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A Cluster-based Routing Scheme to Improve the Network Lifetime in Wireless Sensor Networks with a Mobile Sink

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ABSTRACT: In a wireless sensor network which consists of a base station as a data sink and a number of sensor nodes, the clustering has been adopted as a way of reducing the energy consumption of communication. The clustering, however, has suffered from the rapid burnout of cluster heads. We propose a 2-tier data collection architecture which requires single-hop intra-cluster transmission and direct communication between mobile sink and cluster heads. To maximize the network lifetime, cluster heads are reselected based on the remaining energy level. The clustering and the routing algorithm are processed by the base station and a mobile node navigates among sensor nodes periodically, collects power usage data from each sensor node, and deliver the next clustering and routing information. A clustering and mobile sink navigation path search algorithm based on Voronoi graphs is proposed.

KEYWORDS: sensor networks, mobile sink, clustering, navigation, Voronoi graph

I. Introduction

In most of wireless sensor networks(WSNs), sensor nodes and sink nodes are stationary, that is, they don't move after once deployed at the first phase. If some of nodes are no longer available due to the energy exhaustion, the logical network topology may be changed to prolong the network lifetime. Each sensor node sends collected data to a sink, or a base station. For energy efficiency, cluster-based network topology and routing scheme is very common in this type of data collection. One cluster consists of single cluster head and several member nodes, the member nodes transfer their data to their cluster head, and the heads transfer the aggregated data to the base station. Inevitably, the cluster heads are suffering from rapid energy consumption, so many research works about periodical re-election and replacement of cluster heads have been performed[1].

On the other hand, giving mobility to the sink has gained popularity because it can reduce the energy consumption on each sensor node by direct communication between the mobile sink and the sensor node[2]. Even in case that some nodes have failed or they are deployed sparsely, the mobile sink can maintain the network connectivity and longer network lifetime. Recent development of UAVs(Unmanned Aerial Vehicles) or autonomous cars makes the concept of mobile sinks feasible and plausible.

In this paper, we propose an energy-efficient sensor network management scheme combining clustering and mobile sink. The mobile sink circulates among cluster heads to receive collected data as well as the energy status of nodes to elect new cluster head, and delivers them to the base station. Each sensor node communicates with only its cluster head by single hop transmission. If the energy status of some cluster heads goes beyond some marginal value, the base station elects new cluster heads and updates routing information. In the next round, the mobile sink notifies the topology change and routing information to sensor nodes while collecting sensing data. The network lifetime can be extended because of the rather even energy consumption by periodic head shift, reducing the amount of the data transmission and multi-hop routing, and transferring time-consuming calculation for dynamic clustering to the base station. Clustering and mobile sink navigating path are based on the Voronoi decomposition.

II. Related work

LEACH(Low Energy Adaptive Clustering Hierarchy)[3], proposed by Heinzelman et al., is one of the most popular and pioneering algorithm for WSNs. It utilizes randomized rotation of cluster heads to evenly distribute the energy load among all sensor nodes. Intra-cluster communication uses single-hop direct transmission with a TDMA schedule created by the cluster, and shared with all other members. As fully distributed strategy, a cluster is formed based on the

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received signal strength and the CH nodes acts as router to the base station. CH rotation is performed by getting each node to choose a random number between 0 and 1. If the number is less than a threshold, the node would be a new cluster head.

The cluster setup process including cluster formation, CH selection and routing path computation is time-consuming and energy-intensive, so some researchers developed centralized methods that the base station takes charge of those work[4, 5]. BCDCP(Base-Station Controlled Dynamic Clustering Protocol)[4], presented by Muruganathan et al. is a centralized clustering routing protocol. In this scheme, the energy-intensive computation for cluster setup and routing path is performed by a powerful base station. The main idea is the formation of balanced clusters where each cluster head serves an approximately equal number of member nodes to avoid cluster head overload, uniform placement of cluster head throughout the whole sensor field, and utilization of CH-to-CH routing to transfer the data to the base station. At the cluster setup stage, information on the residual energy of all nodes is sent to the base station(BS). The BS constructs a set of nodes whose energy levels are above the average value, and then form clusters with an iterative cluster splitting algorithm.

Sink mobility is an alternative technology for energy-efficient WSNs. It can avoid extra energy consumption for multi-hop routing since the sensors can transmit their traffic only when sink node is nearby. Hotspot nodes, such as a cluster head or neighbors of base station, are no longer existent. Sink mobility is good for the network connectivity, in case of sparse network or worn-out network with some fail nodes.

