Master's Thesis

Title

Controlled Mobile Sink for Highly Reliable Data Collection in Wireless Sensor Networks

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Abstract

Wireless sensor networks (WSN), which facilitate to observe and to collect environmental information by using sensor devices with wireless communication capability, are significantly expected to apply to various applications such as monitoring of temperature and humidity in agriculture, tracking of animals and etc. In particular, the monitoring application with WSN is utilized in large-scale systems such as structural health monitoring systems and smart metering systems. Structural health monitoring systems can detect damage and degradation of transportation infrastructures such as bridges and tunnels, which avoids the collapses of the structures. Smart metering systems can obtain the usage of electric power from each home automatically. In these systems, secure data collection is strongly required since missing data may lead to terrible accidents in structural health monitoring systems, and electric companies cannot determine electricity bill without the data on usage of electric power. In recent years, those monitoring systems are called for not only by urban areas but also by rural areas where it is difficult to provide network infrastructures. In such systems, devices can be removed and added depending on requirement of the systems. Therefore, the way for a system administrator to access all devices in the system is necessary, however, it is difficult to manage all physically separate systems. In this thesis, we focus on using mobile sinks, which move around a wireless sensor network to collect data from wireless sensor nodes. Mobile sinks can save energy of sensor nodes for improving network lifetime and can assure the reachability of sensing data to sink nodes. Both are important challenges in WSN. We realize reliable data collection, which means collecting all sensing data definitely, by controlling a mobile sink from both inside and outside of networks dynamically. Note that we consider the environmental changes caused by removal or addition of sensor nodes, and the mobile sink completes sensing data collection when those environmental changes occur. We perform computer simulations considering the situation that sensor nodes are deployed at random places in an observed area, and show that our proposed method can realize reliable data collection. In addition, we simulate our proposed method under realistic scenarios, where every sensor node is placed at a certain position corresponding to house position in actual city maps and attenuation of radio waves are considered. Finally, we discuss effectiveness of our proposed method in realistic environment.

Keywords

Wireless sensor networks, reliabile data collection, controlled mobility, simulation, actual city map

Contents

List of Figures

List of Tables

1 Introduction

Wireless sensor networks (WSNs) enable us to observe and to collect environmental information by using sensor devices which have radio communication capability [1, 2]. WSNs are significantly expected to apply to various applications, e.g., monitoring of temperature and humidity in agriculture, tracking of animals and etc [3–7]. This feature greatly attracts attention for the development of monitoring systems. For example, the structural health monitoring system [8–10] allows us to estimate damage levels and degradation condition of transportation infrastructure such as bridges and tunnels by detecting deformation of pillars and cracks in walls. The smart metering system [11–13] allows us to monitor electric utility of each home and measure usage of electric power with a wireless sensor device called *smart meter*. In those systems, highly reliable data collection is required for safety of life and manageability of systems.

Structural health monitoring systems closely related to our lives. Accurate estimates and grasp of degradation degree of bridges and tunnels lead to avoid accidents caused by the sudden collapse of those transportation infrastructure. It is also possible to evaluate the risk of collapse and earthquake-resistance strength by storing information of damage levels after the occurrence of accidents. As for smart metering systems, we can access the information about recent usage of electricity and electric companies charges each home electricity bill according to that information automatically measured and collected by smart meters. Significant demands on these systems are to collect all sensing data without any loss. Meanwhile, there is a requirement for shorter delay time to collect sensing data, however, we give first priority to data collection reliability, that is, we allow comparatively long time to collect sensing data.

These monitoring systems can be built in both urban areas and rural areas, where many buildings stand side by side and a few bridges dot, respectively. Since those may be away geographically from each other, in order to operate those separate systems as single integrated system, a mechanism is required for system administrators to access every system and collect data from it. However, it is difficult to assure collecting all sensing data from those sytems. In urban areas, there are too many sensor nodes at high density, which means high connectivity among sensor nodes, but leads congestion caused by increases in sensing data. Also in rural areas, providing network infrastructure is difficult and small number of nodes are much sparsely put into (Fig. 1). In addition, it is required that the system can be operational when adding and removing sensor devices occur, in other words, systems do not have to add infrastructures at all.

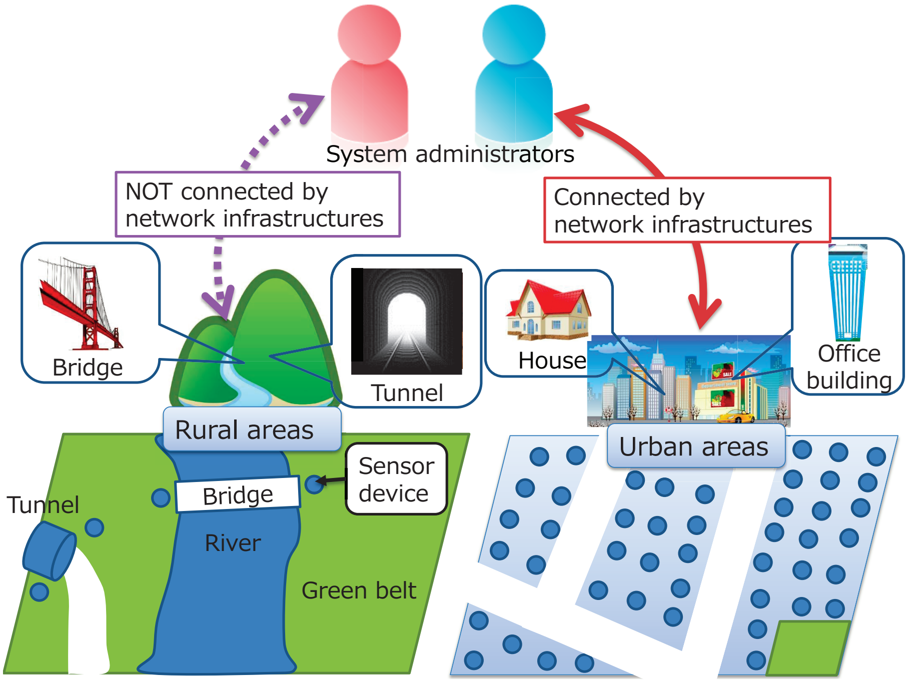

Figure 1: Example of structural health monitoring systems in both urban and rural areas

In many cases, WSNs are composed of many sensor nodes and a few sink nodes which operate in a distributed manner and are connected to each other by wireless communications. Sensor nodes forwards their sensing data to one of sink nodes through multi-hop communications and sink nodes forward those sensing data to system administrators, which makes it possible to collect environmental information in the location where one cannot get into. In this scenario, all sensor nodes are assumed to be reachable to at least one sink node through multi-hop communication. However, this assumption is not always realistic without long distance communication or well-planned deployment of sensor nodes. Then, it is improper for sensor nodes to communicate for long distance while consuming much energy in WSNs, where all sensor nodes are required to reduce energy consumption in order to improve network lifetime. Furthermore, deployment of sensor nodes, considering connectivity among them and reachability to sink nodes, restricts system operation.

Concerning those challenges in WSNs, many research focused on mobile sinks have been conducted [14–18]. Mobile sinks can save energy of sensor nodes and can assure reachability of sensing data to sink nodes by approaching sensor nodes and receiving their sensing data directly. However, most of existing research on mobile sinks aim at only the improvement in network lifetime by planning the optimal path of mobile sinks and routing the sensing data so that the loads for data relay can be distributed among all sensor nodes [16, 18], while there are not much research about the reliability of data collection. Then we believe that "controlled mobility" is a key idea for maintaining network connectivity and data reachability, where mobility of mobile sinks is controlled from both inside and outside of networks dynamically. Many researchers have paid attention to WSNs with controlled mobility for prolonging network lifetime so far [19–22].

Controlling mobile sinks play an important role in WSNs and mobile entities which are equivalent to mobile sinks in realistic environment should be supposed specifically. Then, in recent years, synergy between sensor networks and autonomous robots is attracting a lot of attention, and there are a lot of automatic patrol robots which play roles of mobile sinks or have another objects including the security or the rescue [2, 23].

In this thesis, our purpose is realizing the reliable collection of all sensing data in an observed area with a controlled mobile sink. We assume that sensor nodes are placed at the points of observed objects, paying no attention to connectivity with other nodes. Therefore, there are some sets of interconnected sensor nodes and isolated sensor nodes, we call both of them *sub-network*. Note that those sensor nodes may be removed from the observed area or new sensor nodes may be added in the observed area according to the requirements of systems. We realize reliable data collection of all sensing data under the situation where removal and addition of sensor nodes happen. We define two types of changes caused by node removal and addition, which are to be managed by mobility control.

