Abstract: In this paper, we proposed a node placement strategy in linear networks and mobility control strategy for equally-spaced placements. Our purpose is to maximize the sensing area by solving the problem of unbalanced traffic load in the sensor network. Through simulations, we verify that these strategies have significant benefits on the total sensing area of a given system. Finally, we extend our node placement strategy to a 2-dimensional network and identify its advantages.

Keywords: Mobile robots, Sensor systems, Location, Relays.

1. INTRODUCTION

As mobile robot technology has evolved, its application has been extended to various fields involving exploration, search, and rescue operations. On the other hand, wireless sensor networks (WSNs) have also drawn much attention, because they enable mobile robots to operate efficiently with low cost and low power consumption. A general WSN is distinguished from other networks because it has several limitations, such as in battery power, node density, and data size (David et al., 2004). In particular, power saving is of great importance mostly to prolonging the lifetime of the network. In static WSN, one objective is to extend the lifetime by controlling the activity of each sensor node, whereas primary concern in mobile node systems is to extend the sensing area of the entire system while minimizing energy consumption caused by node movement and communications (Poduri and Sukhatme, 2004).

In static WSNs, several approaches have been suggested to prolong the lifetime. These include reducing redundant idle listening time of sensor nodes and minimizing standby power consumption (Suresh and Raghavendra, 1998) via proper protocol design and advanced methods of hardware implementation. In addition, load balancing is an important factor in considering the lifetime of static WSNs. Let us assume a many-to-one system, where one sink node collects data from many of the other nodes. Nodes closer to the sink node will suffer from high traffic load because they must relay data from the outer nodes, whereas the outer nodes relay less data; hence, the network lifetime becomes more dependent on the closer nodes.

In mobile WSNs, most research is conducted on the assumption that energy consumption by movement control is relatively high, compared to the power consumption by communication protocols. However, as the system evolves and the application area is extended, the power required to move nodes decreases whereas the transmission power increases given the increased volume of multimedia traffic (Akyildiz et al., 2007). Therefore, in mobile WSNs that handle multimedia sensing data, energy consumption by transmission and movement should be considered simultaneously. This is the main topic of this paper.

There are several previous studies on resolving of unbalanced traffic load with node placement optimization (Cao et al., 2008; Cheng et al., 2004; Yu et al., 2005). Our study is different from these in the sense that we consider the mobility of the nodes. In this paper, we do not design any energy-efficient communication protocols. Instead, we attempt to minimize energy consumption via load balancing of mobile sensor nodes. On the other hand, by controlling the position of the nodes, we can balance the load so that the energy consumption among the nodes becomes fair. Here we consider this energy-sensing area tradeoff caused by mobile movement.

The rest of this paper is organized as follows: Section 2 describes the problem and the system model. In Section 3, we illustrate our node placement strategies in linear networks. A movement strategy based on equally-spaced placement will be dealt with in Section 4. In Section 5, we show simulation results and compute performance bounds. An extension to planar networks is considered in Section 6. Finally, we conclude the paper with remarks on future research in Section 7.

2. SYSTEM MODEL AND PROBLEM DEFINITION

Consider a linear sensor network, where \( N \) sensor nodes are placed along a line with a sink node at the left end of the line. Each sensor node has homogeneous initial energy \( P \) and the capacity for mobility. From the node at the right end of the line, the data collected during sensing are transmitted to the sink node sequentially along the linear route.
In Figure 1, \( X_i \) denotes the \( i \)th mobile sensor node from the sink node. The value \( d_i \) is the moving distance of \( X_i \) from the sink node to the final point of \( X_1 \). We assume that each node collects data periodically and the amount of data collected in a unit distance per unit time is constant and equal to the data density, \( D \). If \( X_N \) moves along the distance, \( d_N \), then the amount of collected data is \( D \cdot d_N \). We assume that the energy consumption rate for movement, transmission, and reception are fixed at certain values.

There are three steps in the system; node placement, sensing, and transmission. The optimum placement of nodes is described in Section 3. After placement, each node moves to collect data in the service area which is defined as a line in this paper. During movement, the nodes sense data, such as temperature, height and other information in the form of images, sounds, and video streams. If all nodes finish gathering data, each node sends the data to its neighbor node in the direction to the sink node. For example, \( X_N \) only transmits the collected data to the neighbor node while \( X_{N-1} \) transmits its own data and relays the received data from \( X_N \) to \( X_{N-2} \). Therefore, the closer a node is located to the sink node, the greater the power required to transmit and relay data to the neighbor node.

It can be easily inferred that the exploration area of the nodes closed to the sink node should be less than that of the nodes far from the sink node. To resolve the load imbalance and maximize the entire sensing area of a WSN, in the next section we propose an algorithm that initially places multiple nodes at the optimal point. With sensing nodes placed optimally in the node placement step, the sensing area is maximized and the energy consumption for data delivery and mobile movement is minimized.

