A Study on Effective Data Collection via Satellite-Routed Sensor System

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A Study on Effective Data Collection via Satellite-Routed Sensor System

高効率なデータ収集を実現する衛星センサネットワークシステムに関する研究

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Chapter 1

Introduction

1.1 Background

In recent years, the development of sensor terminals and communication technologies has made our lives more convenient [1, 2]. Many systems using sensor networks (e.g., weather prediction systems, environmental observation systems, and intrusion detection systems) help to construct smart society where device can communicate with other devices [3, 4]. Additionally, disaster prediction systems that utilize wireless sensor networks have attracted attention, especially, after East-Japan Catastrophic Disaster in March 2011 [5]. From the disaster, many people have learned the importance of getting prompt and precise information on disaster such as earthquake and tsunami. Thus, the sensor network system which is able to gather data from large area quickly is needed.

On the other hand, the remarkable development of network environment has taken our society one step closer to ubiquitous communication whereby numerous devices (e.g., personal computers, mobile phones, and smart devices) can be connected to the Internet any time [6, 7]. In the near future, it is expected that, in addition to these devices, every other physical thing on the planet is also going to be hooked up with the network. This concept is the cornerstone to realizing the Internet of Things (IoT) [8–11]. The IoT is expected to comprise millions of heterogeneous smart things, having sensor terminals deployed over home appliances, cars, buildings, and so on [12, 13]. Data collection from these sensor terminals via IoT can improve our lives and help build an intelligent society [14]. Consider some simple yet practical examples as follows. Data collected from thermometer sensor in houses can be used to automatically adjust the temperature of the houses. Data gathered from cars, on a wide area, might be utilized to prevent traffic jams. To materialize such smart systems, it is needed to collect data from these smart things with sensor terminals rapidly and effectively. Indeed, how to collect the data from a huge number of things is an important issue. In addition, data collection concurrently from a wide area also presents a significant challenge to realize smart society. [15]

Since the wireless networks can be flexibly exploited to access many kinds of network devices, they present themselves as an attractive means to communicate with smart things in IoT [16]. In the wireless communication area, several kinds of development such as ZigBee, Bluetooth, Wi-Fi, and Near Field Communication (NFC) are considered as candidates to communicate with these things. However, there remain many areas where the afore-mentioned network services have not yet covered. Moreover, since the network capacity is limited, it is difficult to manage numerous things and to realize concurrent access. As a consequence, we focus on a data collection technique by using the Satellite-Routed Sensor System (SRSS), which is expected as a next generation technology to efficiently collect data from wireless sensor terminals.

In the SRSS, a satellite collects data from sensor terminals and sends the data to ground stations, which manage the data from these sensor terminals. By using the satellite, it is also possible to collect data from areas with inadequate network infrastructures (e.g., disaster-stricken areas) where the ground network facilities were damaged/destroyed [17]. In addition, since the satellite network is superior in terms of simultaneous communication, numerous sensor terminals are able to access the network at the same time [18, 19]. Thus, the SRSS offers a promising solution to realize IoT efficiently and therefore, can help construct the smart society. However, in an environment where a huge number of sensor terminals are attached to many kinds of things such as cars, homes, and buildings, and send data at any time to the satellite, data collisions may occur at the satellite. Therefore, an efficient access control method is necessary for the system.

1.2 Purpose of Research

In this thesis, we aim to construct the model of the SRSS to achieve effective data collection. Especially, we focus on the real-time performance as a very important parameter to improve the performance of the assumed systems such as disaster prediction systems and IoT. Therefore, we consider a new system model with two following efficient approaches which improves the real-time performance of the SRSS.

- **Data collection from sensor terminals via satellite networks**
- **Data aggregation in superdense sensor networks**

At first, we propose a method to efficiently collect data from a large number of sensor terminals by using SRSS. In this proposal, satellite searches the sensor terminals having data to send by dividing sensor terminals to some groups and allocates bandwidth of the satellite like a divide and conquer approach. Moreover, we optimize the delay of total operating time in our proposal with some mathematical expressions. Therefore, our proposed method achieves efficient data collection from numerous sensor terminals and minimizes the delay for the operating time in the system.

Secondly, we propose a method to aggregate data in sensor networks to improve the real-time performance in SRSS. In the case where the number of sensor terminals is too huge, it is impossible to collects the data from the all sensor terminals via satellite directly. Thus, the data aggregation method is required in such situation. However, since the observed data as each sensor terminals is changing all the time, it is difficult to keep the collected data fresh by using existing wireless communication technologies due to the limitation of the network capacity. Therefore, we propose a novel access control scheme to achieve fresh observed data collection from numerous sensor terminals in the wireless communication networks. In this proposal, the timing of sending data by each sensor terminal is controlled by considering how fast the observed data at each sensor terminal changes. As a result, it achieves to avoid traffic congestion while keeping the collected data fresh.

1.3 Summary and Organization of the Thesis

The remainder of thesis is organized as follows. The assumed network configuration of SRSS is presented in Chapter 2. In addition, the existing access control method and their shortcomings are introduced in this chapter.

Chapter 3 describes our proposed method to effectively collect data from numerous things by using a satellite. Additionally, Chapter3 contains an analysis of the operating time in our proposed method. An analysis on waiting time of each sensor terminal is also presented in this chapter.

Chapter 4 our proposed method to effectively collect data from numerous sensor terminals in real-time. An analysis to evaluate freshness of the collected data is also described in this chapter.

Finally, concluding remarks are provided in Chapter 5.

Chapter 2

Data Collection in Satellite-Routed Sensor System

2.1 Introduction

In this chapter, at first, we introduce two existing systems, Automated Meteorological Data Acquisition System (AMeDAS) as an example of sensor networks, and Argos system as an example of satellite-routed sensor systems. The systems are used in many situations recently and provide various information. Although they play an important role in our life, their performance is not sufficient in terms of real time data collection. Additionally, we describe the shortcomings of their systems and discuss the requirements for the next generation satellite-routed sensor system. Secondly, we introduce assumed network model for data collection. In this model, SRSS is utilized for realizing efficient data collection. At last, the traditional access control methods which have been used for multiple-access communications in SRSS are introduced. Moreover, the shortcomings of these existing methods when they are adopted to the supposed environment are described.

The parts of contents in this chapter are refered to the following papers that are written based on our own researches.

- Y. Kawamoto, H. Nishiyama, N. Kato, S. Yamamoto, N. Yoshimura, and N. Kadowaki " On Real-Time Data Gathering in Next Generation Satellite-Routed Sensor System (SRSS)," *2012 International Conference on Wireless Communications and Signal Processing (WCSP 2012),* Huangshan, China, Oct. 2012.
- Y. Kawamoto, H. Nishiyama, Z. Md. Fadlullah, and N. Kato, " Effective Data Collection via Satellite-Routed Sensor System (SRSS) to Realize Global-Scaled Internet of Things, " *IEEE Sensors Journal,* vol. 13, no. 10, pp. 3645-3654, Oct. 2013.

2.2 Existing Sensor Network Systems

2.2.1 AMeDAS

AMeDAS is a sensor network system which is developed by the Japan Meteorological Agency for monitoring weather events such as rainfall, snowfall, and wind speed [20]. The system includes about 1,300 stations and collects weather data from each station [21]. Each station sends collected data to a central operation center every 10 minutes. The central operation center and stations are connected with Integrated Services Digital Network (ISDN) lines.

Although the system has provided information for a long time, its coverage is limited because these stations are connected with wired network. Thus, it is difficult to detect the local anomaly such as concentrated heavy rain, thunder, and blast. In order to observe such kind of localized phenomenon, many sensor terminals need to be deployed extensively. However, since laying new lines to all over Japan is hard for both economical and physical reasons, it is not a realistic way to collect various data with wired networks. Moreover, since wireless networks also have limitations in communication range, it is hard to collect all data from various sensor networks with only ground infrastructure.

