-sink case. To maximize network lifetime and to ensure fairness, we propose (i) how to position multiple sink nodes in a sensor network and (ii) how to route traffic flow from all of the sensors to these multiple sink nodes. Both of the problems are formulated by the linear programming model to find optimal locations of the multiple sink nodes and the optimal traffic flow rate of routing paths in wireless sensor networks. The improved lifetime and fairness of our scheme are compared with those of the multi-sink aware minimum depth tree scheme.

1 Introduction

In a wireless sensor network, each sensor node has a small sensing coverage and a small communication range because increasing the sensing coverage and communication range would consume more battery power. Since each sensor node has a small communication range, each sensor node relays the sensed events to a sink node [1]. As the number of sink nodes is increased, the path length from sensor node to sink node is decreased and the lifetime of the sensor nodes is increased. However, the number of sink node is constrained financially because the cost of the sink node is more expensive than the sensor node.

There has been much research done on traffic engineering in wired networks. The main purpose of traffic engineering is to increases the link utilization by equally balancing the traffic over the network. It is also possible to apply the traffic engineering in a wireless sensor network. However, the purpose should be to increase the network lifetime instead of improving the link utilization,

* This work was supported in part by the Brain Korea 21 project of Ministry of Education and in part by the National Research Laboratory project of Ministry of Science and Technology, 2004, Korea.

C. Kim (Ed.): ICOIN 2005, LNCS 3391, pp. 264–274, 2005.

because the critical resource of wireless sensor networks is the battery power of the sensor node instead of the link bandwidth although the sink nodes do not have an energy constraint since they are connected to a wired network.

In the past, most researches focused on the energy conservation [2][3] or data aggregation [5][6]. Recently, several studies [7][8][9] handle locating the multiple sinks in large-scale wireless sensor networks and optimizing the placement of integration points in multi-hop wireless networks, but any of papers did not consider traffic engineering.

In this paper, a formulation is proposed to improve the lifetime and the fairness of wireless sensor network with multiple sink nodes. We assume that the wireless sensor network shows the cluster architecture [2][3]. In this architecture, the cluster header has data forwarding functionality. The proposed formulations solve two problems, the location of sink nodes and the traffic flow rates of routing paths in the wireless sensor network. We formulate this problem into two types of LP (linear programs). In the first LP formulation, it is assumed that the location and the number of the sink nodes are fixed. The solution of the first LP formulation shows the optimal traffic flow rates of routing paths in the wireless sensor network. In the second LP formulation, instead of assuming the pre-fixed location and number of the sink nodes, the constraint of the maximum number of sink nodes is only assumed. In this case, the solution of the LP formulation finds both the optimal location of sink nodes and the optimal traffic flow rates of routing paths in wireless sensor network. Our main focus is the second LP formulation. It is shown that the proposed formulation increases the lifetime and the fairness of a wireless sensor network by using CPLEX [4] program that is a type of ILP (Integer Linear Programming) solver.

The organization of the paper is as follows: In Section 2, related work is shown such as the sink node location problem in multi-hop wireless network and wireless sensor network. The assumed wireless sensor network model and the proposed LP formulations are presented in Section 3 and in Section 4. In Section 5, the performance of the proposed LP formulation is evaluated by using the CPLEX tool. The conclusion of the paper is in Section 6.

2 Problem Definition

The wireless sensor network model used in this paper refers to [10]. Fig. 1 illustrates the layered sensor model. There are *Application Sensor Nodes* (ASNs) that collect data at the bottom layer. An ASN is a very low cost sensor, and there is a cluster of ASNs that belong to a clusterhead, or *Aggregation and Forwarding Node* (AFN). AFNs are logically located at the higher layer than the lower layer consisting of ASNs only. The AFN aggregates data from a group of ASNs and reduces redundancy of data. AFNs also relay data to sink nodes (or base stations).

Most previous schemes related to the layered sensor networks assume that the location of a sink node is fixed and seek to find the optimal routing paths and traffic flow rates. To the best of our knowledge, there is no work on finding

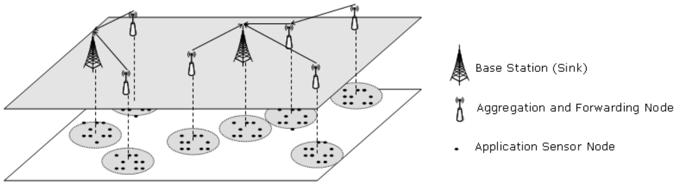

Fig. 1. The layered sensor network model

optimal locations of multiple sink nodes. The optimal locations of sink nodes, also routing paths and traffic flow rate through each path, should be determined to maximize network lifetime and to ensure fairness from the input of the locations of AFNs and the number of sinks to be deployed.