- **Changes in a sub-network:**
  link failures and node failures that do not increase or decrease the number of sub-networks

- **Changes over an observed area:**
  disconnection of a sub-network, joint of sub-networks, or deployment of a new sub-network that increase or decrease the number of sub-networks

For the realization of secure and adaptive collection, we propose two mobility strategies for a mobile sink in order to collect all sensing data definitely and to manage those two changes using controlled mobility. The first strategy is to grasp the number of sub-networks in observed area and the all positions of those sub-networks, and the other is to visit all sub-networks and collect sensing data in each of them, where every sub-network has one or more special nodes to gather and collect sensing data of nearby sensor nodes (we call rendezvous-point nodes). These two strategies are followed by a mobile sink as the following two mobility phases.

- **Phase 1: Mobility for Learning Positions of Sub-networks**
  A mobile sink goes in every corner of the observed area and learns the positions of sub-networks.
- **Phase 2: Mobility for Visit All Rendezvous-point Nodes Using Learned Sub-network Positions**
  A mobile sink visits all sub-networks using learned information in Phase 1. Moreover, each sub-network leads the mobile sink to reach all rendezvous-point nodes with exploiting transmitted route-information messages when the mobile sink enters a sub-network.

In principle, Phase 1 can catch any unexpected changes while it requires a lot of time. Therefore, Phase 1 should be taken repeatedly for every fixed cycles depending on application scenarios. In Phase 2, we use a clustering technique for selecting rendezvous-point nodes to gather all sensing data in each sub-network to them since visiting each node one by one to collect sensing data takes much time. Through the simulation evaluation, we demonstrate that combining of the mobility strategies Phase 1 with Phase 2 can assure to collect all sensing data within the observed area. We also show what kind of situations our proposed method is adequate in realistic environment.

The rest of this thesis is organized as follows. In Section 2, we describe specific applications of WSNs supporting social infrastructures. In Section 3, we explain how to realize the reliable data collection using a controlled mobile sink. Section 4 presents simulation results and finally, we conclude our thesis in Section 5.

2 Social-Infrastructure Supported by Wireless Sensor Networks

In this section, we describe technologies and systems of WSNs which support the management of social-infrastructure.

2.1 Applications for Social-Infrastructure

2.1.1 Structural Health Monitoring System

The structural health monitoring system is one of monitoring systems using sensor devices for critical infrastructures such as high-rise buildings, transportation networks, power networks, and communication networks [8–10]. In these systems, sensor devices observe structural defects of bridges, buildings, and tunnels, including deformation of pillars and cracks in walls, and report the state of them to system administrators for the purpose of maintenance and rehabilitation. Furthermore, regular measurements and analyses of structural problems enable us to warn abnormal state of important infrastructure and avoid occurrence of accidents. In structual health monitoring systems, wireless sensor devices are often utilized for monitoring, therefore, many research have been conducted on the cooperation between those systems and WSN technologies [24, 25].

2.1.2 Smart Metering System

The smart metering system enables us to monitor electric utility meters of each home and measure usage of electric power with "smart meters", which are sophisticated meters that can measure power consumption and communicate with other smart meters [11–13]. The smart meters are assumed to communicate with by not only wired communication but also wireless communication, and then, there are many research on smart metering systems based on WSNs [26, 27]. The measured data can be utilized for the automatic calculation of electricity charges, which does not require manual meter reading. Also the monitoring system of water and gas utilities with smart meters is one of hot topics in this field [28].

2.2 Requirements and Challenges

In above two systems, it is extremely fatal to miss even one monitoring data, which sensor devices or smart meters observe. This is because missing observed data in structual health monitoring systems may lead to overlook signs of collapses of bridges and tunnels, and kill many people. In smart metering systems, power companies cannot charge electricity bill without the measurements of usage of electric power which is monitored by smart meters. Therefore, it is necessary to definitely collect all of monitoring data even if it takes much time for data collection. However, unlike fixed infrastructures such as power networks and communication networks, WSNs systems dynamically change its physical structure due to addition and removal of sensor devices. Therefore, it is quite difficult to manage the number of, the positions of, and the states of sensor nodes, which is required for completing data collection.

In addition, these systems may be built in both urban area and rural area where any wired infrastructures are not developed among them, and respective systems are so away from each other geographically. Then, in order to operate those separate systems, it is desirable for the system administrator to be able to collect and utilize all monitoring data which are observed in each system. However, providing rural area with wired infrastructures may be difficult and it is not reasonable to develop a new infrastructure every time a new system is newly added.

2.3 Solution Approach for Highly Reliable Wireless Sensor Networks

In many systems which support social-infrastructures such as structural health monitoring systems and smart metering systems, WSNs technologies play an important role. Therefore, we believe that it is possible to solve challenges in above systems with WSNs technologies. In this thesis, we aim at realizing highly reliable data collection in WSNs, which is defined as follows.

- Collecting all sensing data even after occurrence of changes in each system due to addition and removal of sensor devices
- Accessing all separate systems and collecting all sensing data in each system

From the viewpoint of WSNs, every separate system is either a set of interconnected sensor nodes or an isolated sensor node. In most cases, all sensing data in each network should be forwarded to one or more sink nodes and they have to deliver data to the system administrator for data collection. However, it is not always true that all sensor nodes are reachable to at least one sink node through multi-hop communication without long distance communication or well-planned deployment of sensor nodes. Here, it is improper for sensor nodes to communicate for long distance while consuming much energy in WSNs, where all sensor nodes are required to reduce energy consumption in order to improve network lifetime. Furthermore, deployment of sensor nodes, considering connectivity among them and reachability to sink nodes carefully, restricts system operation. Then we focus on mobile sinks which move around a wireless sensor network to collect data from wireless sensor nodes since they can save sensor nodes energy and assure reachability of all sensing data to sink nodes by approaching sensor nodes and receiving their sensing data directly. Furthermore, planning traveling paths of a mobile sink is an important challenge in research on mobile sinks [14–18]. Then, for highly reliable data collection, the path planning strategy for mobile sinks has to fulfill the following conditions.

- Mobile sinks can move so that they can access all sensing data
- Mobile sinks go along not only a static path but also another path for detecting newly built systems

Then “controlled mobility” is a key idea for that path planning of a mobile sink, where mobile sink is controlled from both inside and outside of each system dynamically, using local and global information about all systems [19–21]. However, in the concept of controlled mobility, it cannot detect newly built systems with only local information. The mechanisms for acquiring the global information on every system is essential.

3 Reliable Data Collection with Controlled Mobile Sink

Controlled mobile sinks have to acquire the global information about all systems periodically in order to realize highly reliable data collection. There are various ways to get global information such as memorizing the positions of all sensor nodes in advance. Moreover, mobile sinks can always collect all sensing data by approaching all sensor nodes every time. However, in WSNs systems which are built fluidly unlike fixed infrastructures such as power networks and communication networks, it is troublesome for system administrators to update the information about positions of all sensor nodes whenever sensor nodes are removed or added. Furthermore, it takes enormous time for a mobile sink to visit all sensor nodes one by one. Therefore, we propose the combining of two types of mobility strategies for mobile sinks, where one enables mobile sinks to acquire the global information about all systems, the other enables mobile sinks to collect all sensing data using the global information. We describe our proposed method.

3.1 Overview

First, we define the term *observed area* and *sub-network*. An observed area is an area where sensor nodes are deployed and they collect sensing data, and a mobile sink can travels around. A sub-network is a set of interconnected sensor nodes. Note that an isolated sensor nodes is also regarded as a sub-network. In our proposed method, there are one or more sub-networks in an observed area and a mobile sink visits all sub-networks to get all sensing data and carry to system administrators. Since the time for a mobile sink to visit all sensor nodes one by one is too long, in every sub-network, several nodes gather and store the sensing data of nearby nodes (hereinafter we call rendezvous-point nodes). Then, the mobile sink visits all those rendezvous-point nodes and collects stored data (Fig. 2).

For realization of reliable data collection, we propose the combination of two types of sink mobility strategies. We explain two types of mobility strategies below.

Phase 1: Mobility Strategy for Learning Positions of Sub-networks

> A mobile sink goes in every corner of the observed area and remembers the number and the positions of sub-networks by receiving route-information messages, including an identifier for each sub-network, from sensor nodes in each sub-network. The positions of sub-

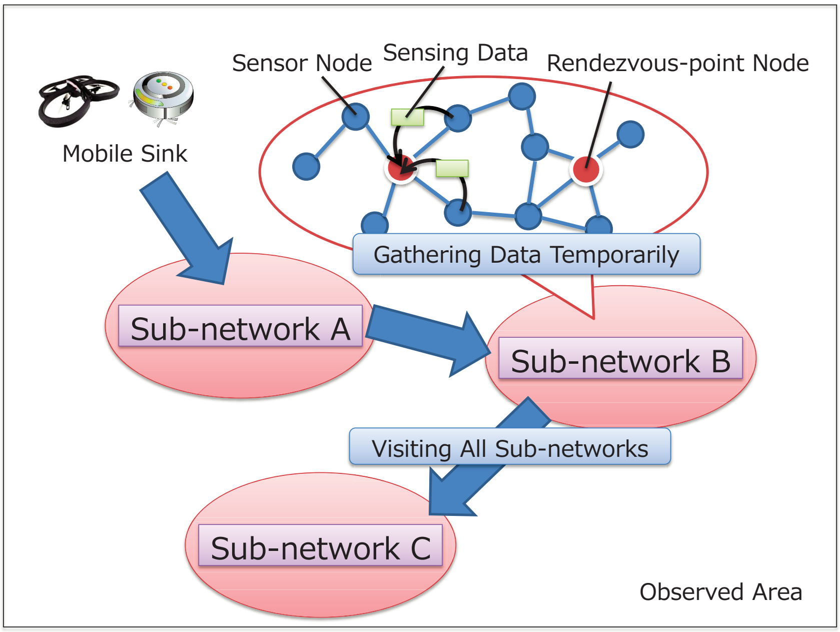

Figure 2: Assumed sub-network model

networks are given by the positions of the mobile sink when receiving route-information messages.

