Multiple-Objective Metric for Placing Multiple Base Stations in Wireless Sensor Networks

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***Abstract*— The placement of base stations in wireless sensor networks affects the coverage of sensor nodes, the tolerance against faults or attacks, the energy consumption and the congestion from communication. However, previous studies mostly focus on the placement of base stations to improve a partial property, not considering all of them. In this paper we propose *Multiple-Objective Metric (MOM)*, which reflects four different metrics for base station placement in wireless sensor networks. First, the ratio of sensor nodes which can communicate with a base station via either single-hop or multi-hop represents the coverage of sensor nodes. Second, the average ratio of sensor nodes after the failure of base stations represents the fault tolerance of a network. Third, the average distance between sensor nodes and their nearest base station represents the energy consumption of a network. Fourth, the standard deviation of the degree of base stations represents the average delay of a network due to congestion. We show that placing multiple base stations using our proposed MOM can fairly increase various properties of wireless sensor networks.**

***Keywords*— Wireless sensor network, base station, positioning, metric.**

I. INTRODUCTION

Wireless Sensor Network (WSN) is an emerging technology used in many application areas. A WSN is composed of a set of sensor nodes and base stations (BSs) which communicate with sensor nodes [1]. Topics on WSNs vary but are mostly focused to a single aspect. Capkun *et al.* proposed a mechanism for secure positioning using distance estimation techniques [2], and Sastry *et al.* introduced the in-region verification problem for secure location verification [3]. However, they are mostly focused on only secure positioning. In the same way, the work on BS positioning in WSNs have been done considering only network performance as a metric [4], [5]. Lazos *et al.* proposed a set of techniques for secure positioning in sensor networks based on directional antennas [6], but it addresses secure positioning for sensor nodes in a WSN, and not BSs.

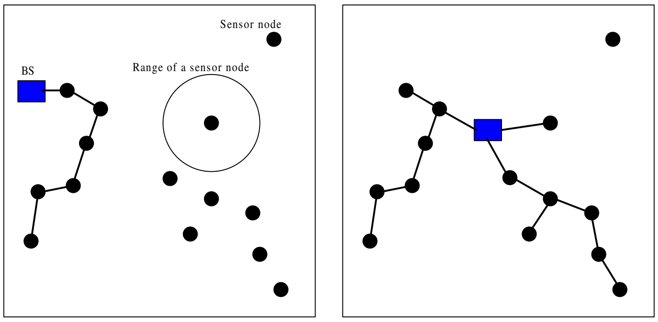
Once a BS is placed at a certain position in a network, various properties of a network is decided. Therefore, it is important to consider the various properties of a network when deciding the position of a BS. In this work we propose *Multiple-Objective Metric (MOM)*, which reflects four different metrics for base station placement in wireless sensor networks. First, the ratio of sensor nodes which can communicate with a BS via either single-hop or multi-hop represents the coverage of sensor nodes. Second, the average ratio of sensor nodes after the failure of base stations represents the fault tolerance of a network. Third, the average distance between sensor nodes and their nearest BS represents the energy consumption of a network. Fourth, the standard deviation of the degree of base stations represents the average delay of a network. Then we derive the optimum position for multiple BSs sequentially. Finally, we perform simulations and show that placing multiple base stations using our proposed MOM can fairly increase various properties of WSNs.

The main contribution of this paper is that placing a BS or multiple BSs at the optimal position is not just a single-objective problem, but a multiple-objectives problem; we should consider various aspect of a network concurrently. We show that considering multiple-objectives can increase the various properties of a network. Moreover, we hope this work will be extended to various studies related to geographical optimality of WSNs.

