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Simultaneous Optimization for Dynamic Sensor Function Allocation and Effective Sensed Data Aggregation in Wireless Sensor Networks

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Abstract

This paper proposes a method to realize sensor function allocation and effective data aggregation simultaneously in wireless sensor networks. This method realizes dynamic allocation of sensor functions so as to balance the distribution of each sensor function in a target monitoring area. In addition, effective data aggregation is performed by using a tree network topology and time division multiple access (TDMA), which is a collision-free communication scheme. By comparing the results from the proposed method with the results from non-optimized methods, it can be validated that the proposed method is 1.7 times more efficient than non-optimized methods in distributing sensor functions. With this method, the network lifetime is doubled, and the number of data packets received at a base station is considerably increased by avoiding packet collisions.

Keywords: *Resource Balancing, TDMA, Distributed Algorithm, Graph Coloring.*

1. Introduction

Recently, wireless sensor networks (WSNs) have attracted considerable attention. However, some problems must be addressed in order to meet real-world demands. These include higher instability, higher uncertainty, and lower power capacity of WSNs when compared to conventional networks. Furthermore, in the case of a WSN, resource allocation problems need to be solved [1]. For example, dynamic sensor function allocation is required in order to realize a data-centric concept [2] that enables users to access the required sensed data from the WSN without having to know about individual sensor nodes. An effective data aggregation method is also required for effectively observing the target field.

This paper proposes a method for the dual optimization of dynamic sensor function allocation and effective data aggregation. In this method, the distribution of each sensor function in the target monitoring area can be balanced by dynamic sensor function allocation. In addition, effective data aggregation is achieved by using a tree communication network that comprises a base station (BS) as the root and adopts a time division multiple access (TDMA) scheme. Our method utilizes a distributed graph coloring algorithm and can simultaneously allocate sensor functions and time slots by using TDMA.

Typically, sensor functions of each sensor node are fixed or statically allocated. However, dynamic sensor function allocation is necessary to realize the data-centric concept and reduce power consumption. In addition, TDMA is an effective method for preventing packet collisions. However, time slot allocation must be realized in order to use TDMA, and it is relatively difficult to realize efficient time slot allocation. CP-TDMA [3] allocates time slots to all the sensor nodes on the basis of edge coloring and probabilistic assignments. However, CP-TDMA cannot completely solve the hidden terminal problem. TRAMA [4] is also a TDMA-based algorithm. The advantage of using TRAMA is that a high percentage of sleep time and better collision probability are achieved; however, overheads in TRAMA are too high to permit communication between nodes without packet collisions. Graph coloring algorithms are often used to solve resource allocation problems [5][6][7]. They provide effective solutions, but are not suitable for WSNs. This is because WSNs are often controlled in a decentralized or distributed manner. The graph coloring algorithms are unfortunately centralized ones and do not take any environmental changes into account.

Compared to the related works, the proposed method has the following features:

- *Sensor function distribution balancing*
  Sensor function allocation is carried out so as to balance the distribution of each sensor function in a target monitoring field. Although the sensing accuracy depends on the total number of sensor nodes deployed in the target field, we can monitor the target field regardless of the number of sensor nodes.
- *Extension of network lifetime*
  Power consumption in a WSN can be reduced by providing a dynamic sleep state in addition to a static sleep state; this helps increase the lifetime of the WSN. The dynamic sleep state also helps in reducing packet collisions and sensing and transmission of redundant data.
- *Robustness*
  Since the sensor function allocation is dynamically performed using the currently available sensor nodes, the proposed method is robust to failures and the disappearance of a node.
- *High scalability*
  To establish a network, it is necessary to ensure that each node communicates only with its neighbors. The proposed method has high scalability for network construction.

2. Wireless sensor network model

In this paper, we consider a WSN that is organized autonomously as follows: first, multiple sensor nodes are scattered across the target field. Next, each sensor node negotiates with its neighboring sensor nodes and determines its sensing task. Then, depending on the sensing task, the node starts transmitting the sensed data to a BS via multihop wireless communication. The network has an automatically generated tree structure, whose root is the BS. The sensing tasks and network structure are continuously and automatically maintained through periodic negotiations between the sensor nodes. Each sensor node is capable of supporting wireless communication and can perform data processing and sensor functions.