Phase 2: Mobility Strategy for Visit All Rendezvous-point Node Using Learned Sub-network Positions

A mobile sink visits all sub-networks using learned information in Phase 1 such as positions of sub-networks. Moreover, each sub-network leads a mobile sink to reach rendezvous-point nodes with transmitted route-information messages when the mobile sink enters it.

A mobile sink can get to know all sub-networks in Phase 1 and can collect all sensing data inside each sub-network in Phase 2. Moreover, the mobile sink executes either phase according to a certain transition rule illustrated in Fig. 3. This is because, with periodical Phase 1 mobility strategy, the mobile sink can catch the environmental changes between sub-networks caused by removal or addition of sensor nodes.

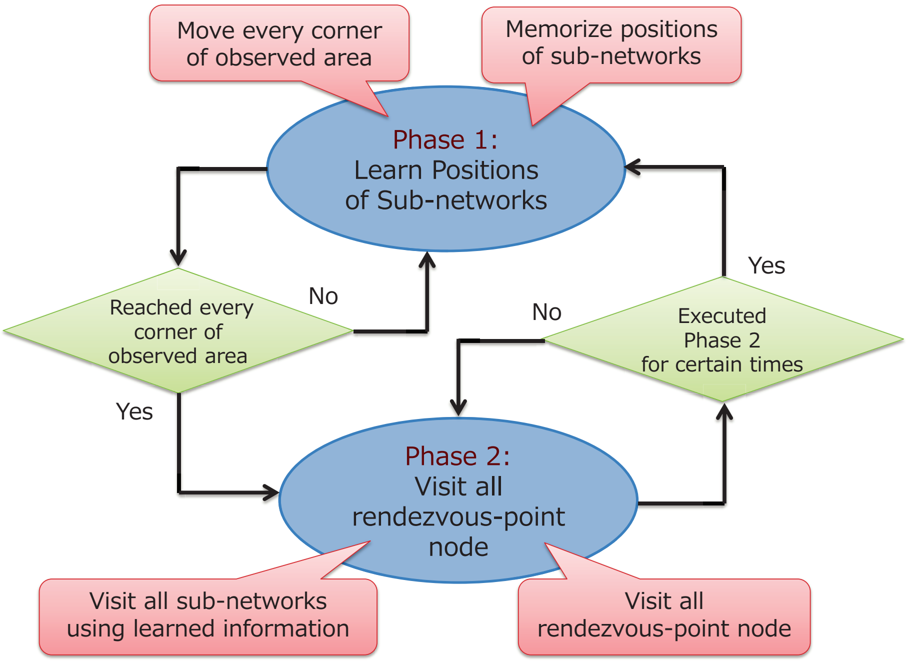

Figure 3: Transition rule between two sink mobility phases

3.2 Gathering and Storing Sensing Data in Sub-networks

Every sub-network needs one or more special nodes, we call them "rendezvous-point nodes" in this thesis, to gather and store sensing data of all sensor nodes inside each sub-network. Furthermore, every sensor node requires routing protocols in order to definitely forward own sensing data to one of rendezvous-point nodes. Then, we elect rendezvous-point nodes using an existing cluster head election algorithm and sensor nodes perform routing control using one of proactive routing protocols.

3.2.1 Rendezvous-point Node Election

Rendezvous-point nodes are special nodes elected in each sub-network to gather and store all sensing data of nearby sensor nodes temporarily. A mobile sink visits these rendezvous-point nodes and receives stored sensing data (described in Section 3.3.2 in detail). We select one or more rendezvous-point nodes for every sub-network using a part of DEECIC algorithm [29] with minor modification since DEECIC is a kind of clustering algorithm which can select one or more cluster

Table 1: Notations in our proposed methods

Notation	Meaning
i	The identifier for each sensor node
S_i	The sensor node whose identifier is i.
$ND(S_i)$	The number of neighbor nodes of node S_i.
$State_i$	The state of S_i, indicating whether S_i belongs any cluster or not. $State_i$ is either **UNCLUSTER** or **CLUSTER**(i, n).
t_{S_i}	The simulation time of node S_i.
T_{max}	A certain upper bound on time for sending **UpdatePacket**, which is given in advanced.
T_{S_i}	The delay time of node S_i for sending **StatePacket**.
T_{flood}	The interval for flooding **PInfoMsg**.
T_h	The interval during which **NTable** can store an $entry$ non-updated.
$netID_i$	The identifier of the sub-network which S_i belongs to.
pID	The identifier of a potential field.
myP_i	The value of potential which S_i has.
$pList_i$	The set of pID which S_i will include in **PInfoMsg**.
$vList_i$	The set of myP_i which S_i will include in **PInfoMsg**.

heads so that loads of data processing on each cluster head can be distributed. The rendezvous-point node election algorithm in DEECIC is described in Algorithm 1 with some terms which are tabulated in Table 1. As shown in line 4, a sensor node S_i broadcasts an **UpdatePacket** to notify its neighbors of its presence at randomly chosen time t $(0 < t < T_{max})$. Then, S_i broadcasts a **DegreePacket** including $ND(S_i)$, which is the number of received **UpdatePackets** until T_{max}, to inform its degree at t $(T_{max} \leq t < T_{max} + T_{S_i})$. T_{S_i} is given as $T_{S_i} = \alpha e^{1/ND(S_i)}$ where α is a constant to ensure $0 < T_{S_i} \ll T_{max}$. In lines 11–22, sensor node S_i waits for a **StatePacket** including a state of a neighbor node, which means that whether the neighbor belongs to any cluster or not. Here, **CLUSTER**(i, n) presents that the node i can reach a certain rendezvous-point node by n hops and **CLUSTER**($i, 0$) means that node i is a rendezvous-point node. Upon receiving a **StatePacket** with **CLUSTER**(s, n), S_i sets $State_i$ to **CLUSTER**($i, n+1$) if $State_i$ is **UNCLUSTERD** or $State_i$ is **CLUSTER**(i, m) while satisfying $m > n + 1$. S_i broadcasts a **StatePacket** if $n + 1 \leq max\_n$ thereafter, which limits coverage of each cluster.

3.2.2 Routing Method for Gathering Sensing Data to Rendezvous-point Nodes

We use potential-based routing [30], which is a proactive routing protocol, for data collection. The potential-based routing is known as a resilient routing protocol to environmental variations because it requires only local information. All sensor nodes update potential, a scalar value calcu-

Algorithm 1 Selection of rendezvous-point nodes in a sub-network

```
// all nodes perform following;
$State_i \Leftarrow$ UNCLUSTER
$t_{S_i} \Leftarrow$ random value between 0 and $T_{max}$
broadcast UpdatePacket at $t_{S_i}$
repeat
    if receives a UpdatePacket then
        $ND(S_i) \Leftarrow ND(S_i) + 1$
    end if
until $t_{S_i} \geq T_{max}$
broadcast DegreePacket at $t_{S_i}$, $(T_{max} \leq t_{S_i} < T_{max} + T_{S_i})$
repeat
    if receive StatePacket with CLUSTER($s, n$) node then
        if $State_i$ is UNCLUSTER then
            $State_i \Leftarrow$ CLUSTER($s, n+1$)
        else if $State_i$ is CLUSTER($i, m$) and $m > n + 1$ then
            $State_i \Leftarrow$ CLUSTER($s, n+1$)
        end if
        if n+1 $\leq max\_n$ then
            broadcast StatePacket
        end if
    end if
until $t_{S_i} \geq T_{max} + T_{S_i}$
if $ND(S_i)$ is larger than all neighbor nodes and $State_i$is UNCLUSTER then
    $State_i \Leftarrow$ CLUSTER($i, 0$)
    broadcast StatePacket
end if
```

lated only with local information—own potential, neighbors' potential, node degrees. In addition, we can utilize this proactive routing protocol for not only data collection but also controlling the mobility of mobile sinks. We previously combined controlled mobility with the proactive routing mechanism in a wireless sensor network, where periodically exchanged route information messages lead a mobile sink toward a data collecting node [31].