2.2.2 Argos system

Argos system is one of the most popular data collecting systems for environmental research and conservation by using sensor terminals and satellites [22–25]. It is operated predominantly by National Oceanic and Atomospheric Administration, Centre National D'Etudes Spatiales, and National Aeronautics and Space Administration. This system is utilized in many situations as exemplified by, observation of air or sea temperature, ocean biological investigation, follow-up survey of migrant bird, monitoring of volcano, etc... In this system, sensor terminals such as remote mobile platforms, fixed stations on the ground, and buoys on the sea collect various data and send them to the satellites which are around the earth on polar orbit at 850 km high. Each satellite communicates with terminals on its coverage which is 5,000 km in diameter. It receives data from sensor terminals and sends the data to ground receiving stations which are deployed all over the world. On the other hand, if the satellite cannot find the stations immediately after receiving data, they store the data until a station is found within their coverage, and send all data at once to the station. Additionally, Argos system uses Doppler location capability to identify the place of each sensor terminal [26]. Doppler location contributes to simple low-power platform because the calculation is performed at the ground stations. Moreover, Global Positioning System (GPS) positions are also transmitted through the Argos system. Since GPS receivers continuously recalculate position fixes, a higher temporal resolution is possible [27].

Since the Argos system uses Low Earth Orbit (LEO) satellites [28] and Doppler location capability, it is possible to communicate with downsize sensor terminals using low power consumption [29], [30]. However, when the satellite is not in view of the ground stations, they have to store the data from sensor terminals for later use. Consequently, the real-time performance is not very good. To achieve real-time communication with LEO satellites, a large number of satellites need to be deployed in a wide area. But it is not trivial because the cost of launching satellites is expensive.

2.2.3 The shortcomings of existing systems and requisites for next generation satellite-routed sensor systems

Although the sensor networks have provided essential services, there are some shortcomings such as their coverages and disaster-resistances. Many of the existing systems for sensor networks based on wired or wireless ground infrastructures are used to collect data from sensor terminals. But the coverage of the networks are limited and creating new infrastructure for remote areas is difficult for both economical and physical reasons. Moreover, they are at risk for disruption by disasters. Therefore, the satellite-routed sensor systems are expected as networks to resolve these problems. Since satellites have large coverage areas, they are possible to collect data from remote areas. Furthermore, they have the advantage that they are not affected by ground disasters.

However, the satellite-routed sensor systems have some research issues under the situation that the real-time data is needed as previously mentioned. In fact, for tsunami detection and volcano monitoring as examples, the real-time performance of the system is one of the most important indexes. Moreover, a large number of sensor terminals need to be deployed in order to collect data from wide area in many circumstances. For example, there are about 1,300 sensors in

AMeDAS, about 4,200 sensors for earthquake detection, and about 190 sensors for tide level monitoring in Japan. Furthermore, a larger number of sensor terminals should be deployed in future systems. Thus, the satellites in the networks need to receive data from several tens among thousands of sensor terminals. Hence, the next generation satellite-routed sensor system are required to consist of numerous sensor terminals and collect data in real time. Therefore, the problem is how we manage numerous sensor terminals with considering real-time performance by limited satellite bandwidth. An efficient way to allocate the bandwidth of satellites to each sensor terminal is imperative.

2.3 Network Model for Data Collection in SRSS

We focus on the data collection by using SRSS to soleve the previously mentioned problems of existing systems. The assumed SRSS comprises a satellite, numerous sensor terminals attached to many kinds of things, and some monitoring stations on the ground which collect the data from the sensor terminals. It collects data simultaneously from the sensor terminals deployed over a wide area. A Geostationary Earth Orbit (GEO) satellite is considered as it is suitable, due to its wide coverage [31], for collecting data from a large number of sensor terminals. In addition, to receive data from a huge number of sensor terminals, the satellite needs to use uplink from the sensor terminals to the satellite. A prominent example of utilizing the satellite link is the multibeam system [32], which is able to efficiently utilize the frequency of satellite because the terminals in the system deployed on separate areas can use the same frequency range. Furthermore, the satellite can concentrate the transmission power to a narrow area and increase its transmission capacity. Thus, in the remainder of this thesis, we consider the SRSS using the multibeam system. The sensor terminals are separated and managed by the satellite in each beam.

Additionally, since sensor terminals are attached to various things, the data generation patterns of the sensor terminals also differ. Depending on the implementation of the sensor terminals, these patterns are broadly classified into three groups, namely constant, periodical, and random generation patterns. For example, there are *Keep-alive Message* as the constant data generation and *Periodic Data Transmission* as the data generated periodically. On the other hand, *Event-triggered Data Transmission* also exists as the randomly generating data [33]. In these types of generated data, we cannnot adjust the data collecting schedule to perfectly match the timing of which the data are generated, especially with randomly generated data. To construct the system to collect data efficiently and flexibly, an appropriate method for random access is, indeed, needed [34]. Therefore, we consider the system whereby numerous sensor terminals randomly access the satellite.

2.4 Existing Access Control Methods

As mentioned earlier, an appropriate method for random access in SRSS for efficiently and flexibly collecting data is needed to facilitate communications between numerous sensor terminals and a satellite. Since the random access causes collisions of data at the terminals receiving the data, many access control methods are developed such as Carrier Sense Multiple Access/Collision Detection (CSMA/CD) and Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) for the common terrestrial networks. However, since many things attached with sensor terminals are deployed over a wide area and they communicate with the same satellite in the supposed network environment, the distance between these sensor terminals is significantly long to detect radio waves from the neighboring sensor terminals. Thus, conventional access control methods are supposed to be used in the communication between the satellite and terminals deployed on the ground even in recent years [35].

2.4.1 ALOHA

The conventional access control methods are classified into two groups, namely contention-based schemes and fixed assignment schemes. As a contention-based scheme, ALOHA [36] is a famous method used in the satellite networks. In the case where ALOHA is used, upon data generation, each terminal on the ground sends the data to a satellite. If collisions occurs at the satellite due to the data received from multiple terminals, each terminal waits for a random time and then resends the data. By using the random waiting time, the terminals can avoid further collisions. Moreover, slotted ALOHA, which is developed by improving the ALOHA is also a general method using random access control. In the slotted ALOHA technique, each terminal is controlled to send the data at a regular interval in contrast with ALOHA, which permits each terminal to send its data at any time. By controlling the sending time, the slotted ALOHA avoids retransmissions which occur due to the data collisions. Thus, the slotted ALOHA achieves higher throughput than that in ALOHA. Furthermore, many schemes, which improve ALOHA or slotted ALOHA, are developed in the work in [37].

2.4.2 TDMA

On the other hand, Time Division Multiple Access (TDMA) is well known as a fixed assignment scheme. In TDMA, the terminals are allocated time-slots (which are the smallest logical units for bandwidth allocation) and send their data during the time-slots by rotation. Since each sensor terminal can send data at different time instants with regular intervals, it is possible to avoid the collisions caused by the overlapping of the timing of data sending [38].

2.4.3 The shortcomings of existing access control methods

However, in the case where numerous terminals are deployed that leads data generation at any time, the performance of these conventional methods decreases drastically. In the case of ALOHA and slotted ALOHA techniques, the increase of the number of terminals causes the increase of probability that more than one terminal send data to a satellite at the same time. As a result, continuous collisions might occur and it causes the decrease of the throughput performance. On the other hand, although fixed assignment schemes achieve higher performance in limited environments such as the case where the terminals generate data constantly, an ineffective time-slots assignment might occur when the data are arbitrarily generated. Additionally, each terminal might need to wait for a long time interval until the time-slots are assigned again in the fixed assignment schemes in the case where numerous terminals are deployed.