We suppose following scenario. Several areas to be investigated are determined. Each area needs an AFN and forms an cluster at least. The optimal AFNs as the sink, routing paths and traffic flow rates are computed before sensor nodes are deployed. AFNs (battery powered) are pre-configured to computed paths and flow rates. AFNs, AFNs as sink nodes (Base Station, wire-connected powered) and ASNs are deployed. Finally, The network starts to collect data. We assume that the number of sink nodes is limited by other environment (e.g., commercial cost).

The entire network is abstracted by two kinds of nodes hereafter. The sensor node(AFN) aggregates data and delivers it to sink nodes(Base Station) and the sink node receives data from sensor nodes. The data volume is also used instead of the data rate and time is disregarded in modeling the traffic flow, since the lifetime of the sensor node is proportional to the traffic volume (number of packets) transmitted from a sensor node if the power consumption of a sensor node in idle mode is negligible.[1]

3 The Proposed Formulation

The proposed formulations in this paper considers network lifetime and fairness. That is, under a constrained sensor node energy, first, to maximize the minimum among data volume generated by each sensor node for ensuring fairness, and then to maximize total data volume produced by nodes for maximizing the network lifetime. The MAX-MIN scheme is known to give good fairness. The given specific network lifetime can be satisfied by limiting sending data volume per unit time with regard to initial energy of sensor node.

[1] In wireless system, the power consumption of interface in idle mode is lower than both the transmission power and the reception power. In addition, the wireless sensor nodes use the power saving mechanism by switching between active state and sleep state. The data transmission/ reception is performed only in active period and we assume the ratio of active period is sufficiently small.

If the location of sink nodes is fixed, routing paths of each sensor node and the data volume through each path can be obtained by Formulation 1.

`Formulation 1.`

Maximize
First, Vol_{min}
Second, Vol_{total}

Subject To

$$\sum_{j \in N \cup S, j \neq i} X_{ij} - \sum_{j \in N, j \neq i} X_{ji} = \Delta_i \quad (\forall i \in N) \tag{1}$$

$$\Delta_i \geq 0 \quad (\forall i \in N) \tag{2}$$

$$X_{i,j} = 0 \quad (\forall i \in S) \tag{3}$$

$$Vol_{min} \leq \Delta_i \quad (\forall i \in N) \tag{4}$$

$$Vol_{total} = \sum_{i: i \in N} \Delta_i \tag{5}$$

$$\sum_{j \in N, j \neq i} \left(P_{ij}^t \cdot X_{ij}\right) + \sum_{j \in N, j \neq i} \left(P^r \cdot X_{ji}\right) \leq E_{init} \quad (\forall i \in N) \tag{6}$$

Variables
Δ_i : Data volume that node i produce
Vol_{min} : The minimum of Δ_i
Vol_{total} : Thetotal sum of Δ_i
X_{ij} : Data volume transmitted from node i to node j
Constants
N : Set of sensor nodes
S : Set of sink nodes
P_{ij}^t : Transmission power per unit data volume from node i to node j
P^r : Recieve power per unit data volume
E_{init} : Initial energy of a seonsor node

Each line means,

(1) Define Δ_i which is data volume produced by node(i).
(2) A sensor node should transmit data more than 0 bit.
(3) A sink node should not transmit any data to other sensor nodes.
(4) The Vol_{min} is the minimum among data volume produced by each sensor node.
(5) The Vol_{total} is total data volume produced by sensor nodes.
(6) A sensor node consumes power when send or receive data. The consumed power cannot be larger than initial energy. Idle power is assumed to be negligible.

The Formulation 1 is an LP (Linear Programming) problem because the location of sink nodes is fixed, so it can be solved in polynomial time by using LP solver. Formulation 1 guarantees the network performance of two type.

Fairness - When the Vol_{min} is maximized, all sensor nodes are guaranteed to generate the data volume of at least Vol_{min} and to communicate with sink nodes. Consequently, the each sensor node can produce the data volume of Vol_{min} regardless of the data volume produced by other sensor nodes.