Construction and Update of Potential Fields In our methods, every rendezvous-point node constructs one potential field that is the shape of concave curve whose bottom corresponds to the rendezvous-point node. Therefore, multiple potential fields may be constructed in each sub-network. Every potential field has a unique identifier pID that corresponds an identifier of the rendezvous-point node. The multiple potential-field construction process is given in Algorithm 2 with some terms tabulated in Table 1.

First, rendezvous-point node i initializes its parameters such as $netID_i, myP_i$ and broadcasts **PInfoMsg** throughout the sub-network (lines 1–10). **PInfoMsg** includes sender's ID, sub-network

ID, potential field IDs (pID), and potential values of each otential field 4. When receiving **PInfoMsg**, a sensor node updates $NTable$, myP_i, and $netID_i$ and broadcasts new **PInfoMsg** (lines 11-44). Here, **NTable** is a table to store information about a potential of neighbor nodes, and its entry is composed of five elements $(src, sub-networkID, pID, pValue, time)$, a source node ID, a sub-network ID, a potential field ID, a potential value in the correspondent potential field, and the time the entry was updated, respectively. **NTable** determines to either registers or modify an entry when receiving **PInfoMsg** which contains information necessary for an entry of **NTable**. When a new entry has the same src and pID in **NTable**, the entry is registered and otherwise the existing entry is overwritten with it. S_i removes an old entry that is not updated for T_h, and it becomes a rendezvous-point node if **NTable** comes to have no entry.

Through the use of **NTable**, S_i updates its sub-network ID ($netID_i$) and potentials (myP_i). $netID_i$ is the lowest value of pID registered in **NTable** and myP_i is updated according to the function in [30] where S_i's potential is calculated as an average potential of its neighbors. When disconnection of a sub-network occurs, $NTable$ may become to have no entry with $netID_i$ of an owner of the table, and therefore, S_i resets own $netID_i$ in that case. Thus, our construction method for multiple potential fields can respond to environmental changes inside a sub-network.

Finally, S_i updates all myP_i and puts it to **PInfoMsg**, and $T_{forward}$ after, it broadcasts a **PInfoMsg**.

Forwarding Sensing Data According to Potential Fields In potential-based routing, all every sensor node has to do is forwarding own sensing data to the sensor node which has the smallest potential in neighbor sensor nodes. Then, all sensing data definitely reach one of rendezvous-point nodes because each of rendezvous-point nodes has smaller potential than the surrounding sensor nodes have.

3.3 Sink Mobility Strategies for Data Collection

In our proposed method, a mobile sink executes the Phase 1 and the Phase 2 mobility strategies alternately. In other words, the mobile sink periodically executes Phase 1 mobility strategy to grasp the number and the positions of all sub-networks in the observed area, and after every execution of Phase 1, the mobile sink repeats Phase 2 for LI times. We describe two types of mobility strategies below.

Algorithm 2 Construction and update of potential fields

```
if $State_i$ is CLUSTER(i,0) then
    $netID_i \Leftarrow i$
    $myP_i[i] \Leftarrow initial\_potential$
    puts $i$ into $pList_i$
    puts $myP_i[i]$ into $vList_i$
    broadcast PInfoMsg($i, netID_i, pList_i, vList_i$) per $T_{flood}$
    clear $pList_i, vList_i$
else
    $netID_i \Leftarrow NULL$
end if
loop
    if receive PInfoMsg($s, netID_s, pLIst_s, vLIst_s$) then
        for $j = 1$ to $k$ do
            update the NTable($s, netID_s, pList_s[j], vList_s[j], t_{S_i}$)
        end for
        for all $entry$ in NTable do
            if $t_{S_i} - entry.time > T_h$ then
                remove the $entry$ from NTable
                if NTable has no $entry$ then
                    $State_i \Leftarrow$ CLUSTER($i, 0$)
                    broadcast StatePacket
                else if NTable has no $entry$ whose $entry.netID$ is $netID_i$ then
                    if $State_i$ is CLUSTER($i, 0$) then
                        $netID_i \Leftarrow i$
                    else
                        $netID_i \Leftarrow NULL$
                    end if
                end if
            end if
        end for
        for $j = 1$ to $k$ do
            update all $myP_i[pList_s[j]]$
        end for
        if $netID_i$ is $NULL$ or $netID_i > netID_s$ then
            $netID_i \Leftarrow netID_s$
        end if
        for $j = 1$ to $k$ do
            puts $pList_s[j]$ into $pList_i$
            puts $myP_i[pList_s[j]]$ into $vList_i$
        end for
        broadcast PInfoMsg($i, netID_i, pList_i, vList_i$) after $T_{forward}$
        clear $pList_i, vList_i$
    end if
end loop
```

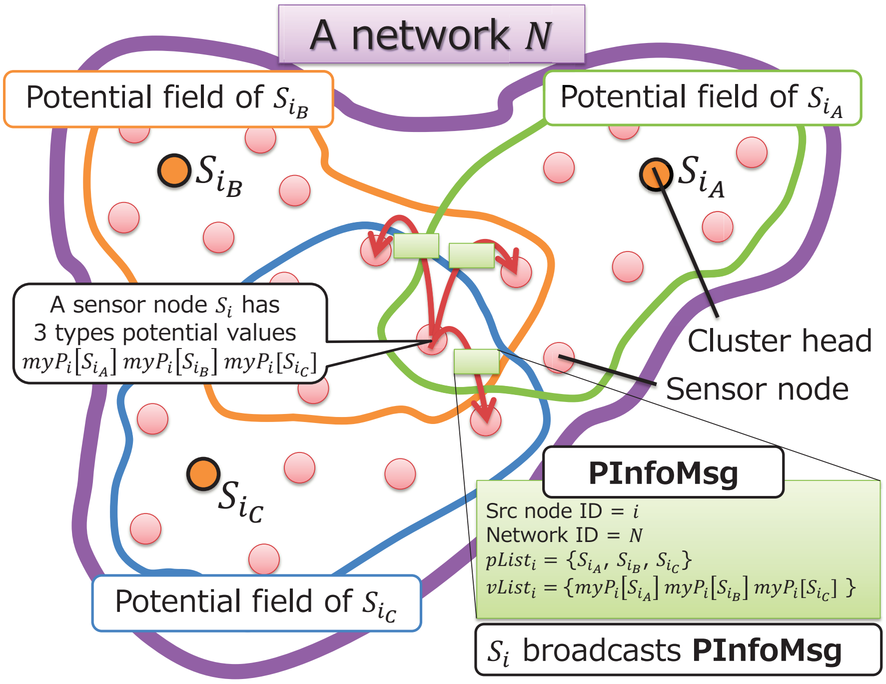

Figure 4: Message format of **PInfoMsg**

3.3.1 Phase 1: Mobility Strategy for Learning Positions of Sub-networks

In Phase 1 mobility strategy, a mobile sink has to periodically check the entire picture of the observed area, such as the positions and the number of sub-networks, to determine the path for collecting data. In order to grasp these information, the mobile sink moves in every corner of the observed area while identifying and memorizing all the different sub-networks.

Sweeps of the Observed Area In our proposal, a mobile sink moves so that it does not overlook even one sensor node placed in the observed area. To begin with, the mobile sink commences to move from a given initial position, which is one of vertices of the pre-defined square region including the whole observed area as illustrated in Fig. 5. Next, the mobile sink goes straight on toward one of nearby vertices until it reaches $\frac{d}{2}$ length short of the vertex, where d is the wireless communication range of the mobile sink and sensor nodes. Then, it takes a right-angled turn toward the other vertex, heads $\frac{d}{2}$, and again turns in the same direction. The mobile sink repeats to the same process until reaching all vertices, then it returns to the initial position.

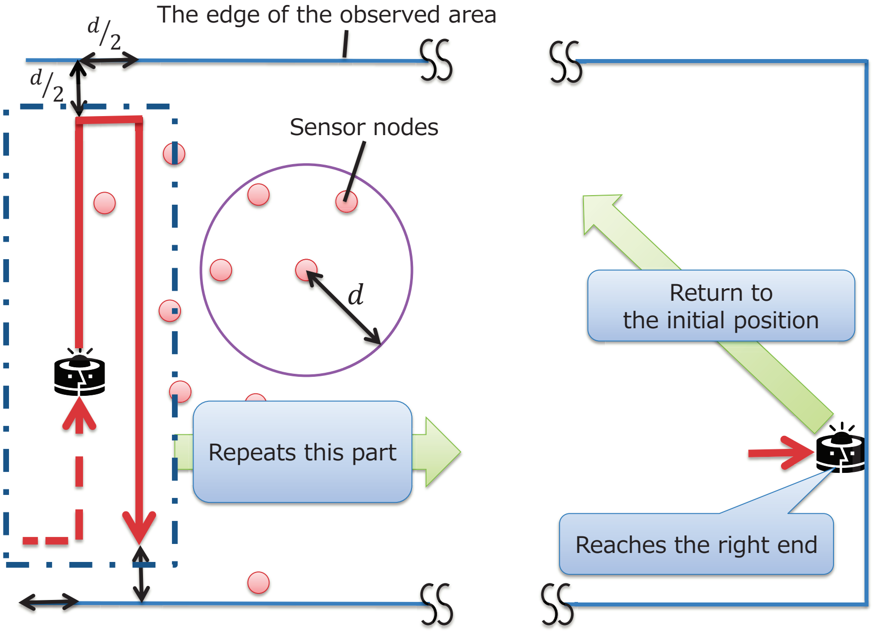

Figure 5: Mobility strategy for detecting all sensor node without any oversight

Memorizing Sub-networks The mobile sink intercepts a message **PInfoMsg**, which all sensor nodes exchange with each other for updating routes and acquires a special identifier (ID) contained in the **PInfoMsg**. This ID is used to identify all sub-networks and remember their positions.