Thus, the performances of both contention-based and fixed assignment schemes decrease in the case where numerous terminals are deployed and the terminals generate data arbitrarily. Therefore, a method to assign bandwidth on-demand to sensor terminals that detects the sending event with a significantly small operation time is required for the SRSS.

2.5 Summary

In this chapter, we described existing sensor network systems and their shortcomings. Thus, we focused on the data collection by using SRSS. Moreover, the traditional access control methods which have been used for multiple-access communications in SRSS were introduced. Furthermore, the shortcomings of these existing methods were described. Therefore, it was understood that an efficient method to collect data from numerous sensor terminals via satellite is required.

Chapter 3

An Effective Data Collection with A Divide and Conquer Approach

3.1 Introduction

In this chapter, we propose the new satellite bandwidth allocation methods to gather data from numerous sensor terminals in an on-demand fashion within a small operation time. As the approach of the data collection methods, we propose two approaches, proactive approach and reactive approach. In the proactive approach, satellite partitions sensor terminals into some groups to avoid data collisions before starting the process of the data collection. On the other hand, in the reactive approach, satellite devide sensor terminals while running the data collection process dynamically according to the number of sensor terminals having data to send. Additionally, to increase real-time performance, the operation time of each proposals is optimized with mathematical analysis.

The parts of contents in this chapter are refered to the following papers that are written based on our own researches.

- Y. Kawamoto, H. Nishiyama, N. Kato, S. Yamamoto, N. Yoshimura, and

N. Kadowaki, ”A Centralized Multiple Access Scheme for Data Gathering in Satellite-Routed Sensor System (SRSS),” IEEE Global Communications Conference (GLOBECOM) 2013, Atlanta, Georgia, USA, Dec. 2013.

- Y. Kawamoto, H. Nishiyama, Z. Md. Fadlullah, and N. Kato, “ Effective Data Collection via Satellite-Routed Sensor System (SRSS) to Realize Global-Scaled Internet of Things, ” *IEEE Sensors Journal,* vol. 13, no. 10, pp. 3645-3654, Oct. 2013.

3.2 An efficient data gathering technique with proactive approach

3.2.1 Proposed algorithm

In this proposed method with proactive approach, we aim to quickly and efficiently gather data from a large number of sensor terminals while avoiding data collisions. The proposed algorithm is shown in Algorithm 3.

In this proposal, satellite partitions sensor terminals into groups with respect to their identification number before starting the data collection process. We define the number of all sensor terminals as N_{s} and the number of the groups as N_{g}. Additionally, each group is given the identification number of the group as G_i where $0 \leq i \leq N_{\mathrm{g}}$. After partitioning, the satellite broadcasts messages to all terminals within each group, one group at a time, to inquire if any sensor terminals have any data to send. We call the messages as Searching Messages (SMs). Each sensor terminal in each group sends back message, namely Receiving Message (RM) which includes the sensor terminal’s identification number to the satellite if they have data to send. According to the number of RMs which the satellite receives from each group, satellite classifies the groups into three

Algorithm 1 Proposed data gathering algorithm

```
Divide all sensor terminals into some groups
/* Start classification phase */
for $i = 0$ to $N_{\mathrm{g}}$ do
    Send SM to sensor terminals in $\mathrm{G}_i$
    if $N_{\mathrm{RM}} = 0$ then
        Classify $\mathrm{G}_i$ as Category-0
    else if $N_{\mathrm{RM}} = 1$ then
        Identify the sensor terminal having data
        Classify $\mathrm{G}_i$ as Category-1
    else $\{N_{\mathrm{RM}} \geq 2\}$
        Detect data collision
        Classify $\mathrm{G}_i$ as Category-2
    end if
end for
/* Move to allocation phase */
for $i = 0$ to $N_{\mathrm{g}}$ do
    if $\mathrm{G}_i$ is classified as Category-1 then
        Allocate time-slots to sensor terminal having data
    else if $\mathrm{G}_i$ is classified as Category-2 then
        Allocate time-slots to all sensor terminals in the group
    end if
end for
```

categories. Here, we define the number of RMs as N_{RM}. If the number of N_{RM} is zero, satellite classify the group as *Category-0*. This means that sensor terminals in this group do not have any packet to send. On the other hand, in the case where a sensor terminal in the group has data to send, it sends back RM to the satellite, that is to say that N_{RM} equals to 1. Then, the satellite knows which sensor terminal has data to send and classify the group as *Category-1*. However, if multiple sensor terminals in same group have data to send, data collision may occur due to the overlapping of RMs. In this case, N_{RM} is equal to two or more. Thus, the satellite cannot identify which sensor terminals have data to send, but know that there are two or more sensor terminals that have data to send within the group by detecting the data collision. Then, the satellite classifies the group as *Category-2*. The satellite repeats until all groups are classified according to the N_{RM}. We refer to this process as classification phase.

After the classification phase, the satellite moves to next phase, namely allocation phase. In the allocation phase, at first, satellite allocates time-slots to the sensor terminal in all groups classified as *Category-1*. Since each *Category-1* group has only one sensor terminal that want to send data, the satellite only need to allocate time-slots for that one terminal from each group classified as *Category-1*. However, the satellite has to allocate time-slots for all terminals from groups that are classified as *Category-2* similar to TDMA fashion. This is done to avoid data collision which could happen in groups classified as *Category-2*.

As mentioned above, the proposed method is able to allocate time-slots in an on-demand fashion and avoid data collisions. It is preferable to have more *Category-1* groups because in the allocation phase *Category-1* group only need time-slots allocation for one terminal while *Category-2* groups need time-slots allocation for every terminals even those that may not have any data. In order to increase the number of groups classified as *Category-1*, the total number of groups should be increase. It is because that the increase of the total number of all groups make the number of sensor terminals in each group smaller and it decreases the probability of overlapping of data sending from multiple sensor terminals. Moreover, the decrease of the number of sensor terminals in each group decreases the operation time to allocate time-slots to the sensor terminals in *Category-2*. Thus, the operation time for allocation phase decrease with the increase of the total number of groups. However, the increase of the total number of groups causes the operation time to increase in the classification phase. Since the satellite broadcasts SM to each group in order, the time used in classifying terminals increases commensurately with the number of all groups. Therefore, there is a trade-off relationship between the operation time for classification phase and allocation phase with the increase of the number of all groups. Thus, in this proposal, the optimal total number is utilized to minimize the total operation time.

3.2.2 Optimization of total operation time

In this subsection, we optimize the total operation time in our proposed method with mathematical expressions. Firstly, we formulate the expected operation time for classification phase. In the classification phase, satellite sends SMs to the groups of sensor terminals at regular interval. We define the length of the interval as t which equal to the length of a time-slot. Additionally, we define the sum of the propagation time which satellite sends SM to sensor terminal and the propagation time which sensor terminal sends RM to the satellite as rtt. Since the expected operation time in classification phase, namely T_{cp}, is expressed as sum of the rtt and sum of the regular interval, t, it is formulated with the number of all groups as follows.

$$T_{\text{cp}}(N_{\text{g}}) = rtt + N_{\text{g}} \cdot t, \tag{3.1}$$

where the rtt is expressed with altitude of satellite, h_{sat}, and light speed, c, as follows.

$$rtt = \frac{2 \cdot h_{\text{sat}}}{c}. \tag{3.2}$$

From Eq. 3.1, it is clearly shown that the expected operation time in classification phase increase with the increase of the total number of groups.