Lifetime - When the idle power of sensor node is negligible, the lifetime of sensor network is dependent on the data volume of transmission and reception. Therefore, if the Vol_{total} is maximized, the lifetime of sensor network is also maximized. Here, the network lifetime means the duration that the batteries of all sensor node have been depleted.

Formulation 1 is modified to apply to cases in which the location of sink nodes is not fixed to get Formulation 2.

`Formulation 2. (for CPLEX)`

Maximize

$$C \cdot Vol_{min} + Vol_{total} \quad (C \cdot Vol_{min} \gg Vol_{total})$$

Subject To

$$\sum_{j \in N, j \neq i,k} X_{ij}^k - \sum_{j \in N, j \neq i} X_{ji}^k = \Delta_i^k \quad (\forall i, \forall k \in N, i \neq k) \tag{7}$$

$$\sum_{j \in N, j \neq i} X_{ij}^i = \Delta_i^i \quad (\forall i \in N) \tag{8}$$

$$\sum_{k \in N, k \neq i} \Delta_i^k \geq -C \cdot S_i \quad (\forall i \in N) \tag{9}$$

$$Vol_{min} \leq \Delta_i^i + C \cdot S_i \quad (\forall i \in N) \tag{10}$$

$$Vol_{total} = \sum_{i \in N} \Delta_i^i \tag{11}$$

$$\sum_{i: i \in N} S_i \leq N_{sink} \tag{12}$$

$$\sum_{j \in N, j \neq i} \left(P_{ij}^t \cdot \sum_{k \in N, k \neq j} X_{ij}^k + P^r \cdot \sum_{k \in N, k \neq i} X_{ji}^k \right) \leq E_{init} + C \cdot S_i \quad (\forall i \in N) \tag{13}$$

$$X_{ij}^k \leq C \cdot (1 - S_i) \quad (\forall i, \forall j, \forall k \in N, i \neq j, j \neq k,) \tag{14}$$

Bounds

$$0 \leq \Delta_i^i \leq C \quad (\forall i \in N)$$

$$-C \leq \Delta_i^k \leq 0 \quad (\forall i, \forall k \in N, i \neq k)$$

$$0 \leq X_{ij}^k \leq C \quad (\forall i, \forall j, \forall k \in N, i \neq j, j \neq k, \text{ node } j \text{ is in the transmission range of node } i)$$

Binaries

$$S_i \quad (\forall i \in N)$$

Variables

Vol_{min} : The minimum data volume generated by each sensor node

Vol_{total} : The total data volume generated by sensor nodes

X_{ij}^k : Data volume transmitted from node i to node j,
node k is the source of data
Δ_i^k : Data volume that node i produce, node k is the source of data
S_i : If node i is a sinknode, $S_i = 1$. else $S_i = 0$

Constants
N : Set of all nodes in network
C : Infinite constant
N_{sink} : The maximum number of sink nodes
P_{ij}^t : Transmission power from node i to node $j$per unit data volume (bit)
P^r : Recieve power per unit data volume (bit)
E_{init} : Initial energy of a sensor node

A binary variable S_i is added to distinguish which node is selected as a sink node or not because the sink nodes is not decided yet. Variable k in X_{ij}^k, Δ_i^k means source node of data. It is just used to reduce useless equations to solve a problem more quickly and to distinguish the data source for debugging. It will also be used for advanced formulation (e.g., limiting hop-count of transmitted data) as future work. Each line means,

(7) Δ_i^k is data volume relayed by node i when the source of data is k.
(8) Δ_i^i is data volume produced by sensor node i.
(9) Only sink nodes can receive data of other nodes. If node i is a sensor node, it should relay received data to other nodes. (see also *2nd line of Bounds*)
(10) Vol_{min} is the minimum among data volume produced by each sensor node.
(11) Vol_{total} is total data volume produced by sensor nodes.
(12) N_{sink} is the maximum number of sink nodes.
(13) A sensor node consumes power when send or receive data. The consumed power cannot be larger than initial energy. Idle power is assumed to be negligible. The energy of sink node is not limited.
(14) Sink nodes do not send data to other nodes. (see also *3rd line of Bounds*)

The Formulation 2 is an M-ILP (Mixed-Integer Linear Program) problem because of integer variable S_i which is used to select sensor nodes for the role of sink nodes. Since M-ILP problems are NP-hard, it will take a long time to solve a problem if the wireless sensor network is huge. However, if the wireless sensor network consists of about 30 sensor nodes, we can get a solution quickly for that. Moreover, 30 sensor nodes (AFNs) will cover very large area in cluster architecture (layered sensor networks). In this paper, Formulation 2 was applied to a sample wireless sensor network and the result is shown in Section 5. Proposing an approximate algorithm that finds a solution in polynomial time will be left to future works.