The mobile sink updates positions of sub-networks according to Algorithm 3. A table **NetTable** for storing sub-network positions is updated every after receiving **PInfoMsg**. A **NetTable**'s entry is the tuple ($netID$, $postion$, RSSI) where $netID$ is an identifier of a sub-network, $position$ is the position where mobile sink received **PInfoMsg** and updated the entry, and RSSI is the received signal strength indication of **PInfoMsg**. An entry is always added to the table if there is no entry whose $netID$ has been already registered, and an existing entry is updated iff the RSSI of a received **PInfoMsg** is greater than existing one with the same $netID$. This is for ensuring that the mobile sink can obtain more accurate positions of sub-networks. Note that the mobile sink demands sensing data to nodes by transmitting a message **SensingDataRequest** when it contacts with sensor nodes in phase 1.

Algorithm 3 Memorizing the positions of sub-networks associating with $netID$ by the mobile sink

```
// The mobile sink moves in every corner of the observed area.
repeat
    if intercepts PInforMsg($i, netID_i, pList_i, vList_i$) then
        if NetTable has no $entry$ with $netID_i$ then
            register NetTable($netID_i, pos$,PInforMsg.$rssi$)
        else
            if PInfoMsg.$rssi > entry.rssi$ then
                update NetTable($netID_i, pos$,PInforMsg.$rssi$)
            end if
        end if
        if $State_i$ is CLUSTER($i, 0$) then
            sends SensingDataRequest to $S_i$
        end if
    end if
until reaches the end of the observed area
```

3.3.2 Phase 2: Mobility Strategy for Visiting All Rendezvous-point Nodes Using Learned Sub-network Positions

The mission of the mobile sink is collecting all *existing sensing data*, which are observed by one of sensor nodes and have not been collected by the mobile sink yet. Then, all *existing sensing data* become *collected sensor data*. In order to realize this, the mobile sink visits all sub-networks and all rendezvous-point nodes.

Visits of All Sub-networks The mobile sink visits and enters all the sub-networks to collect sensing data. The number and positions of sub-networks are memorized in Phase 1. Then, the mobile sink decides the order and the paths to visit them and that is equivalent to solve the Traveling Salesman Problem (TSP) which is known as NP-hard. In this paper, our proposed methods are assumed to be apply to only the delay-tolerant systems. Therefore, the mobile sink visits all sub-networks in the order that it memorized.

Sensing Data Collection inside a Sub-network When the mobile sink enters a sub-network, it has to visit all rendezvous-point nodes inside the sub-network and receive sensing data from them. At this time, the mobile sink utilizes multiple potential fields, that is, utilizes $vList$ in **PInfoMsg** transmitted by a sensor node in order to reach a rendezvous-point node by repeatedly approaching another sensor node which has a smaller value in $vList$. After arrival of the mobile

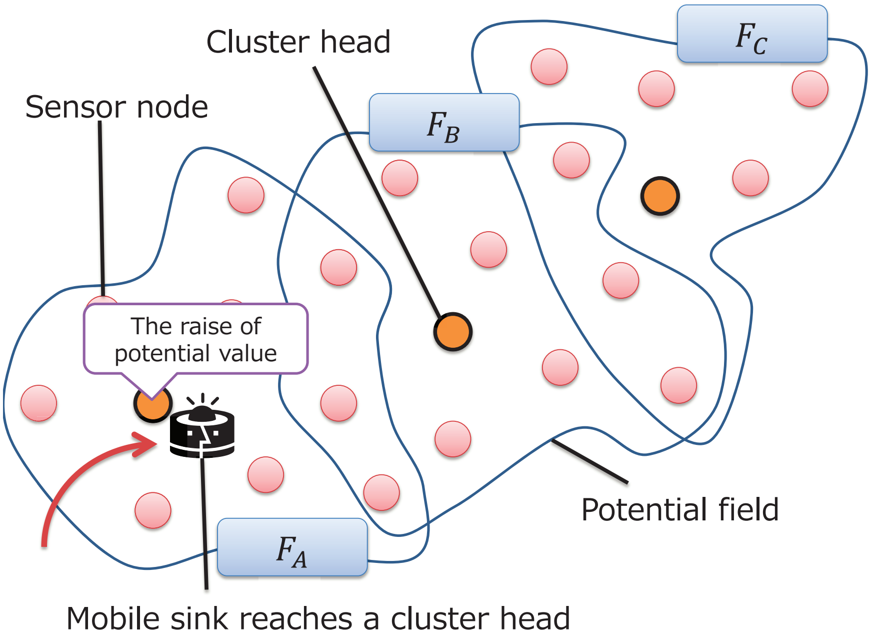

Figure 6: Increase of a potential value of a rendezvous-point node caused by an arrival of the mobile sink

sink to a rendezvous-point node, the rendezvous-point node sends all sensing data which it has to the mobile sink and makes the potential value raise greatly, which decreases the priority of the potential field for a mobile sink against other potential fields because the mobile sink approaches a sensor node with a ‘smaller’ potential value as (Fig. 6). After that, the mobile sink can find a new potential field (Fig. 7).

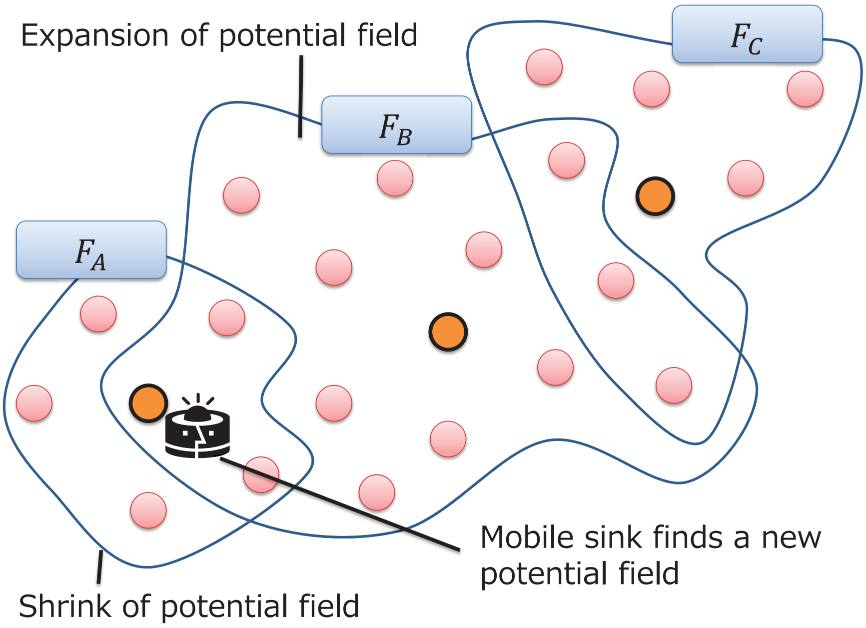

Figure 7: New potential field F_B is detected by the mobile sink after potential field F_A decrease its potential

Table 2: Notations in simulation evaluation

Notation	Meaning
s	The sequence number of each sensing data
CR_s	The collection ratio of sensing data with s
NED_s	The number of sensing data with s which exist in somewhere in the observed area
NCD_s	The number of sensing data with s which is already collected by a mobile sink
$PL_{i,j}$	The probability of that a S_i fails to receive a message from S_j

4 Evaluation

In this section, we simulate our proposed method in two following scenarios:

1. **Random and sparse node deployment**

   In this scenario, sensor nodes are deployed at random placed sparsely. All sensor nodes communicate with each other in an ideal radio environment, namely there are no attenuation of radio waves due to presence of any obstacles, air resistance, and difference of elevation. Moreover, changes of each sub-network due to periodical addition and removal of senor nodes.

2. **Node deployment considering actual city maps**

   In this scenario, sensor nodes are deployed corresponding to each house in the actual city maps. All sensor nodes communicate with each other in a realistic environment where each sensor node may fail to receive messages stochastically. Moreover, changes of each sub-network due to periodical addition and removal of senor nodes.

Firstly, we verify that our proposed method can realize highly reliable data collection in many node deployment patterns by showing the results of simulation in the first scenario. Next, we examine whether our proposed method can realize the highly reliable data collection even in realistic scenarios by showing the results of simulation in the second scenario. Moreover, we examine the validity of our proposed method in realistic situations.