In Figure 2, the three steps of the system are described. In the node placement step, the optimal initial point is settled considering the communication range, maximum power consumption \( P \) and the number of nodes \( N \). The nodes are placed at the initial point, where \( X_1 \) and \( X_{N-1} \) are spaced apart by \( d_{j+1} \). In the sensing step, \( X_j \) moves by \( d_j \) in the direction of \( X_{j+1} \), then senses and collects the data. In this paper, we call the point at a sensing distance of \( d_j \) from the initial placement of the node \( X_j \) as a visiting point. Finally, in the transmission step, \( X_j \) moves back as \( l_j \) the distance between the visiting point and the final point, to guarantee the connectivity of the nodes, then the distance between \( X_j \) and \( X_{j+1} \) is less than \( d_{CR} \), the communicable range.

Throughout the paper, our objective is to find an effective node placement scheme that maximizes the sensing area in linear sensor networks (later extended to planar networks), while minimizing the energy consumption of communications (for data delivery) and mobile movement (for sensing).

3. NODE PLACEMENT ALGORITHM

3.1 Node placement with infinite communication range

The proposed algorithm decides the optimal initial placement of the nodes and the distance \( d_i \). Initial placement and visiting points are calculated with respect to the regarding total sensing area and the connectivity. For the purpose, we consider two cases; in which the communication range is either infinite or finite.

In the node placement step, the proposed algorithm decides \( d_i \) and optimally places nodes so that they can sense and collect as much data as possible and stay connected with each other. To calculate \( d_i \), the total power consumption of \( X_i \), \( P_i \), is obtained by (1), for \( i=1, \ldots, N-1 \).

\[
P_i = P_s(l_i + d_i) + G_{r,i} P_r + (d_i D + G_{t,i}) P_t \leq \overline{P} \tag{1}
\]

The total power consumption consists of power for sensing and communication (receiving and transmitting) for \( i=1, \ldots, N-1 \). \( P_s \) (per unit distance), \( P_r \) (per packet), and \( P_t \) (per packet) are the power values for sensing, receiving, and transmitting, respectively.

The total power consumption should be less than the maximum power consumption \( \overline{P} \). The amount of data delivered from \( X_i \), \( G_i \), can be described by (2).

\[
G_i = \sum_{j=i+1}^{N} d_j D \text{ for } i=2, \ldots, N-1 \tag{2}
\]

A node \( X_i \) relays the data from \( X_{i+1}, X_{i+2}, \ldots X_N \) to \( X_{i-1} \). Under the assumption of the infinite communication range, the node does not necessarily move back to its final point, i.e., \( l_i=0 \).

\[
d_N = \frac{\overline{P}}{DP_t + P_r} \tag{3}
\]

For the last node \( X_N \), the sensing distance \( d_N \) is given as (3), where \( X_N \) only transmits its own sensing data to the neighbor node \( X_{N-1} \). For \( i=1, \ldots, N-1 \), the sensing distance \( d_i \) is given as (4).

\[
d_i = \frac{\overline{P} - \sum_{j=i+1}^{N} d_j D (P_r + P_t)}{DP_t + P_r} \text{ for } i=1, \ldots, N-1 \tag{4}
\]
3.2 Node placement with finite communication range

In practical systems, the communication range, $d_{CR}$, is limited because of the cost and power of the device and it is an important factor for designing a WSN (Adb-Alhameed et al., 2008). Guaranteeing the connectivity between nodes becomes crucial under conditions of limited communication range. In this section, the algorithm in Section 3.1 is elaborated to guarantee connectivity by considering $d_{CR}$. If $X_i$ cannot communicate with the neighbor nodes at the visiting point, it moves to the proper position to transmit the data. We call this proper position the final point. It can be easily shown that if $X_i$ moves from the visiting point more toward the final point, the sensing distance decreases because of limited power consumption.

To find the sensing distance and the final point, the algorithm iteratively calculates the total power consumption of $X_i$ as in (5). By iteratively calculating the total power consumption, the sensing distance and the final point can be derived.
we do not control the initial point of the nodes. The purpose of this section is to maximize the sensing area of the system by controlling the visiting and final points of the nodes. Let \( d_{eq} \) denote equal distances between each adjacent pair of nodes. When nodes are deployed, they communicate with each other to verify the distances, \( d_{eq} \), between them. After they determine the distance, which is smaller than \( d_{CR} \), they can find the visiting and final points that maximize the total sensing area.