Wang et. al[6] proposed a mobile sink routing algorithm with registering in cluster-based architecture. Each sensor maintains a neighbor information table holding the information on the geographical address and energy status. Cluster setup and routing path selection is performed in distributed manner based on the remaining energy, and the mobile sink takes a part in exchange of address information.

TTDD(Two-Tier Data Dissemination)[7], introduced by Luo et. al, adopts a grid structure for network scalability and efficient data delivery to the multiple mobile sinks. Each data source proactively constructs a grid structure, which enables mobile sinks to continuously receive data on the move by flooding queries within a local cell only. Queries from sink nodes can be propagated along the grid until the source node. Only the sensor nodes located in the grid points need to acquire forwarding information. The query messages are propagated along the grid, and only dissemination nodes participate in data transmission.

III. PROPOSED SCHEME

A. *Design Considerations and Assumptions:*

- All nodes in the network are homogeneous and energy-constrained.
- All nodes in the sensor field are stationary after deployment.
- The location of all sensor nodes is known to the base station.
- Links are symmetric.
- The shape and physical characteristic of mobile sink are not restricted, and also have no effect on the performance of the protocol.

B. *Network Structure and Components*:

Fig. 1 shows the overall architecture and basic behaviour of each component. Sensor nodes collect data from surrounding environment and send them to the base station eventually. They are divided into clusters and one of cluster members performs different function as a cluster head(CH). CH aggregates the data from members and transfers them to the mobile sink. In addition to the sensed data, energy states of each node are also sent to the base station for cluster architecture reconstruction. In the same way with the sensed data, the status data are sent from sensor nodes to their cluster heads, and from cluster heads to the mobile sink, and to the base station.

Intra-cluster communication is confined to direct transmission, that is, every node in a cluster should be located within single-hop distance with its cluster head. Members including the head share a TDMA schedule in order to communicate without collision.

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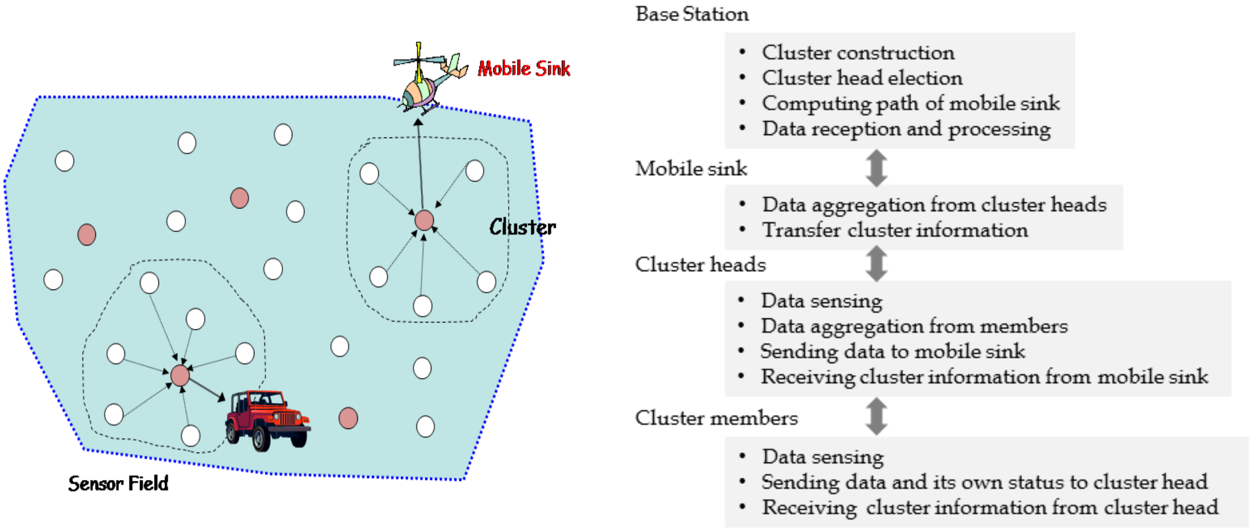

Fig. 1 Architecture of a WSN with mobile sink

C. *Clustering*:

Cluster setup, cluster head selection and creating intra-cluster communication schedule based on TDMA are performed in centralized manner by the base station. Referring to the research work of Wang et al.[8], single hop transmission with maximum transmission power is most power-efficient Thus, we start clustering by partitioning the sensor field based on the maximum transmission range. Cluster setup algorithm is as follows.