Secondly, we express the expected operation time in allocation phase. It is determined by how many groups are classified as *Category-1* or *Category-2* and it depends on the probability that each sensor terminal has data to send when the sensor terminal receives SM. Here, we define average of the probability that each sensor terminal has data to send when the sensor terminal receives SM as p. By using the probability, p, the probability that the group of sensor terminals is classified as *Category-1*, namely $P_{(N_{\mathrm{RM}}=1)}(N_{\mathrm{g}})$, is expressed as follows.

$$P_{(N_{\mathrm{RM}}=1)}(N_{\mathrm{g}}) = {}_{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}}C_1 \cdot p \cdot (1-p)^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}-1}. \tag{3.3}$$

In a similar way, the probability that the group of sensor terminals is classified as *Category-2*, namely $P_{(N_{\mathrm{RM}}\geq 2)}(N_{\mathrm{g}})$, is expressed as follows.

$$P_{(N_{\mathrm{RM}}\geq 2)}(N_{\mathrm{g}}) = \sum_{k=2}^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}} \left\{ {}_{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}}C_k \cdot p^k \cdot (1-p)^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}-k} \right\}. \tag{3.4}$$

Since only the sensor terminal having data to send in *Category-1* group and all sensor terminals in *Category-2* group are allocated time-slots, the operation time to allocate time-slots to these sensor terminals in allocation phase, namely $T_{\mathrm{ap}}(N_{\mathrm{g}})$ is expressed as follow.

$$T_{\mathrm{ap}}(N_{\mathrm{g}}) = N_{\mathrm{g}} \cdot P_{(N_{\mathrm{RM}}=1)}(N_{\mathrm{g}}) \cdot t + N_{\mathrm{g}} \cdot P_{(N_{\mathrm{RM}}\geq 2)}(N_{\mathrm{g}}) \cdot \frac{N_{\mathrm{s}}}{N_{\mathrm{g}}} \cdot t. \tag{3.5}$$

Thus, the total operation time in our proposed method, namely $T_{\mathrm{total}}(N_{\mathrm{g}})$, is expressed as follow.

$$\begin{aligned} T_{\mathrm{total}}(N_{\mathrm{g}}) &= T_{\mathrm{cp}}(N_{\mathrm{g}}) + T_{\mathrm{ap}}(N_{\mathrm{g}}) \\ &= rtt + N_{\mathrm{g}} \cdot t + \Bigg[p \cdot (1-p)^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}-1} \\ &+ \sum_{k=2}^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}} \left\{ {}_{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}}C_k \cdot p^k \cdot (1-p)^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}-k} \right\} \Bigg] \cdot N_{\mathrm{s}} \cdot t. \end{aligned} \tag{3.6}$$

Since there is trade-off relationship between $T_{\mathrm{cp}}(N_{\mathrm{g}})$ and $T_{\mathrm{ap}}(N_{\mathrm{g}})$, $T_{\mathrm{total}}(N_{\mathrm{g}})$ is a convex function with N_{g}. Thus, there is an optimal number of N_{g} to minimize the total operation time in our proposal. We define the optimal number of N_{g} as N_{optg} and it is expressed as follow.

$$N_{\mathrm{optg}} = \arg\min_{N_{\mathrm{g}}} T_{\mathrm{total}}(N_{\mathrm{g}}). \tag{3.7}$$

As mentioned above, the optimal number of groups which is determined by the satellite at the start of our algorithm is concluded by some mathematical expressions. From the expressions which are developed in this subsection, it is understood that the optimal number of groups depends on the probability that each sensor terminal has data to send. Thus, the satellite decides the number of dividing groups by using the probability which is obtained by history of data generating at sensor terminals. By utilizing the history of data generating, our proposal achieves to calculate the optimal number of groups easily from the expressions. Therefore, the proposed method achieves to efficiently allocate bandwidth to sensor terminals with minimal operation time.

3.2.3 Numerical analysis

In this subsection, we confirm the relationship between the operation times of classification phase and allocation phase in the proposed method with numerical analysis. The optimal number of groups in our proposal is also verified to exist. Moreover, the change of the optimal number of groups and the operation time when the optimal number of groups is adopted are investigated.

Table 3.1: Parameter settings

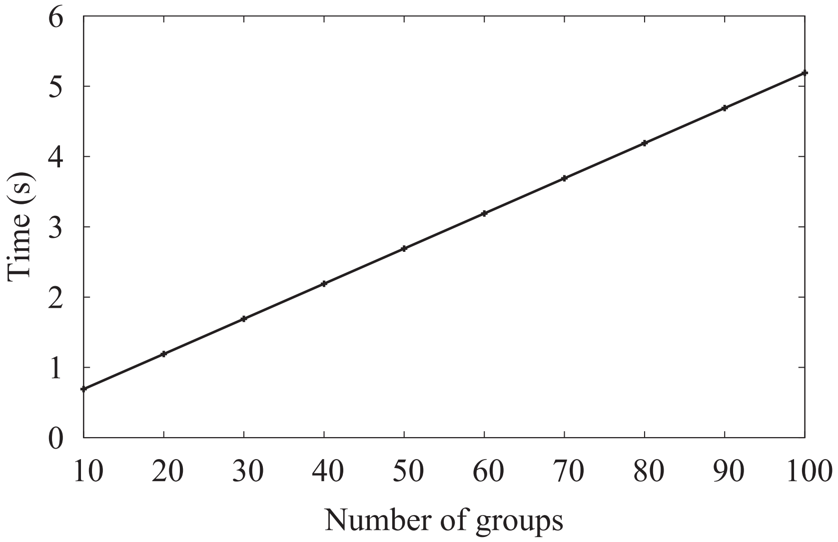
Number of satellites	1
Altitude of satellite (h_{sat})	36,000km
Number of sensor terminals (N_{s})	500-1,500
Time-slot (t)	50ms
Light speed (c)	300,000km/s

3.2.3.1 Parameter settings

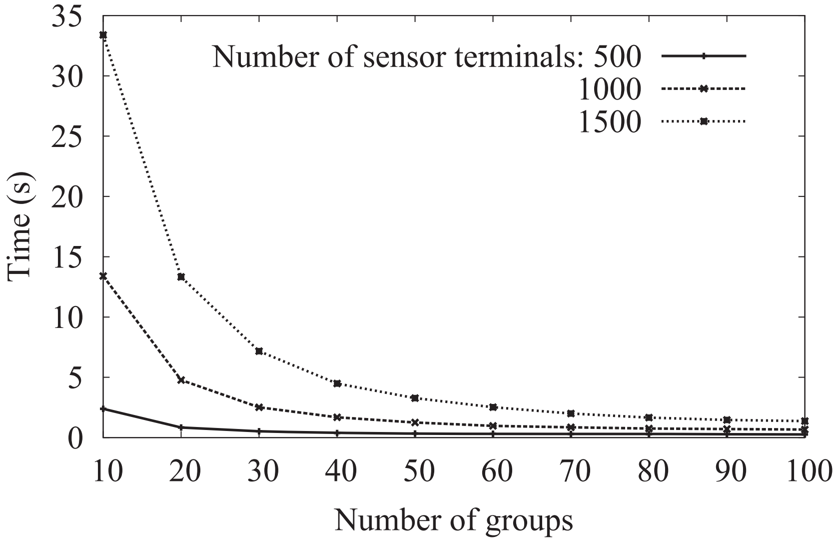
The parameter settings are summarized in Table 4.2. In this numerical analysis, the SRSS constructed by a GEO satellite that has an altitude of 36,000km and sensor terminals is utilized to evaluate our proposal. Additionally, the number of sensor terminals is varied from 500 to 1,500 with the step of 500. Moreover, as the bandwidth allocation scheme, TDMA based allocation where the length of time-slots is set to 50ms is used in the system.