3. Proposed method

An outline of the proposed algorithm is shown in Figure 1. The algorithm consists of three processing periods, as shown in Figure 2, i.e., the control period, active period, and sleep period. Each node periodically repeats these three processing periods. Herein, for convenience, we refer to one periodic cycle as “cycle.” First, in the control period, each sensor node allocates its own sensor function and time slot for TDMA by using a graph coloring algorithm and constructs a tree network structure, whose root is the BS, for effective aggregation of the sensed data. Subsequently, each sensor node exchanges information with its neighboring nodes. Next, in the active period, each sensor node receives the sensed data by using the allocated sensor function and buffers the data in a data forwarding list. In addition, the sensed data received from the child nodes in the communication tree are also buffered in the data forwarding list. These buffered data are then transmitted to the parent node selected in the previous control period. Here, a parent node refers to a directly connected neighboring

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Notations:
self: the node itself in the procedure.
P: a list containing received packets. This list is updated whenever a
packet arrives. (p[0], p[1],…, p[n – 1]); n is the length of P.
ID: node identification.
sensorID: the allocated sensor function ID.
ctrlPeriodTime: the time duration of the control period.

procedure algorithm(){
  self->sensorID = 0;
  self->timeslot = 0;
  P = {}; //cleared

  // If a packet arrives, this main procedure is interrupted and the
  // packet information is added to list P.
  setupPacketReceiveHandler();

  // Main process
  repeat{
    runCtrlPeriod();
    runActiveAndSleepPeriod();
  }
}

procedure runCtrlPeriod(){
  start = random(ctrlPeriodTime);
  wait until start time;

   // Task1: Coloring process
   // Sensor function allocation
  oneHopColoring();
  // Timeslot allocation
  twoHopColoring();

  // Task2: Tree construction/update
  treeConstruction();

  // Notify/Update
  broadcast own new information to the neighboring nodes;