II. SYSTEM MODEL

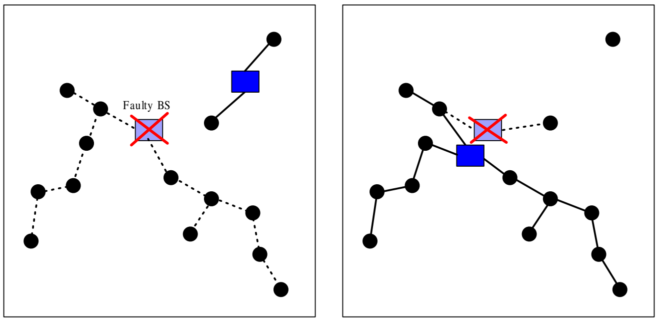
In this section, we define the system models and assumptions for a clear problem definition, simulation and performance evaluation. First, a WSN S is composed of $n(S)$ sensor nodes and i BSs on a $n \times n$ two-dimensional space. Each sensor node gathers the data within its range, and sends them to the nearest BS. Transmission between a sensor node and a BS can be direct, *i.e.* single-hop, or via neighboring sensor nodes, *i.e.* multi-hop. As a result, a WSN can be described as a graph composed of nodes (sensor nodes and BSs) and edges (connection between two sensor nodes or a sensor node and a BS). A previous study introduces the coordinator in a WSN. The coordinator is a sensor node which collects data from adjacent sensor nodes [7]. The difference between a coordinator and a BS is that a BS is a coordinator of coordinators, meaning that the BS collects the data given from the coordinators of smaller WSNs. Moreover, a BS is physically different from sensor nodes, while a coordinator is physically same as sensor nodes.

Only a single sensor can occupy a single x-y coordinate and a coordinate (x,y) is composed of two integers ($0 \leq x \leq n$, $0 \leq y \leq n$). All sensor nodes have equal energy constraints and communication ranges. We also assume that we already know the topology of the deployed sensor nodes, *i.e.* geographical information. Likely, all BSs have equal energy constraints and communication ranges. Each sensor node sends the data to its nearest BS via either single-hop or



(a) S_a: less available (b) S_b: more available

Fig. 1. Availability changes by BS placement



(a) S_a: less tolerant (b) S_b: more tolerant

Fig. 2. Tolerance changes by BS placement

multi-hop communication. Failure can occur to either sensor nodes or BSs. However, we focus on failure of BSs only, because a failures on BSs are much more critical than that of sensor nodes.

III. Multiple-Objective Metric

In this section we introduce Multiple-Objective Metric (MOM), the metric in deriving the optimum position of BSs. First, we review various attributes in a WSN which are effected when the position of a BS is changed. We focus on four major attributes, then we define MOM using the four attributes.

A. Availability of sensor nodes

Each sensor in a network sends data to its nearest BS via either single-hop or multi-hop communication. If the sensor nodes are deployed densely enough for each node to reach its neighboring node, the position of the BS will not be a significant factor. In this case, the sensor nodes can connect to the BS via multi-hop communication with its neighboring nodes. However, when nodes are sparsely positioned, because multi-hop communication can be difficult between the nodes, the position of a BS is very critical. If a node cannot reach the BS within its communication range, the sensor node will be isolated.

To illustrate the availability of sensor nodes in a network, we use the ratio of the number of sensor nodes reachable to a BS to the total number of sensor nodes. Briefly we show

$$AV(S) = \frac{n_c(S)}{n(S)}, \tag{1}$$

where S is a WSN composed of $n(S)$ sensor nodes and $n_c(S)$ is the number of sensor nodes which are able to communicate with any BS in the network. Fig. 1 shows that the availability of sensor nodes are dependent on the position of the BS.

In Fig. 1 (a), a BS is placed on the left side of a network and the number of sensor nodes which are reachable to a BS is 6, while 8 sensor nodes are unable to communicate with a BS. Therefore, $AV(S_a)$, the availability of sensor nodes, is equal to $6/14$. On the other hand, in Fig. 1 (b), a BS is placed on the center of a network and $AV(S_b)$ is $13/14$. Therefore, placing a BS like Fig. 1 (b) is much more effective than Fig. 1 (a). By this simple example, it is shown that the placement of a BS influences the availability of sensor nodes.