3.2.3.2 Numerical results

First, we evaluate the operation time for classification phase, allocation phase, and the sum of both. Fig. 3.6a shows the operation time for classification phase when the number of groups increase. Since Eq. 3.1 does not depend on the number of all sensor terminals, it has same values between different number of sensor terminals. As shown in Fig. 3.6a, the operation time for classification phase increase proportionally to the increase of number of groups. It is because that satellite sends as many SMs as the number of groups at regular interval. On the other hand, it is understood that the operation time for allocation phase decrease with the increase of number of groups from Fig. 3.6b. This is because that the increase of number of groups causes data collision probability to decrease because the number of terminals inside each group decrease with the increase of the total number of groups. Thus, the probability of data collision within each group decreases. Fig. 3.1c represents the total operation time of our proposal with the change of total number of groups. From the results, it is confirmed that there is an optimal number of groups to minimize the total operation time in each case where the number of sensor terminals is different. Additionally, we can see that the large number of sensor terminals causes a long allocation time.

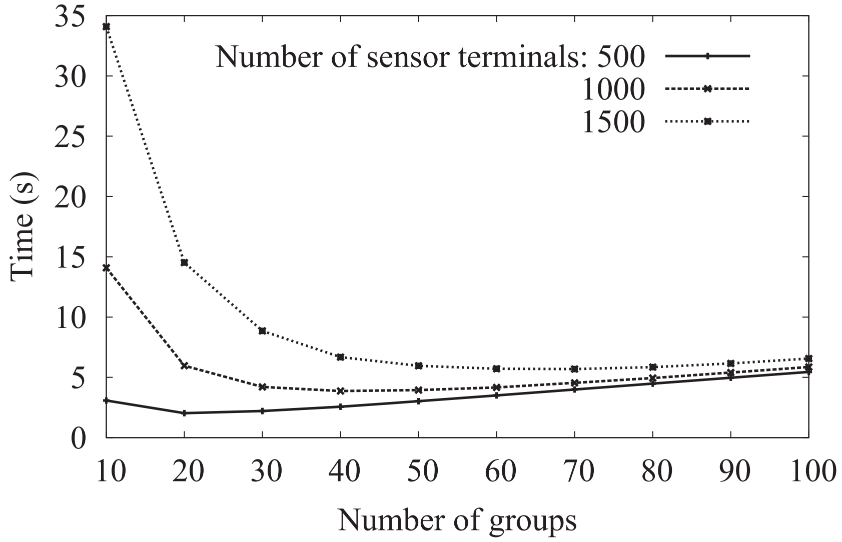


(a) The operation time for classification phase.



(b) The operation time for allocation phase.

Figure 3.1: Operation time for searching phase and allocation phase, and the total time of them.



(c) The total operation time.

Figure 3.1: Operation time for searching phase and allocation phase, and the total time of them. ©2013IEEE

Secondly, we study the change of the optimal number of groups and total operation time when the number of groups is optimized. Fig. 3.2 illustrates the optimal number of groups when the probability that each sensor terminal has data to send when it receives SM varies from 1% to 5%. From Fig. 3.2, it is understood that the optimal number of groups increase with the increase of the value of p. Since larger value of p causes the higher probability that data collisions occur, the larger number of groups is needed to decrease the operation time. On the other hand, Fig. 3.3 shows the change of total operation time when the optimal number of groups is adopted in our proposal. It is clearly shown that the optimized operation time increase with the increase of the value of p. Additionally, the larger number of all sensor terminals need the longer time to gather data from all sensor terminals.

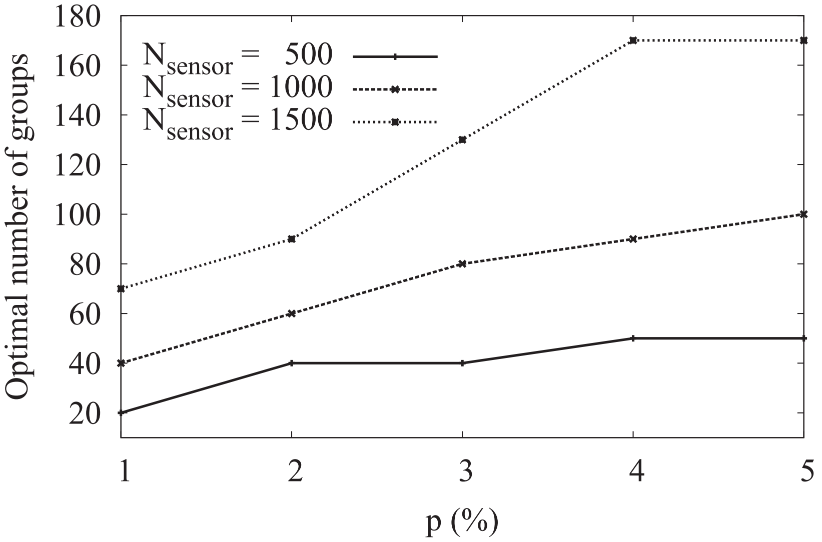


Figure 3.2: The change of optimal number of groups. ©2013IEEE

From these numerical results, we confirm that the optimal number of groups to minimize the total operation time in the proposed method does exist. Additionally, the effect of the value of p on our proposal is investigated. Therefore, our proposal achieves efficient data gathering from numerous sensor terminals in SRSS with small operation time.

3.3 Data Collection with A Proposed Reactive Approach

In this section, we propose a new method to collect data efficiently with reactive approach in SRSS. Since the data collection method which is described in the previous section requires the information obtained by history of data generating at sensor terminals, the performance of the method may decrease with the situation

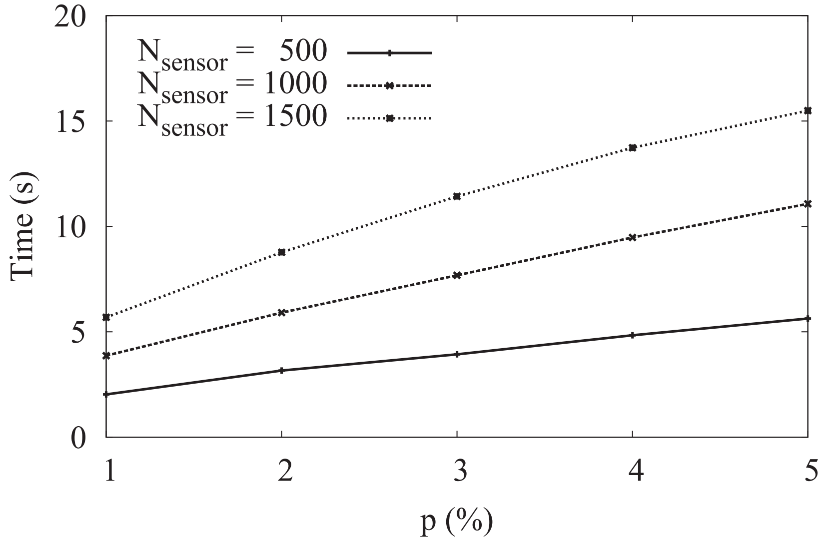


Figure 3.3: The change of total operation time when the number of groups is optimized. ©2013IEEE

where the probability of the data generation changes remarkably over the time. Thus, in this section, we propose a method to collect data efficiently from sensor terminals dynamically according to the number of sensor terminals having data to send.