Step 1: Partition entire sensor field into squares whose length of a side is maximum transmission range d

Step 2: In a $2d \times 2d$ square, select cluster head(CH). CH is a node which is nearest to the center point at initial stage, or a node which has most remaining energy.

Step 3: Construct clusters with Voronoi decomposition[9]

Step 4: Construct complementary clusters collecting nodes which are unable to communicate directly with their CHs

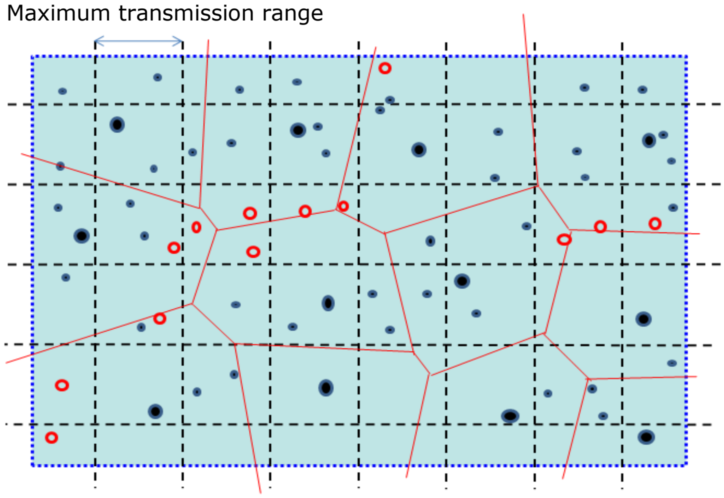

Fig. 2 Clustering

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An example of clustering is shown in Fig. 2. Large circles are CHs and small circles are normal member nodes. Due to the property of Voronoi decomposition, some nodes are located in out or boundary of single-hop transmission range, marked as red circles in the figure. Step 4 of above algorithm is for those nodes which they can be formed another cluster of their own based on the distance.

D. *Navigation Path of Mobile Sink:*

Mobile sink periodically navigates among CHs, collects sensed data and energy level of sensor nodes, and disseminates the cluster information computed by the base station. The power consumption is not a problem for the mobile sink since it can be filled up at the base station, but the delay is fairly problematic because the mechanical movement is far much slower than the radio signal. Thus, we considered 3 alternative path finding algorithms.

(1) TSP(Traveling Salesman Problem) algorithm

TSP is a well-known NP-hard problem which finds a shortest route that visits every city once and returns to the origin city. If this route is used for mobile sink navigation, it is guaranteed that the mobile sink can visit every CHs and communicate with each other. However, unnecessary additional traveling would be a disadvantage if the distance between CHs is much shorter than the transmission range. Path computation time may be another problem, but many heuristics have been developed to reduce computation time. For example, NN(Nearest Neighbor) algorithm has complexity of O(log *n*). The length of path *p* is the minimum value of sum of each distance between nodes.

$$p = \min\left(\sum_{i=0}^{n-1} d_i\right)_{path}$$

where d_i is the distance between CH_i and CH_{i+1}, and *path* is each permutation of CHs. If the node density gets higher, the path gets longer than necessary.