As stated in Section 1, the lifetime of a WSN is dependent on that of the node closest to the sink node. A general WSN works until the node closest to the sink node shuts down. When the \( P_i \) exceeds \( \bar{P} \), \( X_1 \) cannot transmit the data collected by itself and delivered from \( X_2 \). Therefore, the system is invalid. However, with mobility control, if \( X_1 \) suffers from a lack of power, then \( X_2 \) can support it by an increased sensing distance.

As shown in Figure 5, if \( X_1 \) cannot afford to move by \( d_{eq} \) because of lack of power, it moves along \( d_i \) solely to sense data. \( X_2 \) moves to compensate for the distance that \( X_1 \) cannot explore. If \( X_2 \) also has insufficient power, \( X_3 \) supports \( X_2 \). This process is repeated in ascending order.

In this case, \( X_3 \) moves the same distance as in Section 3, when comparing the positions at the initial placement and at transmission. However, the distance between the visiting point and the final point, \( l_{i-1} \), is different from that in Section 3, because the final position of \( X_{N,i} \) is set to the initial point of \( X_N \). This is summarized in (6).

\[
\begin{align*}
    d_N' & = \begin{cases} 
    d_N & \text{if } d_N \leq d_{CR} \\
    d_{CR} + l_{i-1} & \text{if } d_N > d_{CR}
    \end{cases} \\
\end{align*}
\]

(6)

It appears strange that only \( X_N \) follows an activity rule that is different from that of other nodes. However, \( d_N \) must be known to calculate the distances in descending order, from \( N-1 \) to 1. There is no other way to select \( d_N \) directly when we know just initial power of nodes and \( d_{eq} \).

\[
P_i = (l_i + d_j) P_e + \left( \sum_{j=i+1}^{N-1} d_j + d_N' \right) D P_e + \left( \sum_{j=i+1}^{N-1} d_j + d_N' \right) D P_t
\]

(7)

The total power consumption of \( X_i \) is given as (7), where \( l_i = d_i + l_{i+1} - d_{eq} \) for \( i=1, \ldots, N-2 \), and \( l_{N,1} = d_N - d_{eq} \) as Figure 5.\(^1\)

As mentioned above, \( d_N \) acts as in Section 3. Then the final point of \( X_{N,i} \) is given as (8).

\[
d_{N-1} = \frac{\bar{P} + d_{eq} P_e - d_N' D (P_e + P_t)}{2 P_e + D P_t}
\]

(8)

If we assume that the total power consumption of each node is equal to the power limit \( \bar{P} \), then the moving distance of \( X_i \) is given as (9) where \( i=1, \ldots, N-2 \).

\[
d_i = \frac{\bar{P} + (d_{eq} - l_{i+1}) P_e - \left( \sum_{j=i+1}^{N-1} d_j + d_N' \right) D (P_e + P_t)}{2 P_e + D P_t}
\]

(9)

It is also possible that \( X_N \) also moves left to support \( X_{N,1} \) like Section 3. However, in that case, \( d_r \) cannot be calculated in a closed form. Furthermore, using another simple simulation, we find that the above algorithm provides an optimal control in the ESP system.

5. SIMULATION RESULTS

We illustrate the numerical results and compare the sensing area and residual power of each node to verify the improvements of the proposed algorithm. We used \( \bar{P} = 130000mW, P_e = 16000mW/m, P_o = 36mW/packet, P_t = 60mW/packet, D = 30packet/m, d_{CR} = 5m, \) and \( N = 5 \) in the simulation as in Rhami et al. (2003). \( D \) is set to a large value so as to model multimedia data.

In Figure 6 and Figure 7, we compare the total sensing areas of the proposed algorithm with infinite and finite communication ranges, respectively. Both distances are normalized by the total sensing area in the case of infinite communication range (26.46m) With a finite communication range, there is a 5.04% reduction in the sensing area relative to infinite communication range networks. The top, middle, and bottom rows represent the node placement, sensing, and transmission steps, respectively.

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\(^1\) You should give an attention that the definition of \( d_i \) and \( l_i \) is different to Figure 2.
Figure 8 shows the total sensing area for three cases: the optimal node placement strategy, the result from the mobility control algorithm on ESP proposed in Section 4, and the upper bound of the conventional strategy on ESP. With conventional strategy, $X_i$ moves to the initial point of $X_{i+1}$ without support of $X_{i+1}$, then the nodes closed to the sink node suffer from heavy load as explained in introduction. In Figure 8, the distances are normalized by the total sensing area of the optimal placement strategy with finite communication range. The normalized total sensing areas are 1, 0.965, and 0.922 for the optimal node placement algorithm, in mobility control algorithm, and conventional strategy on ESP, respectively. The mobility control algorithm on ESP leads to a 5.19% extension of the sensing area than conventional strategy. It would become larger when data density increases.

Table 1 shows the ratio of the residual power to the initial power for each node. By using the residual power of each node in the conventional strategy, the total sensing area can be extended with mobility control algorithm.