3.3.1 Overview of Proposed Reactive Data Collection Method

We aim at collecting data on-demand efficiently from the sensor terminals, which have some data, to send to numerous other terminals with a significantly small operating time. In the proposed method, the satellite collects data from the sensor terminals on-demand by a "divide and conquer" approach to avoid ineffective bandwidth allocation. Fig. 3.4 shows the example of the process-flow of our proposal in case that there are thirty two sensor terminals. In our proposal, the

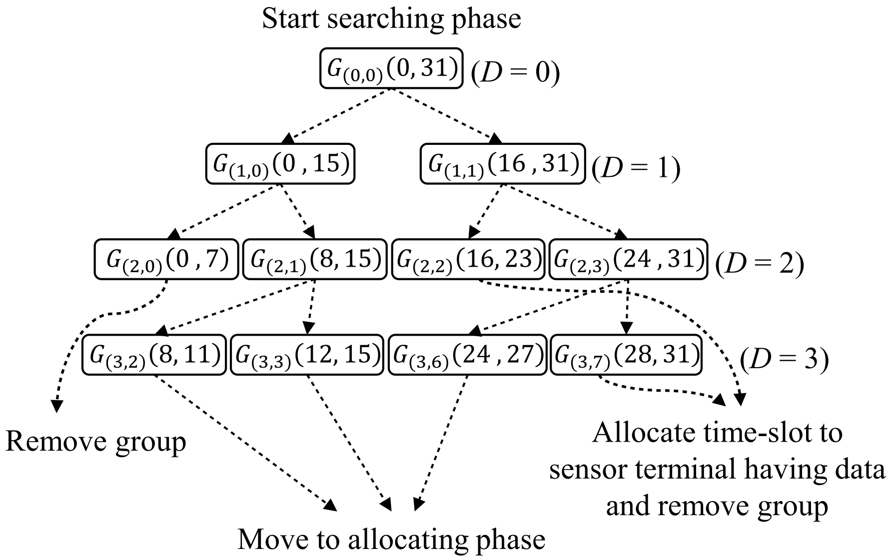


Figure 3.4: An example of the flows to divide a number of sensor terminals into some groups (like a binary partition tree). ©2013IEEE

satellite repeats to divide the sensor terminals into some groups for distinguishing the terminals having data to send. This step is called the searching phase. Each group $\mathrm{G}_{(D,i)}(\alpha,\beta)$ in Fig. 3.4, shows a group, consisting of sensor terminals that have identification numbers ranging from α to β, where D and i indicate the number of “dividing” (or division) processes and the group ID after the dividing is conducted D times, respectively.

By the end of every searching phase, each identified sensor terminal will have a time-slot allocated. After repeating the dividing process several times, the satellite stops dividing the sensor terminals into groups and allocates time-slots to all the remaining sensor terminals by using TDMA, regardless of them having data to send or not, to decrease the total operation time. By allocating time-slots to all the remaining terminals regardless of them having data to send or not, our method can avoid unnecessary time for confirming the existence of data in the

Algorithm 2 Proposed data collection algorithm ©2013IEEE

```
Join all sensor terminals into $\mathrm{G}_{(0,0)}(0, N_{\mathrm{sensor}})$
$D = 0$
$\mathbb{S}(D) = \phi$
Calculate $\Delta_{\mathrm{a}}(D)$ and $\Delta_{\mathrm{s}}(D)$
while $\Delta_{\mathrm{a}}(D) > \Delta_{\mathrm{s}}(D)$ do
  /* Start searching phase */
  while $\mathrm{G}_{(D,i)}(\alpha, \beta)$ exist do
    Send SM to $\mathrm{G}_{(D,i)}(\alpha, \beta)$ in order of $i$
    if $N_{\mathrm{RM}} = 1$ then
      Add the detected sensor terminal to $\mathbb{S}(D)$
    else if $N_{\mathrm{RM}} \geq 2$ then
      Make $\mathrm{G}_{(D+1,2i)}(\alpha, \frac{\alpha+\beta-1}{2})$, $\mathrm{G}_{(D+1,2i+1)}(\frac{\alpha+\beta}{2}, \beta)$
    end if
    Remove $\mathrm{G}_{(D,i)}(\alpha, \beta)$
  end while
  Allocate time-slots to the sensor terminals in $\mathbb{S}(D)$
  $D$++
  $\mathbb{S}(D) = \phi$
  Recalculate $\Delta_{\mathrm{a}}(D)$ and $\Delta_{\mathrm{s}}(D)$
end while
/* Move to allocating phase */
Allocate time-slots to all remaining sensor terminals
```

sensor terminals' buffer. We refer to this step as the allocating phase. In Fig. 3.4, the dividing process terminates at the third iteration, i.e., $D = 3$, and then the allocating phase starts.

The algorithm of the proposal is shown in Algorithm 3. All the considered sensor terminals are added to a group, which is initially described as $\mathrm{G}_{(0,0)}(0, N_{\mathrm{sensor}})$. Secondly, the satellite calculates $\Delta_{\mathrm{a}}(0)$ and $\Delta_{\mathrm{s}}(0)$, which describe the necessary time to allocate the time-slots to all the sensor terminals and the required time to perform the searching phase one more time, respectively. If the value of $\Delta_{\mathrm{a}}(0)$ exceeds that of $\Delta_{\mathrm{s}}(0)$, the satellite starts the searching phase. In the searching phase, the satellite broadcasts searching messages, referred to as SMs, to each group $\mathrm{G}_{(D,i)}(\alpha, \beta)$ at a regular interval. The interval has the duration of a single time slot that is t time units long. If the sensor terminals, which already received the SMs, also have data to send, they return the received messages, denoted as RMs, to the satellite. Then, the satellite proceeds to the next step according to the number of the RM(s) returned to it from the terminals. We define the number of returned RMs from a group of terminals as N_{RM}. If N_{RM} equals one, the detected sensor terminal is added to the set of the sensor terminals, which are allocated time-slots, namely $\mathbb{S}(D)$. On the other hand, in the case where the number of sensor terminals having data to send exceeds than one, the collision of RMs must occur at the satellite. As a result, the satellite is unable to identify the sensor terminals returning the RMs to it. Thus, if the data collision is detected at the satellite, the satellite divides the sensor terminals into two groups according to the identification number of each sensor terminal. The satellite repeats this process while $\mathrm{G}_{(D,i)}(\alpha, \beta)$ remains when the depth of the tree is D. After that, the satellite allocates time-slots to the sensor terminals in $\mathbb{S}(D)$ and the sensor terminals start to send the data during their allocated time-slots. Moreover, the satellite repeats the searching phase after increasing D by one.

An example of the process flow of the afore-mentioned proposal is depicted in Fig. 3.5. The figure demonstrates the process whereby some sensor terminals are divided to several groups according to the identification number of each sensor terminal. Each circle represents a sensor terminal and the number in the circle indicates the identification number of each terminal. In addition, the gray circles are sensor terminals having data to send. As shown in Fig. 3.5, if there are some sensor terminals having data to send in the group, the dividing process is repeated. In this case, after dividing twice (i.e., when the value of D is two), the sensor terminals are divided to four groups, and one of these groups is guaranteed to include only a single sensor terminal having data to send while another having