  wait until the end of the control period, ctrlPeriodTime;
}
```

Figure1. Outline of the proposed.

node in the vicinity of the root of the communication tree. Every node repeats the abovementioned process, and an observer can obtain all the sensed data from the deployed sensor nodes. Finally, in the sleep period, the sensor node goes into a sleep state and remains inactive for a given time.

We assume that all the sensor nodes are synchronized and their state transitions are carried out simultaneously. In practice, to realize the proposed method, we use a traditional sensor network synchronization method such as reference broadcast synchronization (RBS) or flooding time synchronization protocol (FTSP) [8][9]. With these methods, it is possible to achieve millisecond-order synchronization. In addition, if a packet arrives, the main procedure shown in Figure 1 is interrupted and the packet information is immediately added to the packet list P. Here, if a node does not receive any packet from a neighboring node for a given period of time, the node removes the ID of the corresponding neighboring node from the neighboring node list.

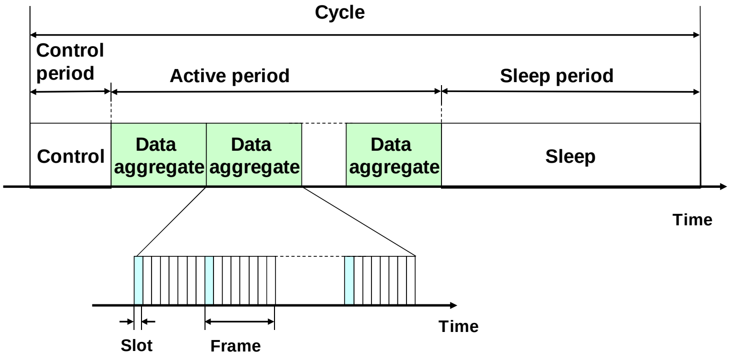

Figure 2. Processing periods and their corresponding time slots in the proposed method

3.1. Control period

The control period is very important in our method and performs the following two tasks.

Task 1: *Dual optimization using a distributed graph coloring algorithm*

To perform sensor function allocation and the time slot allocation in TDMA, we use a distributed graph coloring algorithm called dynamic probability-function or DP algorithm, which we have had proposed in a previous study [10]. In the coloring algorithm, each color refers to an integer number, starting from zero. The color allocated to a node should be different from the colors of its neighboring nodes. The maximum number of the useable colors is limited, and it depends on the applications. The coloring rule for each sensor node is relatively simple. Each node changes its color periodically in response to the colors of its neighboring nodes. However, in the DP algorithm, a probability function that calculates the time taken for color change with respect to the number of neighboring nodes is introduced; hence, adverse side effects caused by the simultaneous color change of neighboring nodes can be suppressed.

- *Sensor function allocation*
  In order to balance the distribution of each sensor function, each sensor node uses the DP algorithm to allocate to itself a sensor function that is different from that of its neighboring nodes; this process is referred to as “oneHopColoring()” and is shown in Figure 1.
- *Time slot allocation for TDMA*
  We adopt a TDMA communication scheme to realize stable communication between sensor nodes without packet collisions. In TDMA, the packet-sending time for each node is limited and assigned to a specific time slot in a periodic time frame. In addition, the time slot for each node is different from that for the others. In general, TDMA control is realized in a centralized manner; that is, the BS allocates a time slot to each node. However, it is difficult to implement this approach since our target is a decentralized WSN. Therefore, we apply our coloring algorithm to time slot allocation in TDMA. This enables autonomous and dynamic time slot allocation.

For time slot allocation, each node should be assigned a time slot that is different from that of the two-hop reachable nodes. This is because for realizing a multihop wireless

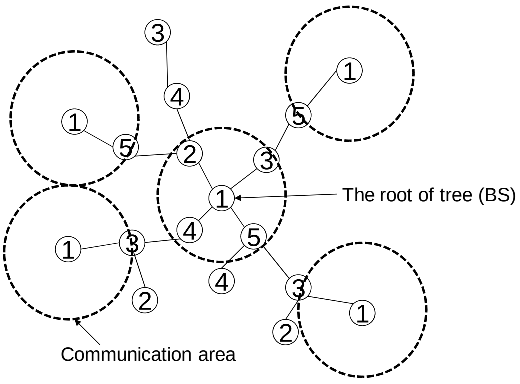

Figure 3. Example of an acceptable time slot allocation. The number on each node represents the time slot number