We also examine the total sensing area of each system while varying the number of nodes from 3 to 10. The results are shown in Figure 9. The distances are normalized by the total sensing area of the optimal node placement algorithm with finite communication range. As the number of nodes increases, the sensing areas of the mobility control algorithm and conventional strategy cases decrease relative to the optimal node placement case. Figure 9 shows that the optimal node placement clearly improves the performance of the system in terms of the total sensing area. When nodes are pre-deployed, our mobility control algorithm extends over the total sensing area, even though performance in this case is lower than that of the optimal node placement algorithm.

### Table 1 Residual power ratio of each node

<table>
<thead>
<tr>
<th></th>
<th>$X_1$</th>
<th>$X_2$</th>
<th>$X_3$</th>
<th>$X_4$</th>
<th>$X_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Node Placement &amp; Mobility Control algorithm</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Conventional Strategy on ESP</td>
<td>0.094</td>
<td>0.188</td>
<td>0.282</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10. Tree model node placement strategies in a 2-dimensional WSN network.

6. PLANAR NETWORK

In this section, we extend the optimal node placement algorithm to 2-dimensional planar networks. In the previous sections, the sensing range of each node is ignored because it is a linear WSN. However, in this section, the sensing range of nodes is considered as an important factor. Therefore, we add a new variable $r$ that represents the radius of the sensing range. According to the report by Cheng et al. (2004), there are two kinds of placement in a 2-dimensional WSN: the linear approximation mode and the star mode. Cheng concluded that the star mode is more efficient than the linear approximation mode in terms of total power consumption. For this paper, we examine a new model, which we call as the tree model. It is a hierarchically deployed model, as represented in Figure 10. Each circle on which nodes are located is denoted as a node level. Level 1 indicates the smallest circle, and the levels increase as the circles move outward.

The simulation is similar to that in Section 5. The reason for this is that, by making upper-level nodes move for sensing relatively small areas compared to lower-level nodes, the traffic load of the system is balanced when the upper-level nodes relay the data from the lower-level nodes. However, the problem becomes much more complicated when it is extended to 2-dimensional area. The routing algorithm...
becomes more complex than the linear system. In addition, node placement for the total sensing area covers the entire region. Hence, it is extremely hard to find an optimal placement strategy. Therefore, we provide heuristic algorithms based on the insights from the linear network. Our heuristic node placement strategy is to decide the proper placement of nodes so that all of nodes can sense the assigned areas and collect all data from the nodes aggregating towards the center. Our purpose is to minimize the number of nodes given a certain circle shaped region. We compare the tree model heuristic strategy and the star mode strategy and the linear approximation method in Figure 11, in terms of the total number of nodes needed to cover the entire region. We use same parameters as in Section 5, \( P = 1300000 \text{mW}, P_s = 16000 \text{mW/m}, P_v = 36 \text{mW/packet}, P_e = 60 \text{mW/packet}, D = 30 \text{packet/m}, \) and \( d_{CR} = 5 \text{m}. \) We add one more variable, setting the sensing range to \( r = 1 \text{m}. \)

The linear approximation method requires more nodes to cover the region. The reason for this is that more nodes must be deployed to relay the data at the terminal side of networks, where the traffic load is much heavier. However, as the radius increases, the overlap in the sensing area also increases. Therefore, performance for the star mode becomes worse than that for the linear approximation method. With the tree model, we can reduce the overlap in the sensing area while increasing the traffic load. By controlling the distances between the levels, the number of nodes can be reduced. With 400 nodes, the tree model can cover a circle that has radii of 24m, whereas radii of 18m and 19m can be covered by the linear approximation method and star mode, respectively.

7. CONCLUSIONS

In this paper, we investigate the problem of optimal mobile node placements in linear WSNs. We also illustrate an optimal moving strategy on ESP to solve the problem of unbalanced traffic load. Simulation results show that this strategy has significant benefits. Lastly, we consider a planar model and verify that a tree model has advantages especially in terms of entire sensing area.

This study has various applications in WSN, which treats multimedia data, especially on placement of mobile sensors for exploration. It is possible to explore larger area with fewer sensors when applying the node placement algorithm, introduced in this paper. It can lead to a valuable contribution to multimedia WSN, where its initial topology is controllable, like ecosystem exploration, planet exploration, and ocean exploration. The mobility control algorithm applied to ESP system is also able to give an impact to SON (Self-Organized Network) (Bernd, 1994) with mobile nodes when it is expanded to randomly deployed nodes systems.

Challenges for future work will include application of power control of transmission of data considering the distances between nodes, detailed analysis of 2-dimensional network systems, and extending the mobility control algorithm to systems with randomly deployed nodes.

Fig. 11. Number of nodes as a function of the radius of region.

8. REFERENCES