4 Performance Evaluation

In this chapter, the result of a simulation by Formulation 2 is analyzed. Fig. 2 is a sample network that is used for simulation. 20 nodes are deployed randomly

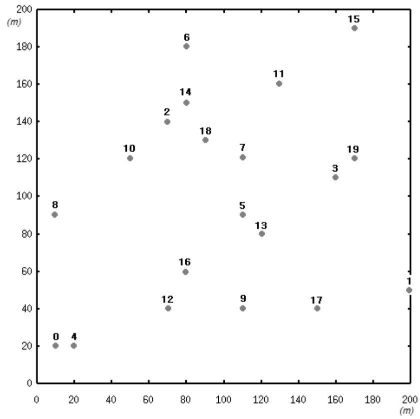

Fig. 2. A sample sensor network

Table 1. The node's number selected as sink node in fully-connected sample network

The number of sink nodes	Formulation 2	m-MDT
1	5	5
2	11, 16	9, 14
3	0, 11, 17	8, 11, 17
4	4, 10, 11, 17	1, 8, 11, 12
5	1, 4, 10, 11, 13	1, 4, 5, 10, 11

in 200 x 200(m). The parameters of Formulation 2 are |N| = 20 (the number of nodes), $C = 7000$, $N_{sink} = 1, 2, 3, 4$ or 5, $P^t_{ij} = 0.5 + 0.00013 * dist(i,j)^4$(nJ/bit) [11], $P^r = 0.5$(nJ/bit), $E_{init} = 100$(nJ). For the comparison with the proposed formulation, m-MDT (multi-sink aware Minimum Depth Tree) is used. The link cost is energy that is consumed when unit data is transmitted through the link. It has been known that MDT can route packets with minimal energy consumption.[12]

The simulation result in the sample network are compared in Table 1 and Table 2. We simulate two cases, one in fully-connected network and the other in which the transmission range of a sensor node is $60m$. Although the node's number to be selected as sink node is the same as No.5 when there is only one sink node, the result shows that there is a difference in selected sensor nodes as sink nodes between Formulation 2 and m-MDT in case that the number of sink nodes is 2,3,4 or 5.

Fig. 3 and Fig. 4 show that Vol_{min} by Formulation 2 is much bigger than that by m-MDT though both select the same sensor node as sink node when there is only one sink node in the network. This is because m-MDT allows a sensor node to select only one path which is the shortest path (low energy consumption) to communicate with the sink node. In the m-MDT algorithm,

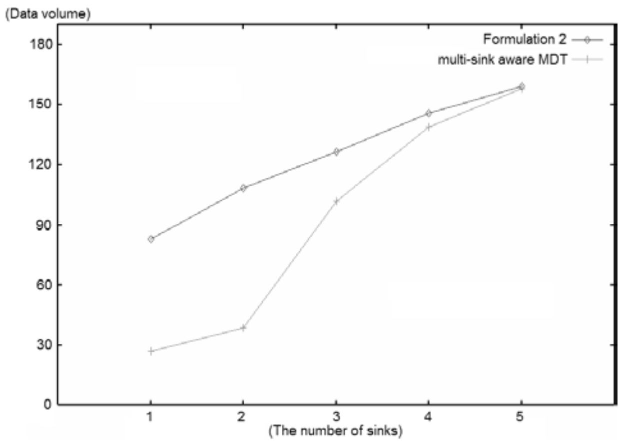

Fig. 3. The comparison of Vol_{min} in fully-connected network

sensor nodes around sink node always consume more energy than nodes far from the sink node. Therefore, sensor nodes far from the sink node cannot send data to the sink node even if they have a lot of energy. On the other hand, Formulation 2 considers not only the shortest path but also other available paths when a sensor node communicates with the sink node, so the maximum of Vol_{min} can be found by Formulation 2. Fig. 5 and Fig. 6 are detailed figures to show that Formulation 2 allows many paths unlike m-MDT, which allows only the shortest path of the tree architecture.