network, it is necessary to avoid the packet collisions that result from hidden terminals or nodes. An example of time slot allocation is shown in Figure 3. Here, each number indicates the allocated time slot number for the corresponding sensor node. In this example, stable communication is realized because each node has a time slot that is different from the time slot of the two-hop reachable nodes, and packet collisions do not occur even if nodes with the same time slot number send packets simultaneously.

We modified the DP coloring algorithm to solve the time slot allocation problem as follows: each sensor node should be allocated a color without any color conflict with the two-hop reachable nodes. This modification is relatively simple and can be applied to the WSNs studied herein. This modified coloring algorithm is called “twoHopColoring()” and is shown in Figure 1.

Task 2: *Tree construction*

For realizing a data aggregation path to a BS, a tree structure whose nodes comprise the deployed sensor nodes is considered. The BS is the top or root node of the tree. Actual data aggregation is performed using the TDMA scheme, and the sensed data are transferred toward the BS from a node to its neighboring node in an appropriate time slot through a multihop path in the tree topology. Thus, for effective transfer of the sensed data to the BS, the tree topology should be balanced such that each multihop path from a node to the BS is as short as possible. In the tree construction algorithm used in this study, each node selects a node that is the nearest to the BS from the neighboring node list, and a connection between the two nodes is then established. This process is performed by all nodes individually, thereby resulting in an automatically constructed tree structure. This structure is maintained throughout the control period.

Capability for multisink sensor networks

A multisink WSN is a robust system in terms of data aggregation since the sensed data can be aggregated via other BSs in the event of damage to even a single BS. Moreover, the loads and power consumption of the BSs and the relay nodes are balanced, because of which the lifetime of the WSN is increased. In our algorithm, Task 1, which allocates sensor functions and time slots to each sensor node, does not depend on the number of BSs. Furthermore, each sensor node constructs the shortest path to the nearest BS in Task 2. Thus, the proposed method can be directly applied to multisink sensor networks without any modifications.

3.2. Active period and sleep period

The active period has multiple data aggregate spans, and each data aggregate span consists of time frames and time slots, as shown in Figure 2. Thus, for one active period, each sensor node can send multiple packets using the TDMA communication method. In other words, the number of packets transmitted by a node in each active period can be regarded as the number of assigned time frames.

In order to increase the total network lifetime from the viewpoint of battery power consumption, each sensor node switches the data aggregate span to the sleep span, in which the sensor node sleeps. In other words, each sensor node decreases its sampling rate. Figure 4 shows an example of the relationship between the data aggregate span and the sleep span. In this figure, the active period is assumed to comprise four data aggregate spans. For example, if the power remaining in the battery ranges from 50% (2/4) to 75% (3/4), a sensor node performs the data aggregation in three spans and sleeps during the remaining span of the active period. Here, a sensor node must perform the data aggregation at least once in each active period.

In the sleep period, each sensor node simply changes to the sleep state for a given time so that power consumption is reduced.

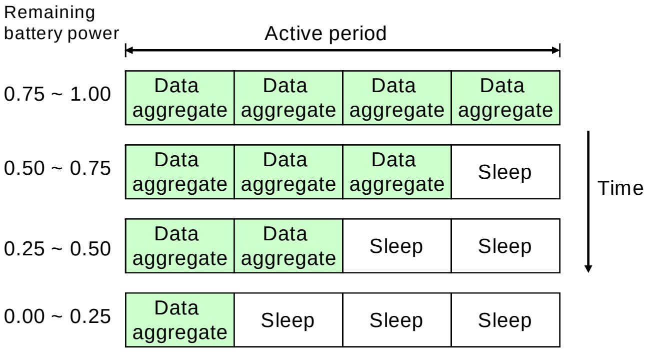