B. Tolerance of a network against BS failure

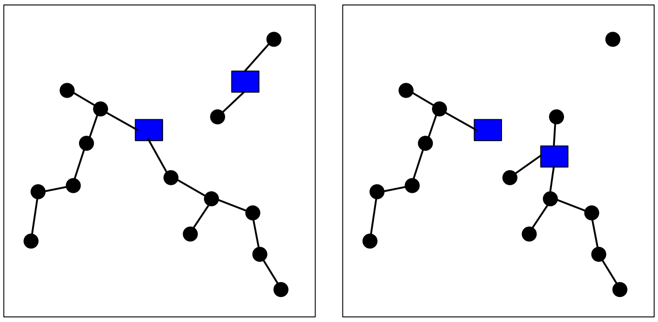
In a WSN with a single BS, if a BS becomes inactive by intentional attacks or unexpected failures, the entire sensor nodes in the network will be unable to transmit the data. Therefore placing multiple BSs is necessary when failure of a BS is possible. Also, the placement of multiple BSs influences the tolerance of a network against BS failure: single failure or multiple failure.

We measure the tolerance of a network against BS failure using the ratio of the number of reachable sensor nodes after BS failure to the number of reachable sensor nodes before BS failure. $TO(S)$, the tolerance of a network against BS failure is briefly shown as

$$TO(S) = \frac{\sum_{k=1}^{i-1} n_c(S_k)}{(i-1)n(S)}, \tag{2}$$

where i is the number of BSs, S_k is network S after the failure of k BSs, and $n_c(S_k)$ is the number of sensor nodes which are reachable to a BS in the network S_k. Except the number of inactive BSs is 0 or i, possible number of BS failure is 1 to $i-1$. For each case, the minimum $n_c(S_k)$ is chosen from various values. For example, the failure of BS1 disables more sensor nodes than the failure of BS2 in a WSN with two BSs, we choose $n_c(S_k)$ under the failure of BS1. This method can reflect the worst case of all possible cases. As shown in Eq.(2), we consider $i-1$ possible cases of partial breakdown by summing up and averaging them.

Fig. 2 illustrates that the tolerance of a network against BS failure is strongly related to the placement of BSs. In Fig. 2 (a), one of two BSs becomes inactive and the number of sensor nodes which can transmit data to a BS is changed from 14 to 2. Thus $TO(S_a)$ is 2/14 in this case. In Fig. 2 (b), similarly, we can calculate that $TO(S_b) = 12/13$. Although $AV(S_a) = 1)$ is slightly better than $AV(S_b) = 13/14)$, placing two BSs like S_a can make a network less tolerant to BS failure than S_b when comparing $TO(S_a)$ and $TO(S_b)$ $(2/14 < 12/13)$.



(a) S_a: higher congestion (b) S_b: lower congestion

Fig. 3. Congestion changes by BS placement

C. Energy consumption of sensor nodes

Energy-awareness in WSNs is one of the major issues and there have been various studies about this issue so far [10]–[15]. Especially, [10] and [11] propose repositioning of a mobile BS for reducing energy consumption of an entire network. We use the average single-hop distance between each sensor nodes and its nearest BS as the measurement of energy efficiency, since Vass *et al.* showed that minimizing this metric can increase network lifetime efficiently in [11]. The metric is represented as

$$EC(S) = \frac{1}{i}\sum_{j=1}^{i}\left(\frac{\sum_{k=1}^{n(S)} d(b_j, v_k)^{\alpha}}{n(S)}\right), \quad (3)$$

where $d(b_j, v_k)$ is the one-hop distance between a base station b_j and a sensor node v_k. We average d^{α} since energy spent in transmitting a bit over a distance d is proportional to d^{α} ($2 \leq \alpha \leq 4$) [4].