The proposed formulation in this paper significantly increases Vol_{min} by using many paths for communications and by admitting determined data volume to each link. In case there is only one sink node in a fully-connected network, the Vol_{min} by proposed formulation, 82.97, is about 3 times bigger than the Vol_{min} by m-MDT, 28.56. The reason that the location of the sink node selected by each algorithm is different is also caused by whether multi-path is available or not. Moreover, most of the nodes transmit almost the same data volume in Fig. 5 and Fig. 6. This means that the MAX-MIN scheme works well for fairness in this scenario, and network fairness is increased to compare with m-MDT. Since

Table 2. The node's number selected as sink node in sample network, the transmission range of a node is $60m$

The number of sink nodes	Formulation 2	m-MDT
1	5	5
2	7, 12	6, 9
3	4, 11, 17	0, 13, 14
4	4, 10, 11, 17	4, 10, 11, 17
5	1, 4, 10, 11, 13	1, 4, 5, 10, 11

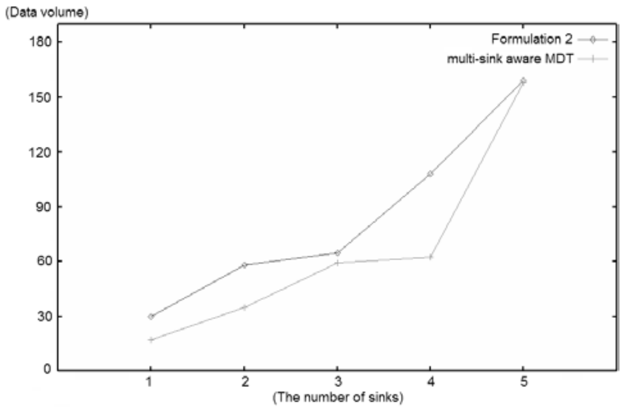

Fig. 4. The comparison of Vol_{min} when the transmission range of sensor node is $60m$

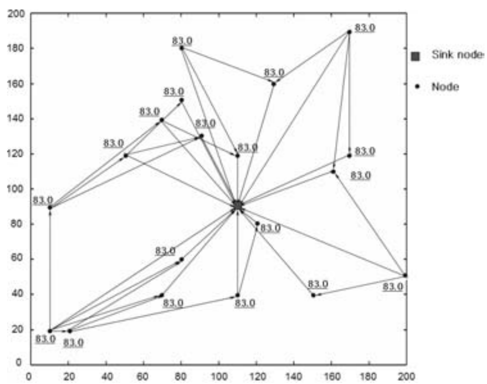

Fig. 5. Routing paths and data volume by Formulation 2 in fully-connected network, the number is data volume produced by each sensor node

m-MDT organizes the network into a tree architecture, there is a wide difference of the data volume produced by each node.

5 Conclusion

In this paper, the formulation to find the optimal locations of the multiple sink nodes and to find the optimal traffic flow rate is proposed. Maximizing network lifetime and ensuring fairness are the main objectives of this linear programming formulation. The proposed scheme is compared with m-MDT (multi-sink aware Minimum Depth Tree), and the results show that the proposed scheme improves network lifetime and fairness significantly. The proposed formulation allows sensor nodes to communicate with the one or more sink nodes through multiple

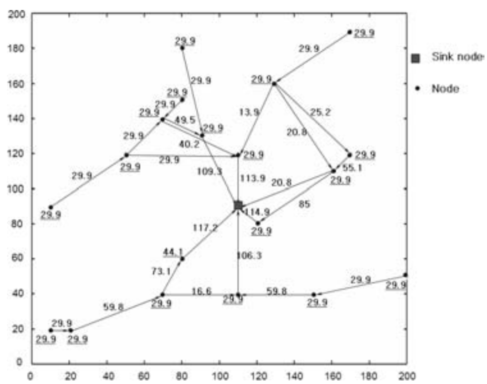

Fig. 6. Routing paths and data volume by Formulation 2 when the transmission range of node is $60m$, $\underline{xx.x}$ is data volume produced by each sensor node, $xx.x$ is data volume of each path

paths. The numerical results reveal that the number of the sink nodes is vital in the performance evaluation, so that the trade-off between the performance improvements and the deployment cost of the sink nodes should be taken into account carefully.

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