Figure 4. Example of the sampling rate changes. In this case, four data aggregate spans exist in each active period

4. Evaluations

In order to evaluate the effectiveness of the proposed algorithm, the following simulation-based experiments were conducted. First, we created four network topologies with different number of nodes—50, 100, 150, and 200—in a field of area 100 m × 100 m. Here, the location of each node was defined by using x- and y-coordinates whose values range from 0 to 100 m. In addition, the communication radius between the sensor nodes was assumed to be 20 m. In these networks, the average degree of each node, i.e., the average number of neighboring nodes, for the 50-, 100-, 150-, and 200-node topologies was 5.2, 10.3, 13.1, and 14.7, respectively; and the number of sensor functions in each sensor node was set to 4. The proposed algorithm was applied 10 times to each network under the abovementioned conditions, and the average of the 10 times trails was used for evaluating the effectiveness of the proposed algorithm. The energy consumption model was based on the Crossbow MICAz model, which is one of the most commonly used sensor network nodes [11]. To reduce the simulation time and verify the behavior of the WSN under low-power conditions, the battery power of each sensor node was initially set to 0.4 mAh.

For comparison, five other methods were also examined. In the first method, a tree structure was constructed, but communication among the sensor nodes was performed in a random manner. This method was referred to as "Random."

In the second method, called "Sensor only," the sensor function allocation task was invoked, but the transfer of packets among the sensor nodes was random; this method did not have a tree structure. Thus, packet collisions often occurred in this method.

In the third method, called "TDMA only," a time slot was allocated to each sensor node; however, the sensor function allocation was not carried out with the use of our graph coloring algorithm.

In the fourth method, called "Ideal," data aggregation in each cycle was constantly fixed at "1." In this method, one cycle was composed of the three abovementioned processing periods, i.e., the control, active, and sleep periods, as shown Figure 2. In addition, the total number of data aggregate spans was set to 5. This implies that each node aggregated the sensed data in one data aggregate span and slept during the other four data aggregation spans. All the other features of this method were identical to those of the proposed method. In this method, the sleeping time of each node was sufficiently long. Thus, it was ideal for realizing a long network lifetime. Therefore, we called the fourth method "Ideal."

In the fifth method, called the "Greedy" method, sensor function allocation and time slot allocation were performed individually using the coloring algorithm. In the experiments carried out with this method, the number of time slots was fixed at 20. Our method is represented as "Proposed."

4.1. Balance in the distribution of each sensor function and the number of aggregated packets

In order to show the effect of sensor function allocation and time slot allocation, "Proposed," "Sensor only," "TDMA only," and "Random" were evaluated from the viewpoint of the distribution of various types of sensor functions and the number of aggregated packets. In order to evaluate the effectiveness of these methods, we introduced a measure. This measure was calculated by using the following procedure: first, the field in which the sensor nodes were scattered was divided into small areas. Next, in each small area, the variance of frequency distributions of the colors that were mapped to the nodes was calculated. Finally, the measure was defined as the sum of the variances of all the divided areas. A small calculated measure implied that the colors were relatively uniformly mapped, and this was a favorable condition.