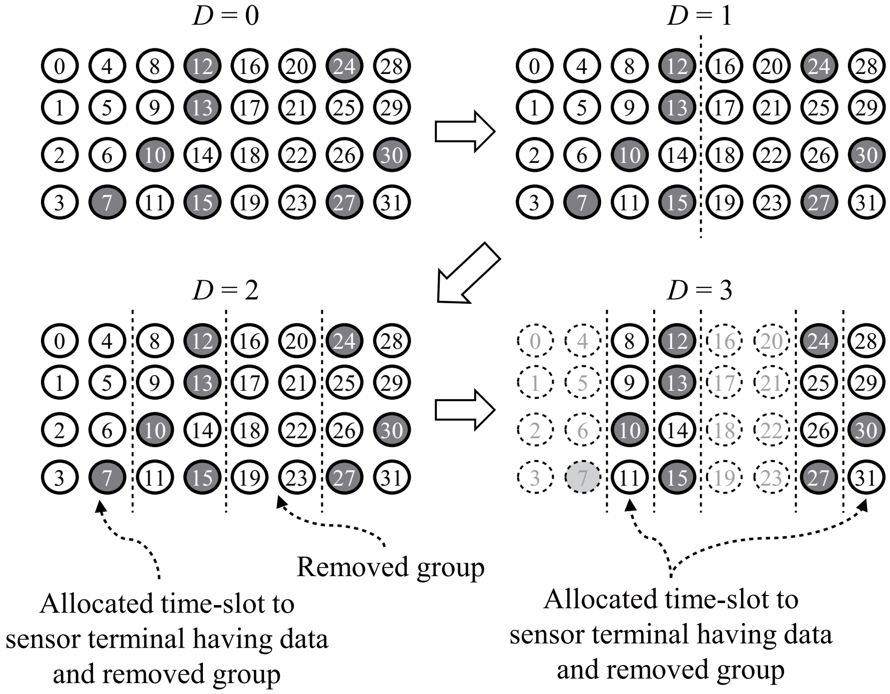


Figure 3.5: An example of the processes involved in our proposal. ©2013IEEE

no terminal having data to send. Then, the dividing process to the two groups is stopped, and the sensor terminal detected to have data to send is allocated appropriate time-slots. On the other hand, since the each of the other two groups have more than one sensor terminal having data to send, these groups are divided into two further groups, respectively. After this division (i.e, when the value of D becomes three), it becomes clear that the two of these remaining four groups have only one sensor terminal having data to send. Thus, each of the sensor terminals included in these two groups is allocated time-slots by the satellite. By this way, the number of sensor terminals, which identified as having the data to send, increases with the value of D. However, since the satellite has to send SMs each time to the sensor terminals group when the value of D increases, the operation time of the above mentioned searching phase increases also.

Therefore, in the proposed scheme, the searching phase is stopped after a certain number of times of dividing even if there remain groups including more than one sensor terminal having data to send. After stopping the searching phase, the satellite allocates time-slots by using TDMA to all the sensor terminals in each of the remaining groups whenever the terminals have data or not. This allocation phase leads to decreasing the wasted time of the searching phase. In addition, the value of D, based on which the satellite stops the searching phase, is set to the larger value of the following two parameters, $\Delta_{\mathrm{a}}(D)$ and $\Delta_{\mathrm{s}}(D)$.

In the proposed method, since the number of groups is small when the value of D is small, the value of $\Delta_{\mathrm{s}}(D)$ is also small while the number of the remaining sensor terminals is large at that time. Thus, the searching phase is supposed to continue for a certain period. After repeating the searching phase on several occasions, since the total number of the sensor terminals decreases by the searching phase, $\Delta_{\mathrm{a}}(D)$ decreases, while the number of groups increases with the value of D, which causes an increase in $\Delta_{\mathrm{s}}(D)$. Therefore, the searching phase is stopped, and the allocation phase commences when $\Delta_{\mathrm{s}}(D)$ exceeds $\Delta_{\mathrm{a}}(D)$. As a consequence, the total operating time is minimized. In the following section, a detailed analysis on the operating time of our proposal is presented.

3.3.2 Minimizing Operating Time in Proposed Reactive Approach

In this subsection, we mathematically analyze the amount of time required for the searching and allocation phases, respectively, when the value of D changes. Furthermore, the minimized total operating time in the proposed method is expressed analytically.

3.3.2.1 Formulation of the operating time of the proposed reactive approach

First, we formulate $\Delta_{\mathrm{s}}(D)$, which denotes the amount of time required for the searching phase at certain depth of the tree. $\Delta_{\mathrm{s}}(D)$ is expressed as the sum of the Round Trip Time (RTT) between the satellite and the sensor terminals.

Since the satellite sends SMs to each group at a regular interval, t, the total amount of RTT is represented as the sum of the propagation time, during which the satellite sends SMs to each group of the terminals, the propagation time during which terminals having data to send in each group returns RM to the satellite, and sum of the regular intervals. Thus, it depends on the distance between the satellite and sensor terminals [29], and the number of remaining groups. Here, we define the amount of time of the RTT and the number of remaining groups as rtt and G_{r}, respectively. Thus, the necessary time to wait until the satellite finishes sending SMs at a regular interval and RM returns from the sensor terminal which receives the SM at last is expressed as the sum of rtt and $(G_{\mathrm{r}}(D)-1)\cdot t$. Therefore, $\Delta_{\mathrm{s}}(D)$ is expressed as follows.

$$\Delta_{\mathrm{s}}(D) = rtt + (G_{\mathrm{r}}(D)-1)\cdot t, \tag{3.8}$$

where the rtt is expressed with altitude of satellite, h_{sat}, and light speed, c, as follows.

$$rtt = \frac{2\cdot h_{\mathrm{sat}}}{c}. \tag{3.9}$$

On the other hand, let $\Delta_{\mathrm{d}}(D)$ denote the required time to allocate time-slots to the sensor terminals having data to send that are detected in the searching phase when the depth of the tree is D. Then, $\Delta_{\mathrm{d}}(D)$ can be expressed with the number of sensor terminals allocated time-slots and the size of the time-slot, t.

Since the number of sensor terminals, which have been allocated time-slots, is expressed as an absolute value of the set of the detected sensor terminals, $\Delta_{\mathrm{d}}(D)$ is formulated as follows.

$$\Delta_{\mathrm{d}}(D) = |\mathbb{S}(D)| \cdot t. \tag{3.10}$$

Moreover, since $|\mathbb{S}(D)|$ equals the number of the groups, which include a sensor terminal sending RM to the satellite when the depth of tree is D, it is defined as the product of $G_{\mathrm{r}}(D)$ and the probability, $P_{(N_{\mathrm{RM}}=1)}(D)$, that each remaining group includes a sensor terminal having data to send. Since we define the number of sensor terminals in each group as $n(D)$ and the number of all sensor terminals as N_{all}, the probability, $P_{(N_{\mathrm{RM}}=1)}(D)$, is expressed with a likelihood that each sensor terminal has data to send, p, as follows.

$$P_{(N_{\mathrm{RM}}=1)}(D) = {}_{n(D)}C_1 \cdot p \cdot (1-p)^{n(D)-1}, \tag{3.11}$$

where

$$n(D) = \frac{N_{\mathrm{all}}}{2^D}. \tag{3.12}$$

Therefore, $|\mathbb{S}(D)|$ is formulated as follows.

$$|\mathbb{S}(D)| = P_{(N_{\mathrm{RM}=1})}(D) \cdot G_{\mathrm{r}}(D). \tag{3.13}$$

Now, we express the amount of time required for the allocation phase. Since it depends on the number of the remaining groups, it is also formulated as a function of D. In our proposal, the satellite allocates all sensor terminals in the remaining group. Thus, Δ_{a} is represented as the product of the number of these sensor terminals and the size of the time-slot allocated to each sensor terminal as follows.

$$\Delta_{\mathrm{a}}(D) = n(D) \cdot G_{\mathrm{r}}(D) \cdot t. \tag{3.14}$$

3.3.2.2 Minimized total operating time of the proposed reactive approach

In the remainder of this section, we introduce and analyze the minimized total operating time in the proposed method. In our proposal, the satellite determines whether to continue the searching phase or move to the allocation phase by calculating the time required for each phase. From the expressions, discussed in the preceding section, it is evident that the amount of time for each phase depends on $G_{\mathrm{r}}(D)$. Since the groups of the sensor terminals remain or are removed according to the number of returned RMs from each group in each searching phase, the value of $G_{\mathrm{r}}(D)$ changes with the increase of the value of D. When the value of D increases, the groups including more than one sensor terminal having data to send remain. We define the probability that the group remains as $P_{(N_{\mathrm{RM}} \geq 2)}$, which is expressed as follows.

$$P_{(N_{\mathrm{RM}} \geq 2)}(D) = \sum_{k=2}^{n(D)} \left\{ {}_{n(D)}C_k \cdot p^k \cdot (1-p)^{n(D)-k} \right\}, \tag{3.15}$$

where the value of k denotes the number of the sensor terminals having data to send that are included in the group.