D. Average congestion of BSs

We propose standard deviation of BS degree as a metric of congestion. Degree of a BS is the number of sensor nodes which are communicating with the BS. Since one BS covers many sensor nodes, these sensor nodes may suffer delay to communicate with the BS; congestion occurs while data transmission is in process. Standard deviation of BS degree illustrates how evenly the sensor nodes are distributed among deployed BSs. $CO(S)$, standard deviation of BS degree, is

$$CO(S) = \sqrt{\frac{1}{i}\sum_{j=1}^{i}(D_j - \bar{D})^2}, \quad (4)$$

where D_j is the degree of the jth BS, $\bar{D}$ is the average degree of all BSs and i equaling the total number of BSs.

Fig.3 shows how placement of BSs affects the average congestion of a WSN. In Fig.3 (a), two BSs communicate with 14 sensor nodes; $\bar{D}$, the mean degree of BSs, is 7. Then $CO(S_a)$ is calculated as follows:

$$\sqrt{\frac{1}{2}\Big((12-7)^2 + (2-7)^2\Big)} = 5.$$

Similarly, we can calculate $CO(S_b)$ using $\bar{D} = 6.5$, which is

$$\sqrt{\frac{1}{2}\Big((6-6.5)^2 + (7-6.5)^2\Big)} \simeq 0.7071.$$

If degrees of BSs are all close to the mean degree, then the standard deviation is close to zero; it means sensor nodes are fairly allocated to given BSs. However, if degrees of BSs are far from the mean degree, then the standard deviation is far from zero; it means sensor nodes are concentrated to partial BSs and the possibility of data congestion is increased. Therefore, placing BSs like the second case reduces congestion of a network than the first case.

E. Integration of four metrics

So far we introduced four different metrics, each metric represents different property of a WSN. The next procedure is integrating those four metrics into one new metric. There are two main approaches to solving an optimization problem that involves multiple objective functions [16]. One approach is to solve problem a number of times with each objective in turn. When solving the problem using one of the objective functions, the other objective functions are considered as constraints. The other approach is to build a suitable linear combination of all the objective functions and optimizes the combination function. In this case, it is necessary to attach a weight to each objective function depending on its relative importance [17]. In this paper we use the second approach to combine multiple objective functions, since it can efficiently derive the value of combined properties without multiple iterations. In addition, the normalization of objective functions is required if a value of each function is distributed differently. One of the commonly used normalization is projecting the minimum value to 0 and the maximum value to 1. Both $AV(S)$ and $TO(S)$ have a value from 0 to 1. Also, 1 represents the best and 0 represents the worst value; thus no normalization is required to these two metrics. However, the maximum value of $EC(S)$ and $CO(S)$ is over 1, and a lower value is better for both energy consumption and congestion. We normalize these two metrics using the minimum and maximum value of each metric, which are

$$EC_n(S) = 1 - \frac{EC(S) - EC_{min}(S)}{EC_{max}(S) - EC_{min}(S)},$$

and

$$CO_n(S) = 1 - \frac{CO(S) - CO_{min}(S)}{CO_{max}(S) - CO_{min}(S)},$$

where $EC_{min}(S), CO_{min}(S)$ and $EC_{max}(S), CO_{max}(S)$ are the minimum and the maximum values of $EC(S)$ and $CO(S)$ respectively. $MOM(S)$, a unified metric by summing up four normalized metrics with weight factors, is defined as

$$\beta AV(S) + \gamma TO(S) + \delta EC_n(S) + \epsilon CO_n(S),$$

where β, γ, δ and ϵ are the weight factors for four metrics ($\beta + \gamma + \delta + \epsilon = 1$). When there is only a single BS ($i = 1$), both $TO(S)$ and $CO(S)$ are equal to 0, since a single point of failure makes an entire network inactive and the degree of