4.1 Random and Sparse Node Deployment

In order to verify our proposed method, we perform computer simulations for various patterns of sensor nodes deployment and evaluate the reliability of data collection. Furthermore, we examine the relation between the reliability of data collection and sensor nodes arrangement.

4.1.1 Evaluation Scenario

We assume a 1000 m by 1000 m square region including the whole observed area and deploy 100 sensor nodes S_i $(i = 0..99)$ at random positions in the observed area, where the communication range of the sensor nodes is represented by a circle of radius 100 m. Sensor nodes observe surrounding environmental phenomena every hour and forward a packet to one of rendezvous-point nodes with potential-based routing. The packet includes sensing data, i of sender, and a sequence number s. We remove a sensor node which is randomly selected from S_i and add a new sensor node into random place of the observed area every four hours. The mobile sink whose speed is 5m/s starts to move at 100 s and executes Phase 1 mobility strategy at the beggining of the simulation.

In order to evaluate reliability of data collection, we perform computer simulations for 86,500s and calculate CR_s according to Eq. (1) every sequence s. In this thesis, the reliability of data collection indicates the level of achievement at certain time, which is the percentage of the number of sensing data are exactly collected to all sensing data which should be collected at that time. Then, we evaluate the reliability of data collection by introducing a new evaluation index “achievement level of data collection (ALDC)” every hour, which is given by Eq. (2). Note that s_{cur} is a sequence number of sensing data which a mobile sink has to collect at that time, which means that all sensing data with less than s_{cur} are already collected, and s_{th} is a sequence number of sensing data which should be collected by the mobile sink.

Since sensor nodes generate new sensing data every hour, s_{th} increases one every hour. We continue to increment s as long as CR_s is equivalent to 1, which means that all sensing data whose sequence number is s after the calculation of CR_s are collected. Figure 8 illustrates the goal of CR_s while Fig. 9 illustrates the goal of ALDC.

We evaluate ALDC every hour and show their differences for LI = 1, 5, and 10. Note that we simulate this scenario with 100 patterns of node deployments to evaluate the proposal with various arrangements of sensor nodes.

$$CR_s = \times \frac{NCD_s}{NED_s} \tag{1}$$

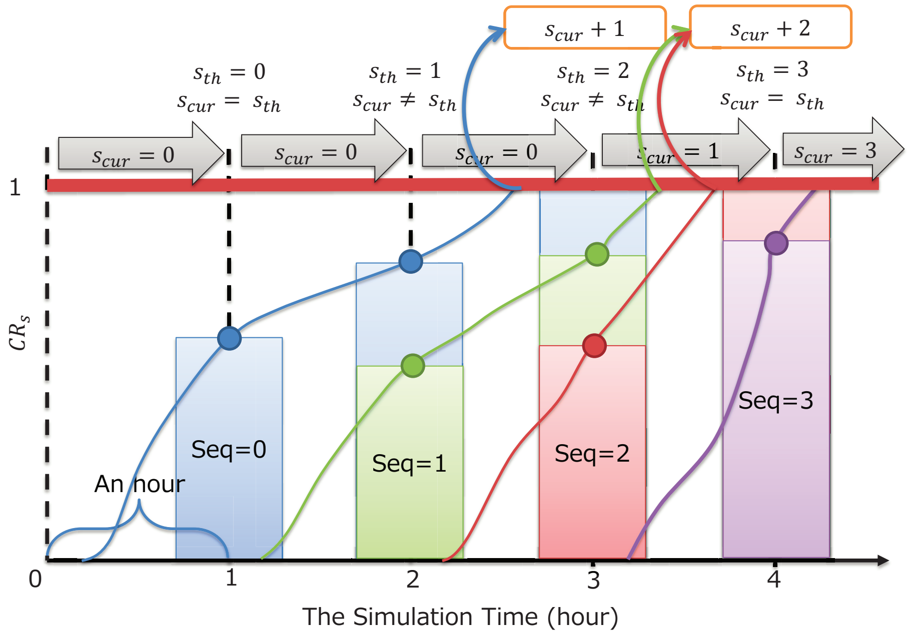

Figure 8: Goal of CR

$$ALDC = \begin{cases} 1 & (s_{th} = 0) \\ CR_{s_{cur}} + s_{cur} & (otherwise) \end{cases} \tag{2}$$

4.1.2 Simulation Results

Figure 10 indicates three types of transitions of ALDC with different color lines, corresponding to various situations. Note that x axis is simulation time, and y axis indicates ALDC, and the red line corresponds to the case where the reliable data collection is successful every hour. Namely, what a line gets closer to the red one means that the more highly the reliable data collection is realized. The values of $CR_{s_{cur}}$ at each hour are given by the averages of those in different arrangement of sensor nodes. At the 4, 8, 12, 16, and 20 hours, a sensor node is randomly selected to be removed from the observed area and a new sensor node is added at random place. Therefore, changes over the observed area, such as disconnection of a sub-network, joint of sub-networks, or generation of a new sub-network, may happen and each ALDC may fail to reach the red line at that time, and may get away from it. Furthermore, each ALDC recovers every an interval which is equivalent to LI. This is because the mobile sink executes Phase 1 mobility strategy every LI hours in order to

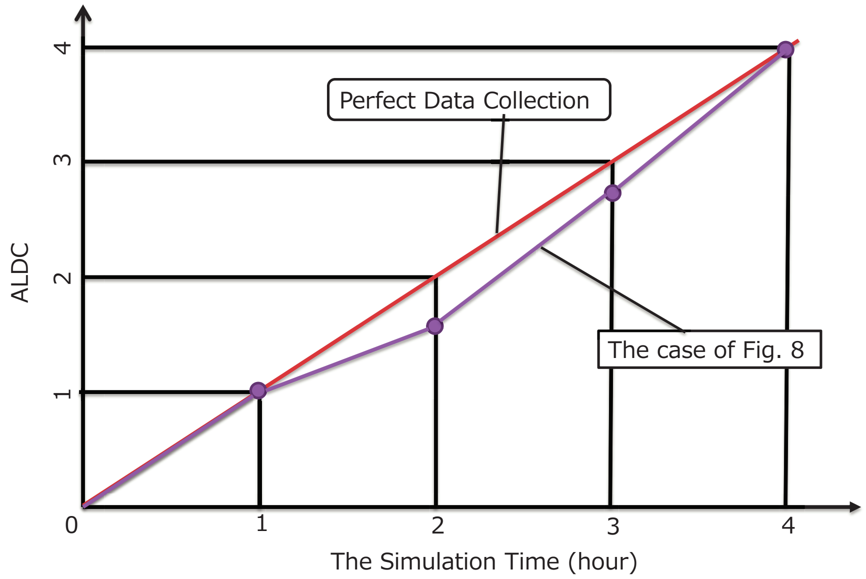

Figure 9: Goal of ALDC

memorize the positions of sub-networks. Thus, it can be said that our proposal method can realize the highly reliable data collection in the situations where some changes between sub-networks occur due to removal and addition of sensor nodes.

4.2 Node Deployment Considering Actual City Maps

In order to examine whether our proposed method is valid in realistic scenarios, we perform computer simulations for three arrangements of sensor nodes, which model actual city maps in Japan, and evaluate the reliability of data collection.

4.2.1 Evaluation Scenario

We assume three square regions cutting parts of actual city maps in Japan and define them as observed areas and deploy sensor nodes as many as the number of houses in each city map. The communication range of each sensor node is represented by a circle of radius 50m. Every sensor node has a unique parameter $lossfactor (-1 \leq lossfactor \leq 1)$ which represents causes of attenuation such as presence of any obstacles, air resistance, and difference of elevation. Note that

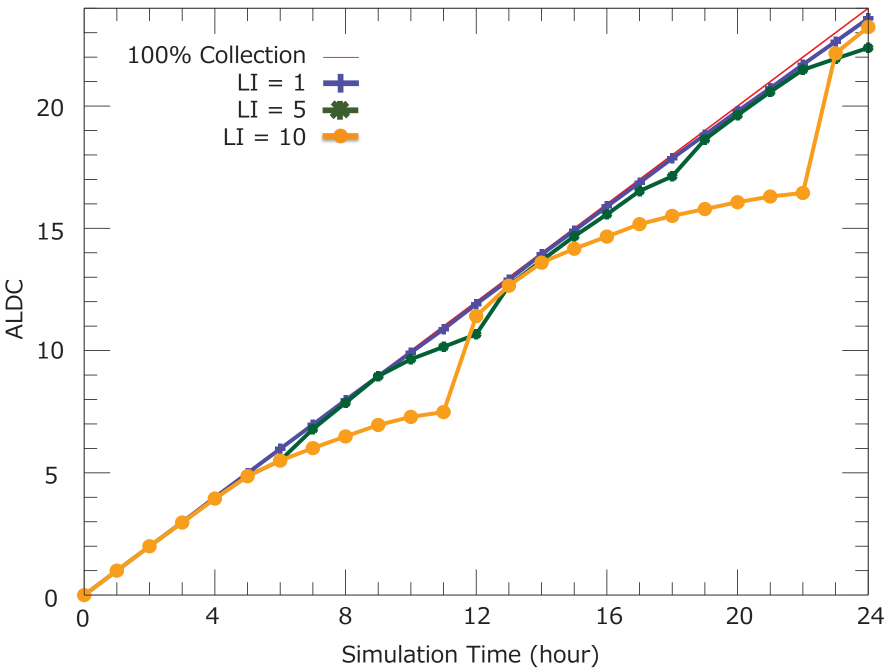

Figure 10: Fluctuation in ALDC over simulation time

$lossfactor$ of mobile sinks is always given by a constant value 1. The sensor nodes observe the surrounding environmental phenomena every hour and forward the packet including the sensing data, i of sender, and a sequence number s, to one of rendezvous-point nodes with potential-based routing. Since it is quite difficult to formulate the probability that a sensor node S_i fails to receive a message from the other sensor node S_j due to multiple causes, we simply calculate (3) for the probability of failure.