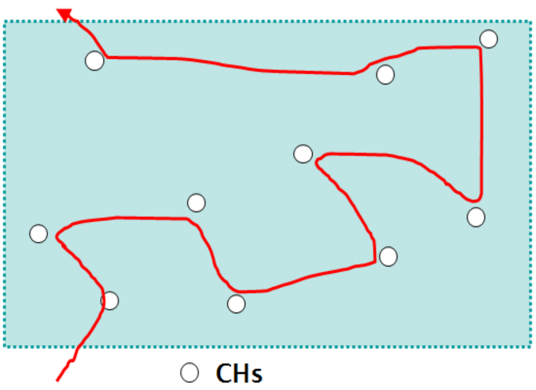

Fig. 3 Path by TSP algorithm

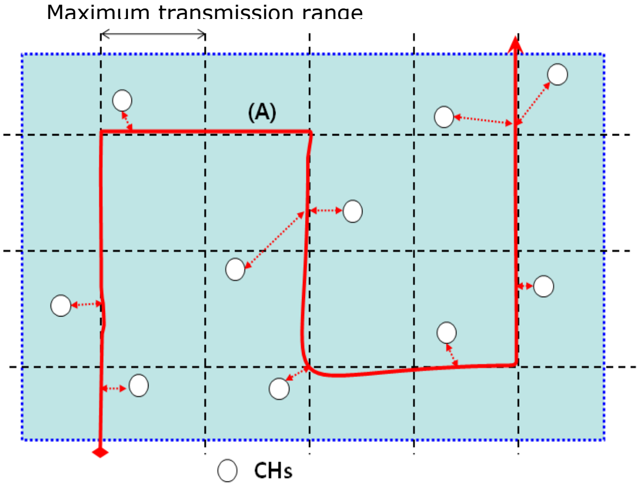

Fig. 4 An example of zigzag path

(2) Zigzag path based on the maximum transmission range

As shown in Fig. 4, the sensor field is partitioned with the maximum transmission range *d*and the mobile sink runs along the border line of partitions. The mobile sink make turns at the boundary of sensor field and after moving forward 2*d* . With given length of sensor field, d, and starting point, the mobile sink can navigate the sensor field without complex path computation. Assuming the sensor field is a square shape and *l* is the length of a side, path length *p* will be calculated with following equation regardless of density of sensor nodes.

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$$p = l + 3kd - 2d, \text{where } k = \left\lfloor \frac{l}{d} \right\rfloor + 1$$

Zigzag path is very simple and fairly efficient, but there is also unnecessary path such as (A) point in Fig. 4 at the point of low node density.

(3) Path using Voronoi decomposition

A Voronoi graph is constructed in order that a vertex joins 3 adjacent areas including one CH each. Then, the mobile sink visits each vertex as shown in Fig. 5.

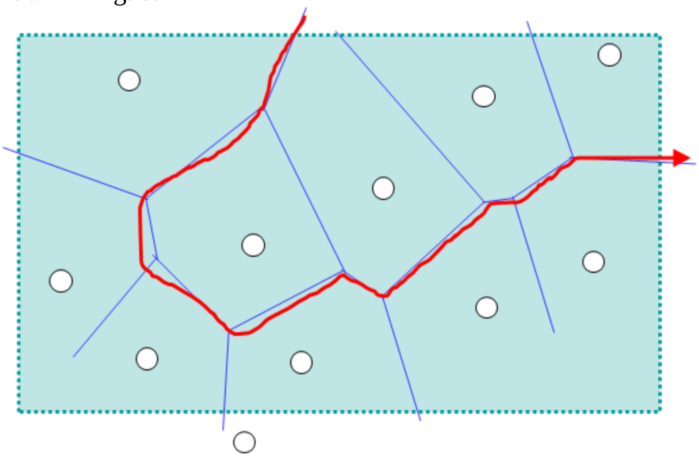

Fig.5 Path using Voronoi Decomposition

If the node density is too low, there is some possibility that the communication is not available due to the long distance between neighbour nodes. In this case, a virtual node is inserted between those two neighbour nodes, and then the Voronoi graph is newly constructed.

For the two dimensional space, the complexity of Fortune's algorithm that performs Voronoi decomposition is O($n$log(n)). If the virtual node insertion and recomputation are repeated k times, the complexity becomes O(knlog(n)). But because this case is applied when usually k<<$n$or n is very small number, the increased complexity is not so serious.

Path length of Voronoi graph depends on the node density and the number of clusters. If the node density is high, the length is longer than that of zigzag path.If the density is very low, the path length will converge to that of TSP path. For appropriate density, it is shown that the Voronoi path is shortest. In any cases, the amount of unnecessary path is not very long compared to TSP and ziazag.

IV. SIMULATION RESULTS

We evaluate our scheme in terms of the path length of mobile sink and network lifetime compared to the network without mobile sink. The simulation environment is set up with the parameters listed in Table 1.

Table 1 Network Parameters

Parameter Name	Value
Size of sensor field	100m×100m
Number of the sensor nodes	10, 50, 100
Length of the packet	2000bits
Initial energy of the sensor nodes	2J
Energy consumption on circuit	50nJ/bit
Channel parameter in free-space model	10pJ/bit/m2

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We proposed 3 ways of finding navigation path for mobile sink. The delay is important factor, so we calculated the average path length of each method for 10, 50, 100 nodes. The nodes are deployed on random position in 100×100m sensor field, and the simulation was performed 10 times for each case. As shown in Fig. 6, zigzag path is identical regardless of the number of nodes. Voronoi path is shorter than zigzag when the density of nodes is low, while it increases proportional to the number of nodes as TSP path does. However, in our scheme, the mobile sink doesn't need to communicate with all sensor nodes but only with cluster head, so Voronoi path can be a good choice.