Figure 5 shows the experimental results. The x-axis represents the number of nodes scattered in the WSN, and the bar graphs represent the newly introduced evaluation values. The evaluation values obtained for the "Proposed" and "Sensor only" methods indicated that these methods were approximately 60% (1/0.6 = 1.7 times) more efficient than the "TDMA only" and "Random" methods. Since our distributed coloring algorithm was employed in these two methods, the results show that this algorithm is effective at balancing the distribution of sensor functions.

The line graphs in Figure 5 provide a summary of the results obtained for the simulation of the total number of packets received at the BS. The number of packets received at the BS in the "Proposed" and "TDMA only" methods was considerably larger than that in the

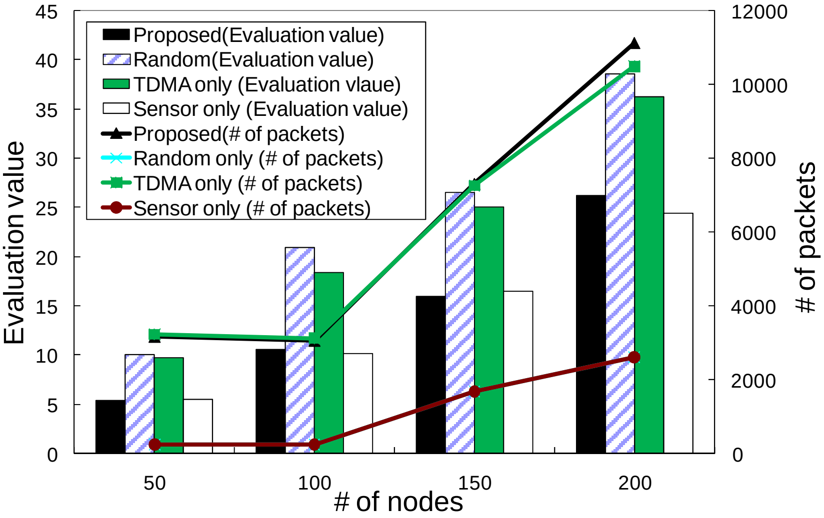

Figure 5. Variance of the number of sensor functions deployed and the number of packets. The x-axis represents the number of nodes scattered in the field, the left y-axis represents the evaluation value, and the right y-axis represents the number of packets received by the BS. (Note that the bar graphs of the "Random only" and "Sensor only" methods overlap.)

"Random" and "Sensor only" methods. For 50-node and 100-node deployments, the number of packets received at the BS in the "Proposed" and "TDMA only" methods increased 14.3 times. This was because packet collisions were prevented to a considerable extent. Generally, in the TDMA scheme, if many sensor nodes are deployed in the target field, it is difficult to completely avoid packet collisions because of the lack of time slots. The ratio of the number of packets received at the BS in the "Proposed" and "TDMA only" methods to that in the "Random" and "Sensor only" methods was smaller in the 150-node and 200-node deployments than in the 50-node and 100-node deployments. However, the ratio was still more than 4.3. This result indicated that in the TDMA scheme, the "Proposed" and "TDMA only" methods were effective in avoiding packet collisions; thus, efficient and stable data transfer could be achieved in these methods.

From these simulation results, it can be confirmed that with the proposed method, balance in the distribution of each sensor function can be achieved in addition to effective data aggregation.

4.2. Network lifetime vs. the number of aggregated packets

Figure 6 plots the number of packets received at a BS during one cycle over time when 50 nodes are deployed in the target field. In this figure, the x-axis represents time, and the y-axis represents the number of packets received at the BS. The lines in the plot differ with the method applied and the location of the BS. Two different cases were considered for the location of the BS. In the first case, the BS is located at a corner of the field, i.e., BS = (0,0). In the second case, the BS is located at the center of the field, i.e., BS = (50,50). From the figure, it can be observed that the BS received many packets from the WSN in one cycle in the "Greedy" method; however, the network lifetime in this method was shorter when compared to the network lifetime in the other methods. On the other hand, although the network lifetime of the "Ideal" method was longer than that of the network in the other methods, the number of packets received at the BS in one cycle was smaller in the "Ideal" method than in the other methods. In the proposed method, the number of packets received at the BS was initially identical to that in the "Greedy" method. The number of aggregated packets received at the BS in one cycle decreased