$$PL_{i,j} \;=\; |lossfactor_i - lossfactor_j| \times 10\% \tag{3}$$

Furthermore, we assume that each sensor node may be removed from the observed area at five percent every four hours, and removed sensor nodes will be deployed at same place after four hours. The mobile sink whose speed is 5m/s starts to move at 100s and executes Phase 1 mobility strategy at the setout, and LI is always four. Then, We list up the three scenarios below.

- Touhaku country, Tottori, Japan (illustrated in Fig. 11)
- Fukuoka city, Fukuoka, Japan (illustrated in Fig. 12)

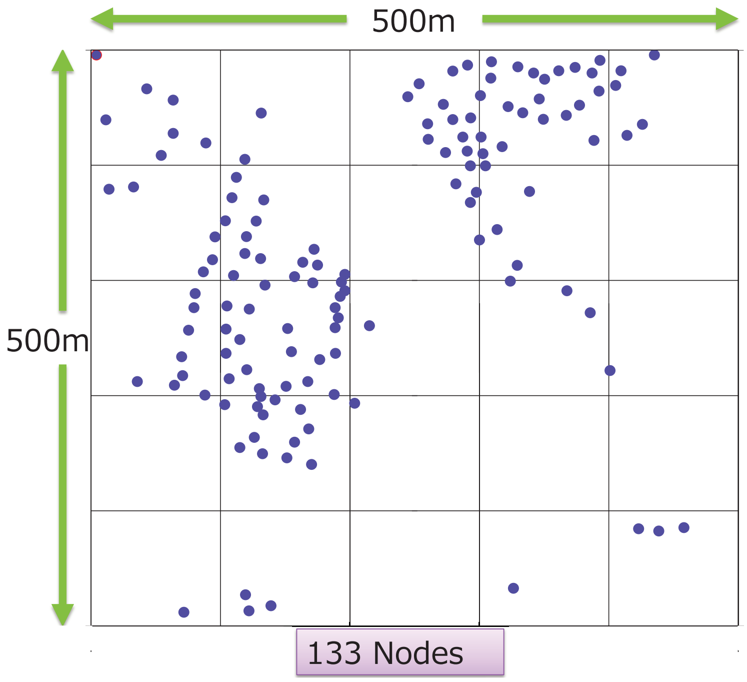

Figure 11: Arrangement of sensor nodes in Tottori

- Hirosaki city, Aomori, Japan （illustrated in Fig. 13)

We perform computer simulations according to above scenarios for 86,500s and measure ALDC every hour and show their transition as simulation results.

4.2.2 Simulation Results

Figure 14 shows that, in the scenario for Tottori where sensor nodes are deployed sparsely and the number of sub-networks is six initially, ALDC is stably high. Moreover, it can be said that mobile sink can access not only sub-networks which are built by multiple sensor nodes but also isolated sensor node.

Figure 16 shows that, in the scenario for Fukuoka where sensor nodes are deployed quite densely and only a sub-network exists initially, ALDC sometimes reaches 100% collection and at other times not. This is because one sub-network has so many sensor nodes and rendezvous-point nodes that mobile sinks cannot visit all rendezvous-point nodes within an hour. For visiting a rendezvous-point node, mobile sinks have to receive a potential information of the rendezvous-point node. In the scenario for Fukuoka, however, it can take considerable time for each **PInfoMsg**

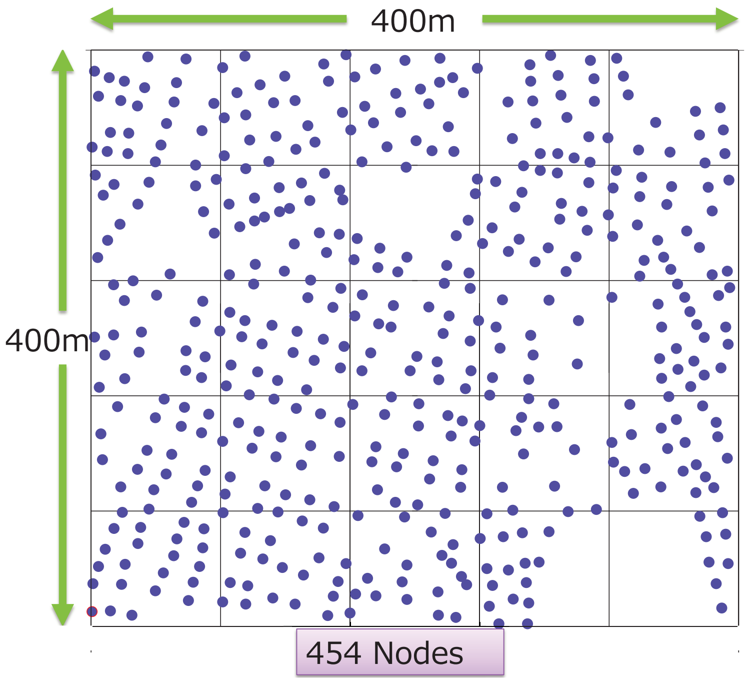

Figure 12: Arrangement of sensor nodes in Fukuoka

to spread around the sub-network, and mobile sinks can wander for a long time 15. In the worst case, mobile sinks can never reach any rendezvous-point nodes. In our proposed method, mobile sinks execute Phase 1 mobility strategy periodically and go in every corner of the observed area. Therefore, ALDC recovers every nearly LI hours.

For the same reason, in the scenario for Aomori where quite densely and only a sub-network exists initially, ALDC sometimes reaches 100% collection and at other times not as Fig. 17 shows.

Thus, our proposed method can realize the highly reliable data collection under the realistic scenarios while it takes much time to collect all sensing data in some scenarios. Moreover, from simulation results, it can be said that our proposed method is adequate in the situations, where sensor nodes are deployed sparsely and each sub-network is not so large, rather than the situations, where considerable number of sensor nodes are deployed and each sub-network has many sensor nodes, from the view point of ALDC at every hour.