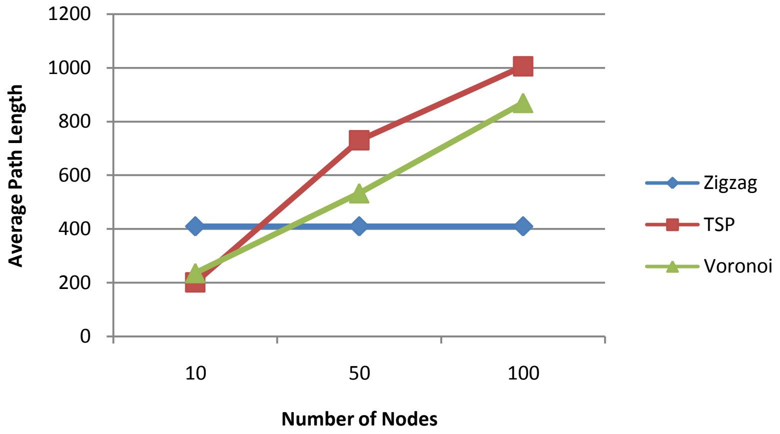

Fig.6 Average path length vs. number of nodes

Fig. 7 shows the comparison result between cluster-based sensor network without mobile sink and with mobile sink. For this simulation, 50 sensor nodes are randomly placed in a square field of varying network areas with the base station located at least 100m away from the closest sensor node. In case of no mobile sink, each cluster head communicate with the base station via multi-hop routing. Therefore the larger network area, the more energy dissipation is shown. Besides, it suffers from rapid exhaustion of some nodes near base station and much shorter network lifetime.

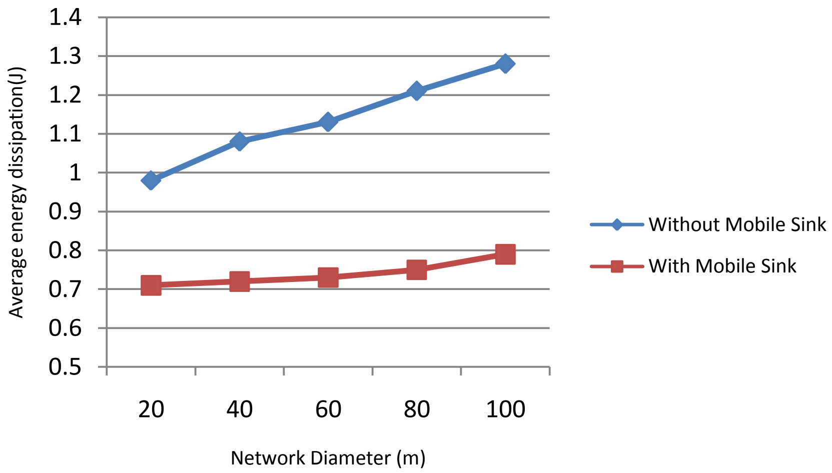

Fig. 7 Average energy dissipation over varying network size

V. CONCLUSION AND FUTURE WORK

We proposed an energy efficient sensor network management scheme combining cluster-based architecture and a mobile sink. The simulation results showed that the proposed scheme makes nodes consume energy more evenly, and

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can improve the network lifetime compared to the case of no mobile sink. Cluster setup and mobile sink navigation path using Voronoi decomposition are proven to be useful.

We assumed just one mobile sink for simplicity, but multiple mobile sinks are more common. Our scheme can be easily adapted with multiple mobile sinks by partitioning the sensor field and one-to-one match with a sink, but some parameters may be tuned for real world applications. We have not considered the sleeping period which is prevalent technique for minimizing the energy consumption of sensor nodes. It will be another challenge to integrate sleeping protocol with our scheme.

While achieving longer network lifetime, the mobile sink scheme should be tolerant to the longer delay because the mechanical movement can never surpass electronic signal speed.

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BIOGRAPHY

Hyeon-Ju Yoonis working as a faculty member of Department of Computer Engineering at Kumoh National Institute of Technology, Korea since 2005. She earned the Ph.D. degree in computer engineering from KAIST(Korea Advanced Institute of Science and Technology) in 1997. Her research areas of interest are computer systems including operating system, distributed system, and embedded systems.

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