with a decrease in the power remaining in the node battery. For example, the number of packets decreased from 1000 to 800 in cycle 10, as seen in Figure 6. This shows that in each sensor node, reduction in battery power consumption was given priority over data aggregation. As a result, the proposed method realized a longer network lifetime than the "Random" and "Greedy" methods. However, in the proposed algorithm, a tradeoff was made between the number of aggregated packets and network lifetime. For example, for monitoring the environment for a long time, the duration of sleep time in one cycle should be large in order to extend the network lifetime, and this is easily realized in our method.

Figure 7 shows the average power remaining in the batteries of all the nodes that are deployed in the WSN, where in 50 nodes are scattered in the target field. The x-axis shows the simulation time, and the y-axis shows the initial power of the battery (0.4 mAh). The lines in the plot differ with the method applied and the location of the BS. Each dot in the figure corresponds to the average number of active nodes at a given time, and the vertical error bar

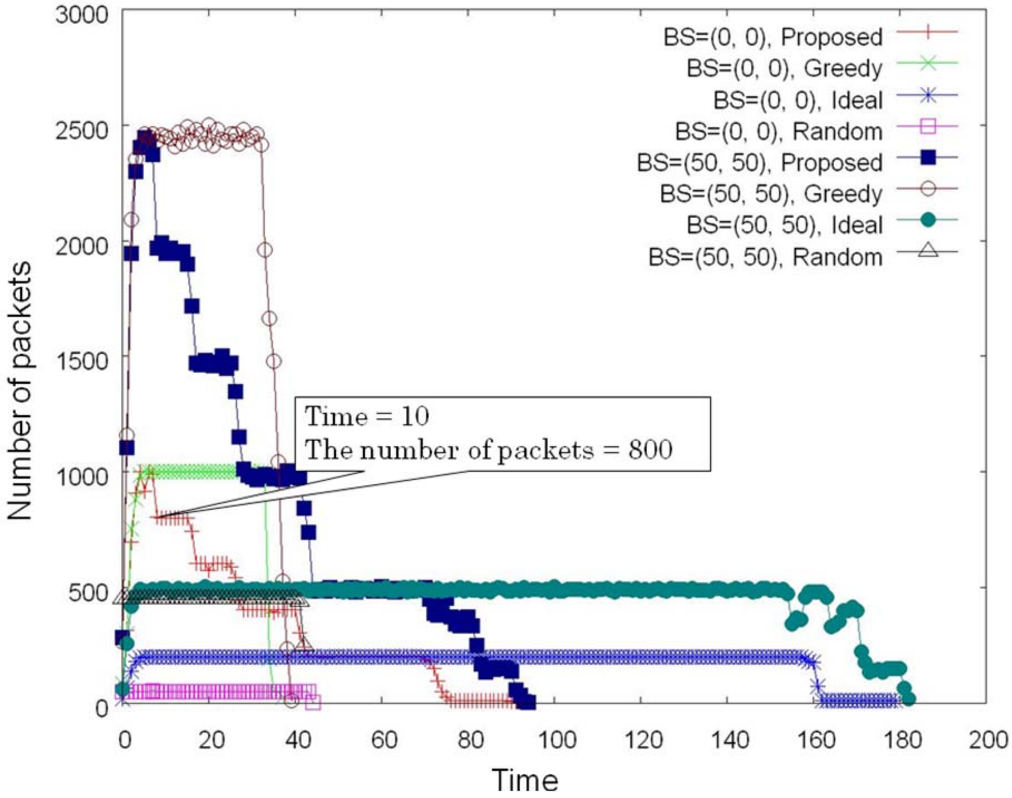

Figure 6. The number of packets received at the BS in one cycle. The number of nodes is 50. The x-axis represents time, and the y-axis represents the number of packets received at the BS in one cycle

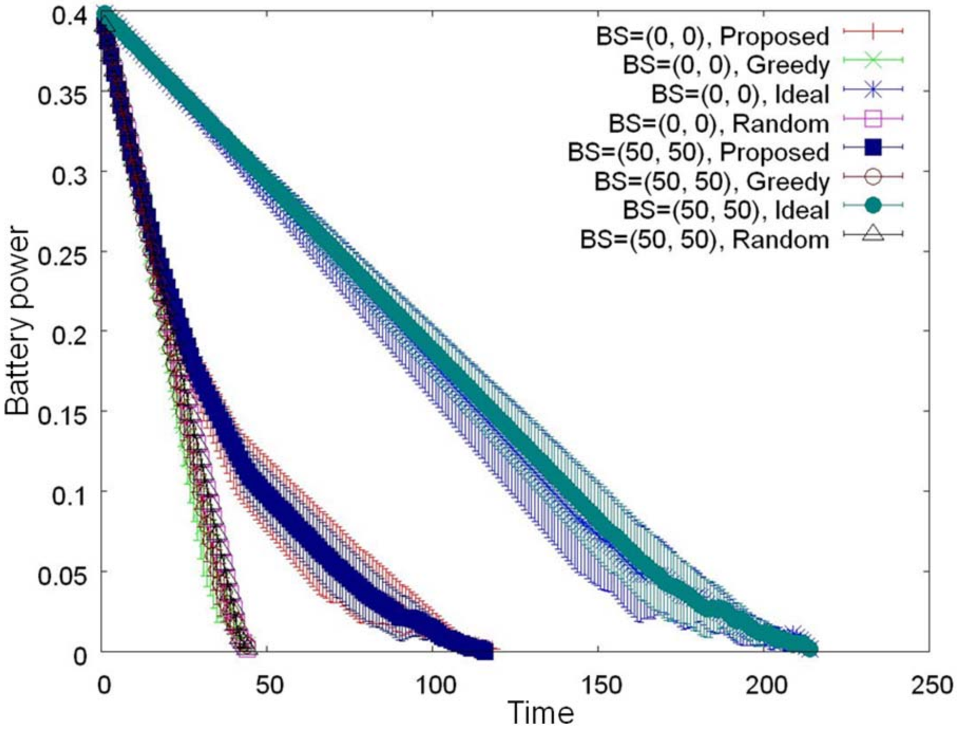

Figure 7. Battery power. The number of nodes deployed in the network is 50. The x-axis represents time, and the y-axis represents the average battery power

associated with the dot corresponds to its variance. As is evident from the figure, battery power consumption was reduced in the proposed method; further, the node lifetime in the proposed method was almost double the node lifetime in “Random” and “Greedy” methods, in which the sleep time is zero. This implies that the sleep time must be extended in order to reduce the battery power consumption. Furthermore, node lifetime in the proposed method was one-half that of the node lifetime in the “Ideal” method although each node often had more than one child node and was thus involved in relaying packets from these child nodes.

From Figures 6 and 7, it can be seen that with the proposed method, the network lifetime and the number of packets received at a BS are optimized and effective data aggregation is realized. The evaluation results are similar in all the other cases where 100, 150, and 200 nodes were scattered in the target field.

4.3. Area coverage of each sensor function

We also evaluated the area coverage of each sensor function. Area coverage is defined as the ratio of the area covered by the sensor function to the area of the target field. In this evaluation, we assumed that the area coverage of each sensor function is equal to the communication area. Figure 8 shows an example of area coverage. The x-axis represents the x-coordinate of the target area, while the y-axis represents the y-coordinate of the target area. The target area is denoted by different patterns. Each pattern represents the range of the number of packets received at a BS in one cycle. In this figure, the area coverage is the ratio of the shaded area to the entire area. Figure 8 shows that more than 91% of the area can be

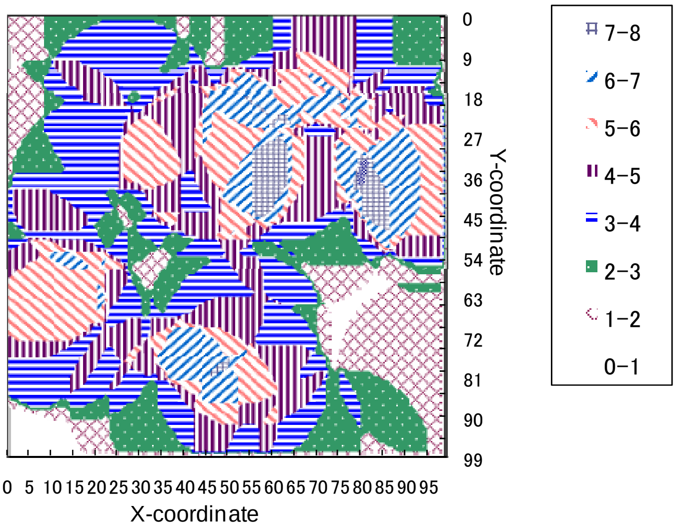

Figure 8. Area coverage of sensor function “1” when the “Ideal” algorithm is applied. The number of nodes is 150