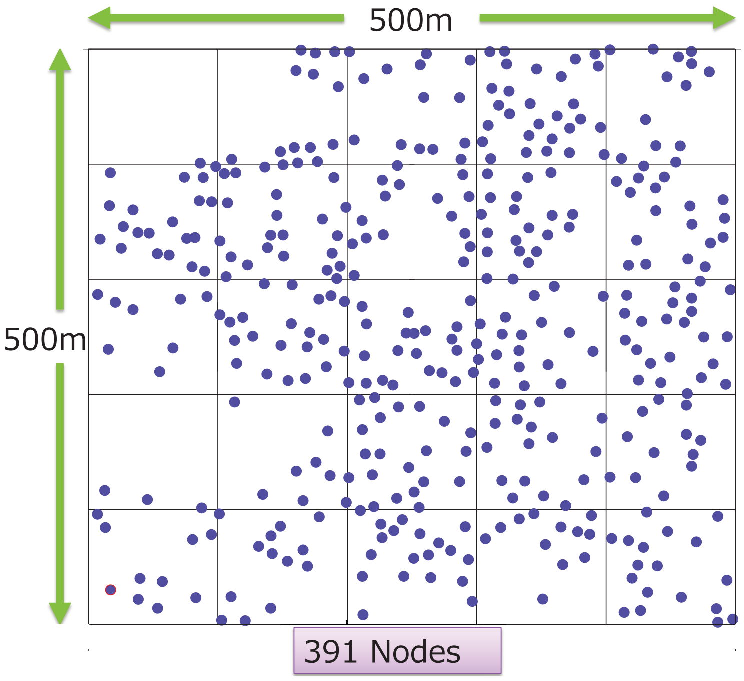

Figure 13: Arrangement of sensor nodes in Aomori

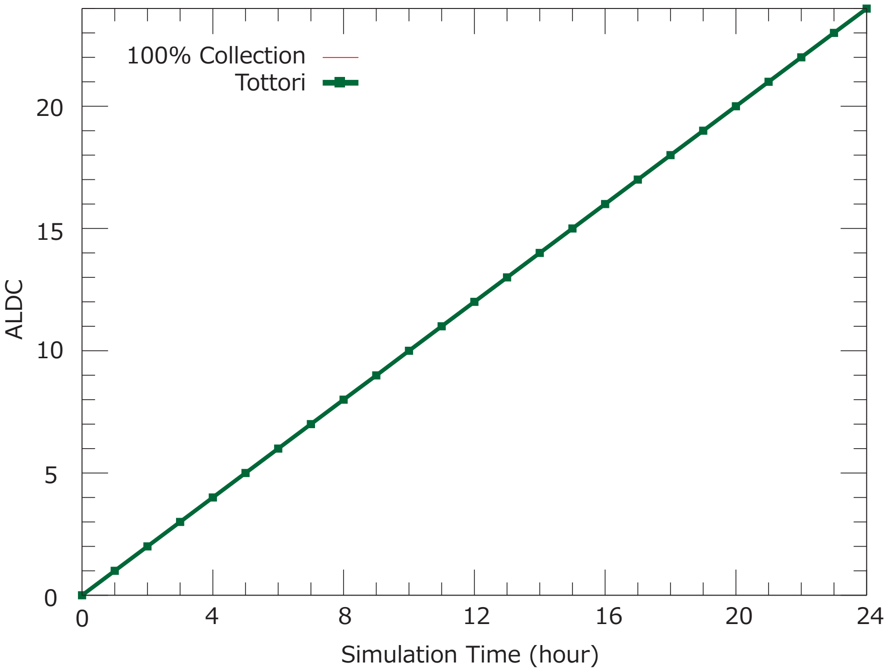

Figure 14: Stably high ALDC throughout the simulation in the case of Tottori

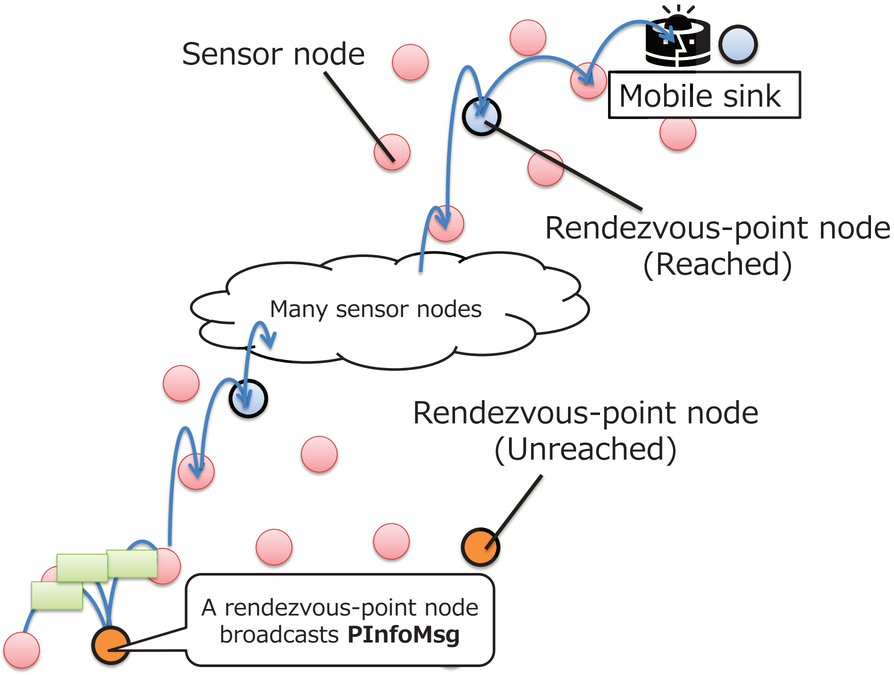

Figure 15: Spread of **PInfoMsg** takes long time in the situations where a sub-network has many rendezvous-point nodes

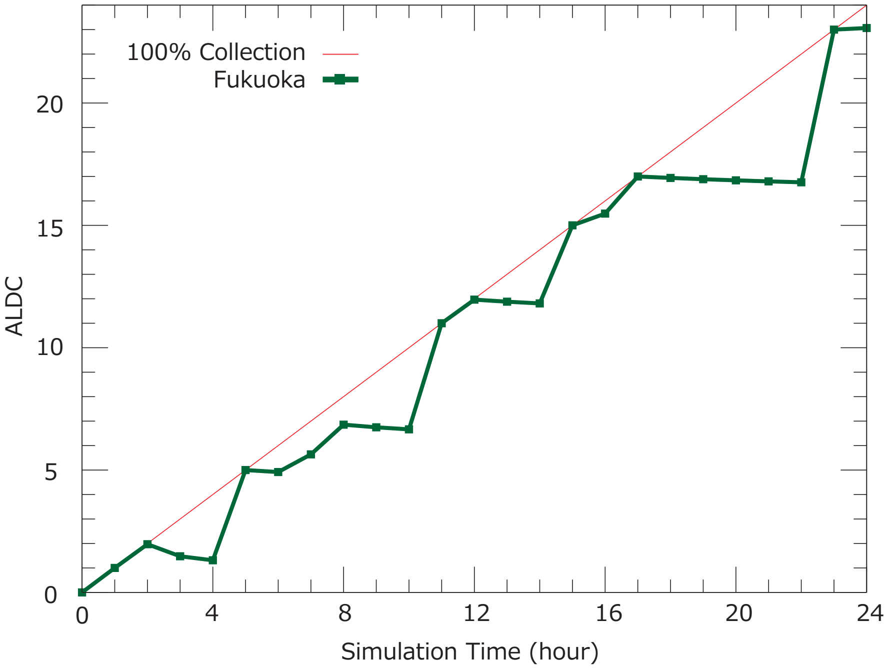

Figure 16: Fluctuation in ALDC over simulation time in the case of Fukuoka

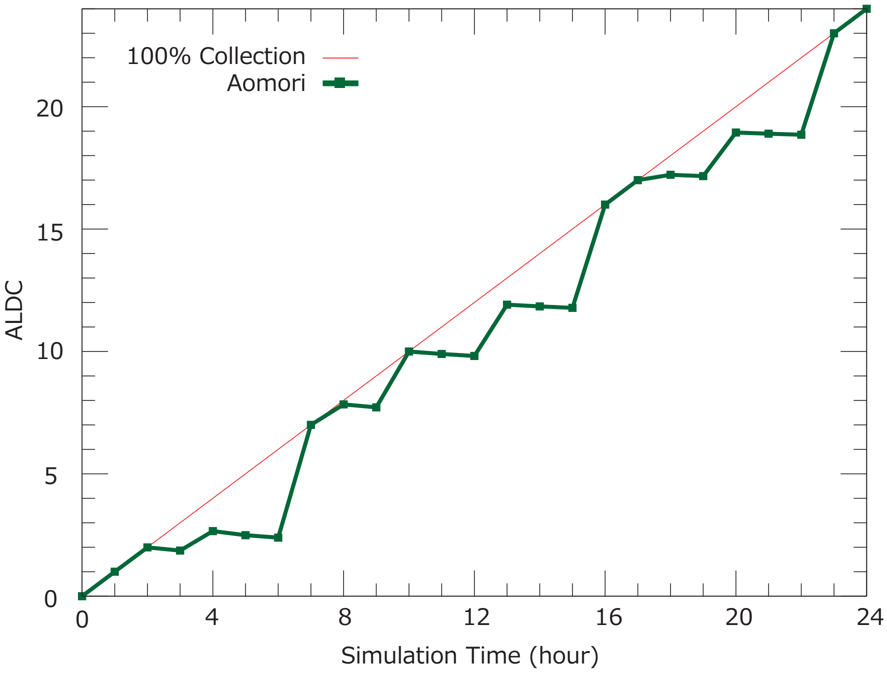

Figure 17: Fluctuation in ALDC over simulation time in the case of Aomori

5 Conclusion

In this thesis, we propose two mobility strategies for mobile sinks in WSNs and realize reliable data collection with a controlled mobile sink. One strategy is for learning positions of sub-networks and the other is for visitign all rendezvous-point nodes using learned sub-networks positions, and the controlled mobile sink executes those strategies alternately to collect all sensing data while detecting all sub-networks in the observed area. Through the simulation evaluation under the scenario where changes in sub-networks over the observed area due to removal or addition of sensor nodes are considered, we demonstrate that our proposed method can realize highly reliable data collection. Moreover, we simulate our proposed method in the realistic situations, where every sensor node is deployed at the position corresponding to the position of each house in actual city maps, and demonstrate that our proposed method can realize the highly reliable data collection under the realistic scenarios while it takes much time to collect all sensing data in some scenarios.

In this thesis, we allow comparatively long time to collect sensing data. Therefore, our proposed method is invalid from the viewpoint of the reliability for an hour in the situations where sensor nodes are deployed quite densely and each sub-network is large. Then we have to consider mechanisms for collecting sensing data in a sub-network which takes shorter time than our proposed method.

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