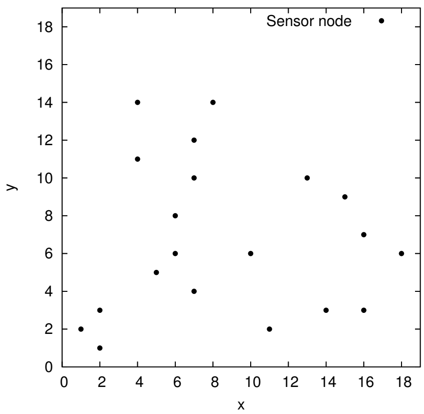


Fig. 4. Sensor location in the network

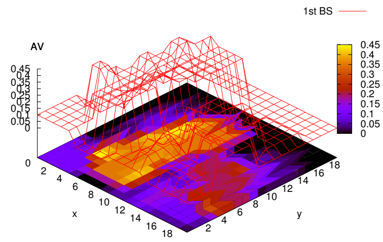
the BS is equal to the average degree. Thus, we consider the availability of sensor nodes and the average distance between sensor nodes and BSs only, while $TO(S)$ and $CO_n(S)$ are constants, when placing the only BS.

IV. Placement of Multiple Base Stations

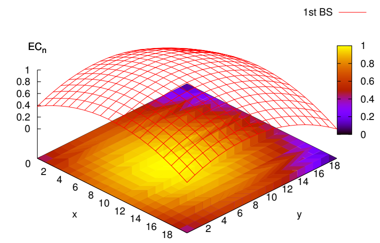
Next, we show results in locating the optimal position for multiple BSs with respect to MOM. Fig. 4 shows a random deployment of 20 nodes in a 20×20 grid square. All sensor nodes placed in the simulated area have same communication range, the $2\sqrt{2}$ radius. There are two ways to search the optimal position of multiple BSs: greedy search vs. exhaustive search. Greedy search is to place multiple BSs one by one at a time, while exhaustive search is considering all possible cases of placing i BSs at the same time. We use greedy search to find the optimal placement of multiple BS in this paper. Although there is a possibility of sub-optimality, greedy search can remarkably reduce the time and space complexity than exhaustive search. Previous studies deal with the complexity of BS (relay) placement [8], [9], but we do not focus on finding heuristics here. The procedure for placing BSs to the optimal position is as follows.

First, we find the optimal position for the initial BS. In placing the initial BS, we only consider two metrics, $AV(S)$ and $EC_n(S)$; $TO(S)$ and $CO_n(S)$ are always 0 as we already mentioned. Fig. 5 shows the distribution of $AV(S)$, $EC_n(S)$ and $MOM(S)$, respectively. $AV(S)$ appears to be higher when the BS is placed at the position where the density of sensor nodes is high, as shown in Fig. 5 (a). On the other hand, $EC_n(S)$ becomes higher when the BS is placed near the center of the network. Fig. 5 (c) is the distribution of $MOM(S)$, which we gave the equal weight factors 0.5 to both $AV(S)$ and $EC_n(S)$ to calculate the metric. Through these simulations, we can figure out that the position that makes MOM the highest is (9,4) in the example network topology shown in Fig. 4.

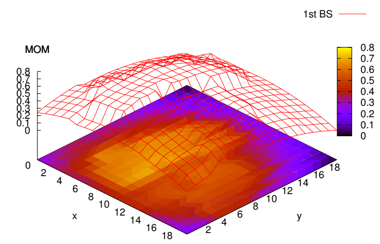
Second, by placing the second BS we aim to achieve higher node availability, tolerance against the fault of BSs, energy efficiency of the entire network and congestion avoidance. We re-evaluate four metrics for the placement process of the second BS. For subsequent deployment of additional BSs, we



(a) $AV(S)$



(b) $EC_n(S)$



(c) $MOM(S)$

Fig. 5. Metric distribution for the initial BS placement

repeat the same procedure as the calculation for the second BS. The second BS is placed on $(14, 5)$ in Fig. 4, with the initial BS placed on $(9, 4)$. Similarly we can find $(6, 12)$ as the position of the third BS, which maximizes $MOM(S)$ in the network.