monitored. Area coverage is very important for environmental surveillance, and higher area coverage is preferable. The experimental results are shown in Table 1. In this table, each value refers to the area coverage. “BS location” refers to the location of the BS, “Method” represents the sensor function, “# of nodes” refers to the sum of the nodes deployed in the WSN, “Sensor function” refers to the function allocated to each sensor, and “Avg.” refers to the average value of the area coverage of the sensor function. From Table 1, it can be seen that a high area coverage can be achieved with the proposed method. In particular, the area coverage is as high as 90% when the number of scattered nodes is 150 and BS = (50, 50). On the other hand, the area coverage in the “Random” method is relatively low in almost all the cases. Contrary to our expectations, the area coverage in the “Greedy” method was low since the network lifetime in this case was short. We could realize a long lifetime in the “Ideal” method by sacrificing on area coverage. This means that a long network lifetime and a high area coverage cannot be simultaneously achieved in the “Greedy” and “Ideal” methods. The area coverage and network lifetime in the proposed method are better than the area coverage and network lifetime in the other methods.

5. Conclusions

We proposed a method for the simultaneous optimization of sensor function allocation and time slot allocation in TDMA. This method was based on a distributed graph coloring algorithm and realized dynamic sensor function allocation while taking into consideration the balance between the distributions of the sensor functions in the target monitoring area. In addition, by using the TDMA scheme, wherein time slots were dynamically assigned to the appropriate sensor nodes, packet collisions were avoided. A tree network structure was introduced for effective data aggregation. The tree topology was autonomously generated and maintained so as to shorten the data transfer paths between the sensor nodes and the BS. The experimental results showed that sensor function allocation was more balanced in the

Table 1. Area coverage of each sensor function calculated on the basis of the number of packets received at the BS

Method	# of nodes	Sensor function				Avg.
		0	1	2	3	
BS location: corner of the field, (0,0)						
Proposed	50	0.41	0.40	0.42	0.42	0.41
Proposed	100	0.53	0.51	0.53	0.53	0.52
Proposed	150	0.54	0.54	0.55	0.54	0.54
Proposed	200	0.72	0.72	0.72	0.73	0.72
Greedy	50	0.58	0.57	0.58	0.54	0.57
Greedy	100	0.86	0.83	0.86	0.87	0.86
Greedy	150	0.73	0.72	0.73	0.73	0.73
Greedy	200	0.78	0.79	0.79	0.79	0.78
Ideal	50	0.36	0.33	0.32	0.31	0.33
Ideal	100	0.38	0.39	0.36	0.38	0.38
Ideal	150	0.54	0.54	0.55	0.55	0.55
Ideal	200	0.74	0.74	0.74	0.74	0.74
Random	50	0.10	0.10	0.13	0.11	0.11
Random	100	0.12	0.12	0.12	0.12	0.12
Random	150	0.36	0.33	0.39	0.30	0.35
Random	200	0.48	0.49	0.49	0.48	0.48
BS location: center of the field, (50,50)						
Proposed	50	0.67	0.63	0.66	0.69	0.66
Proposed	100	0.83	0.84	0.83	0.85	0.84
Proposed	150	0.90	0.91	0.90	0.91	0.90
Proposed	200	0.87	0.87	0.87	0.87	0.87
Greedy	50	0.74	0.62	0.63	0.64	0.66
Greedy	100	0.84	0.84	0.85	0.81	0.84
Greedy	150	0.89	0.90	0.89	0.90	0.89
Greedy	200	0.88	0.88	0.88	0.88	0.88
Ideal	50	0.74	0.65	0.67	0.69	0.69
Ideal	100	0.88	0.90	0.89	0.87	0.89
Ideal	150	0.93	0.93	0.93	0.93	0.93
Ideal	200	0.91	0.91	0.91	0.91	0.91
Random	50	0.48	0.44	0.45	0.50	0.47
Random	100	0.65	0.65	0.65	0.68	0.66
Random	150	0.72	0.79	0.75	0.75	0.75
Random	200	0.86	0.85	0.86	0.85	0.85

proposed method than in non-optimized methods. In addition, as a result of collision-free communications, the number of data packets received at the BS in the proposed method increased from 4.3 to 14.3 times the number of data packets received at the BS in non-optimized methods. Furthermore, the network lifetime in the proposed method was double that in other individual optimization or non-optimized methods; further, high area overage could be achieved with the proposed method.

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