Next, we compare the efficiency of MOM with other single-objective metrics. Table I shows the results of optimal placement of the third BS by each single metric and MOM. We can see that placing a BS using MOM can increase four properties of a network in balanced manner, while using a single metric only increases the corresponding property of a network. The difference between MOM and other single metrics is well shown in Fig. 6. Placing BSs at the position which maximizes $AV(S)$ increases the availability of sensor nodes the best, but cannot effectively increase the other properties: tolerance against failure of BSs, energy efficiency and congestion avoidance. Likewise, placing BSs at the position which maximizes $EC(S)$ increases the energy efficiency the best,

TABLE I

OPTIMAL THIRD BASE STATION PLACEMENT FOR EACH METRIC

(x,y)	$AV(S)$	$TO(S)$	$EC_n(S)$	$CO_n(S)$	$MOM(S)$
$(0,1)$	**0.9**	0.471	0.442	0.260	0.518
$(9,3)$	0.70	**0.933**	0.913	0.237	0.708
$(9,7)$	0.60	0.467	**1**	0.237	0.613
$(3,12)$	0.85	0.471	0.730	**1**	0.763
$(6,12)$	0.85	0.882	0.857	0.916	**0.876**

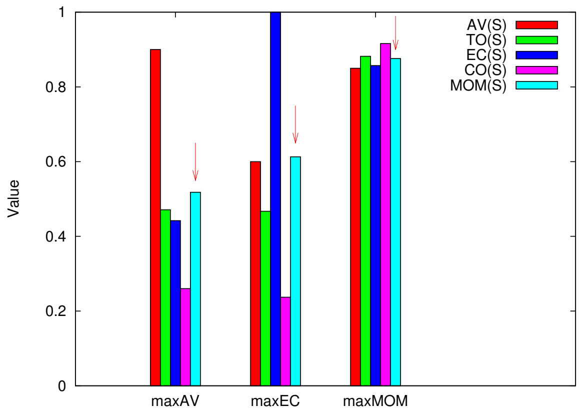


Fig. 6. Comparison of metric values for the third BS placement

but cannot effectively increase node availability, tolerance and congestion avoidance. However, placing BSs at the position which maximizes $MOM(S)$ increases four properties of a network evenly: the availability of sensor nodes up to 85%, tolerance against failure of BSs by 88.2%, energy efficiency of a network by 85.7% and congestion avoidance by 91.6%.

by considering all four metrics with the use of $MOM(S)$, $(12,5)$ turns out to be the optimal position for placing the BS. From this we can see that the best position for a single metric may not be qualified to be the optimal position when all four metrics are considered. This shows that in finding the optimal position for the BS, although all metrics may not be at its best, considering all four metrics and using the MOM is the optimal method.

V. CONCLUSION

In this work we have proposed *Multiple-Objective Metric (MOM)* which reflects four different metrics, for placing multiple base stations at the optimal position in wireless sensor networks. First, the ratio of sensor nodes which can communicate with a base station via either single-hop or multi-hop represents the coverage of sensor nodes. Second, the average ratio of sensor nodes after the failure of base stations represents the fault tolerance of a network. Third, the average distance between sensor nodes and their nearest base station represents the energy consumption of a network. Fourth, the standard deviation of the degree of base stations represents the average delay of a network. Through simulation results, we show placing multiple base stations using our proposed MOM can increase various properties of wireless sensor networks fairly. Also, we can customize the metric using weight factors so that the characteristic of a network can be considered flexibly. In this paper we used greedy search, but it can lead the result to local-optimum. Our future work is to study the heuristic position search algorithm, which can derive more optimal results than greedy search and less complex than exhaustive search.

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