Since each group, which includes more than one sensor terminal having data to send, is divided into two groups, the number of groups when the value of D changes to $D+1$ is expressed as follows.

$$G_{\mathrm{r}}(D+1) = 2 \cdot G_{\mathrm{r}}(D) \cdot P_{(N_{\mathrm{RM}} \geq 2)}(D). \tag{3.16}$$

As shown in the above expressions, the number of the remaining groups changes with the increase of value of D. According to the change of the value of $G_{\mathrm{r}}(D)$, Δ_{s} and Δ_{a} change and the satellite determines to move to the allocation phase when the value of D increases to some level. Here, we define the value of D at that time as D_{opt}, which minimizes the total operating time by avoiding ineffective searching. From Eq. 3.16, the number of the remaining groups (when the value of D equals that of D_{opt}) is expressed as follows.

$$G_{\mathrm{r}}(D_{\mathrm{opt}}) = \prod_{D=0}^{D_{\mathrm{opt}}-1} \left\{2 \cdot P_{(N_{\mathrm{RM}} \geq 2)}(D)\right\}. \tag{3.17}$$

Hence, the expected minimized total operating time, namely $\Delta_{\mathrm{t}}(D_{\mathrm{opt}})$, is described as the sum of the time for the searching phase and that for allocating time-slots to the sensor terminals detected in the searching phase while the value of D becomes D_{opt}, and the time required to allocate the time-slots to all the sensor terminals in the remaining group(s) at that time. Thus, it is expressed as follows.

$$\Delta_{\mathrm{t}}(D_{\mathrm{opt}}) = \sum_{D=0}^{D_{\mathrm{opt}}-1} \{\Delta_{\mathrm{s}}(D) + \Delta_{\mathrm{d}}(D)\} + \Delta_{\mathrm{a}}(D_{\mathrm{opt}}). \tag{3.18}$$

Furthermore, if the value of D exceeds D_{opt}, $\Delta_{\mathrm{s}}(D_{\mathrm{opt}})$ which is larger than Δ_{a} is added to the total operating time. Thus, $\Delta_{\mathrm{t}}(D_{\mathrm{opt}} + 1)$ is always larger than $\Delta_{\mathrm{t}}(D)_{\mathrm{opt}}$. In other words, D_{opt} always minimizes the value of Δ_{t}. Therefore, D_{opt} is declared as follows.

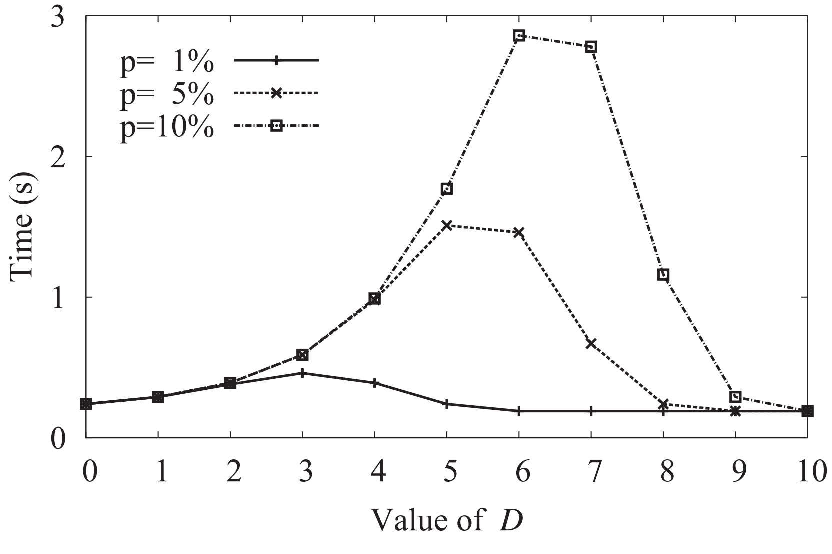
$$D_{\mathrm{opt}} = \arg\min_{D} \Delta_{\mathrm{t}}(D). \tag{3.19}$$

3.3.2.3 Numerical results of the operating time of the proposed reactive approach

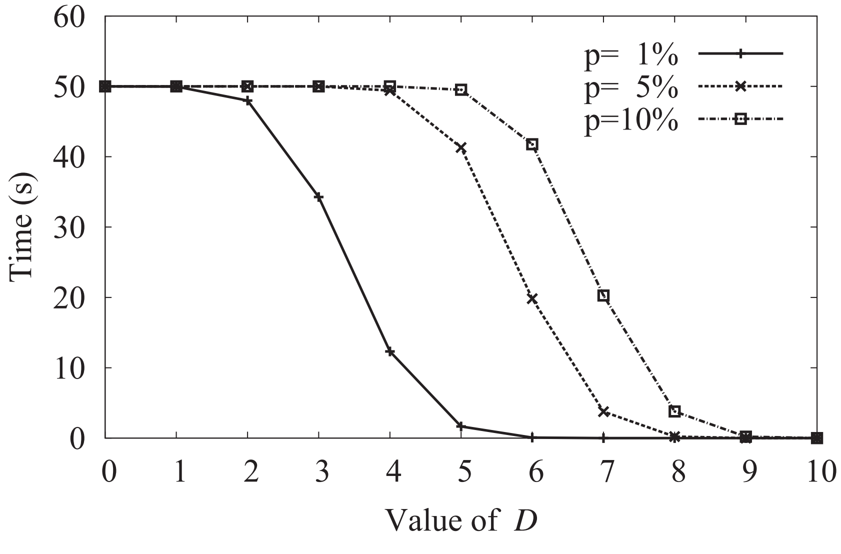
Here, we verify the change of the operating time in our proposed method with numerical analysis. In addition, the correctness of the afore-mentioned mathematical analysis is also presented.

Our supposed network comprises a satellite and numerous smart things having sensor terminals on the ground. A GEO satellite is considered as it is suitable to collect data from a wide area on the ground due to its high altitude and large coverage. The altitude of the satellite is set to 36,000km. Moreover, a TDMA-based system is considered to be used by the satellite to allocate bandwidth to the sensor terminals. The time-slot length is set to 50ms in our considered system. In order to simplify the verification, we consider the bandwidth allocation in a beam of satellite and a channel in the beam. Thus, the satellite allocates time-slots to hundreds to thousands of sensor terminals in a channel.

First, we verify the change of the expected operating time in our proposed method, which includes the expected required time for the searching and allocation phases when the value of D changes. In this verification, we set the number of sensor terminals as 1,000. Fig. 3.6 demonstrates the change of Δ_{s}, Δ_{a}, and Δ_{t} when the value of D changes from zero to 10. When the value of D becomes 10, each group which is divided ten times includes just one sensor terminal. Thus, the searching phase is necessarily stopped at that time when the number of all sensor terminals is 1,000.

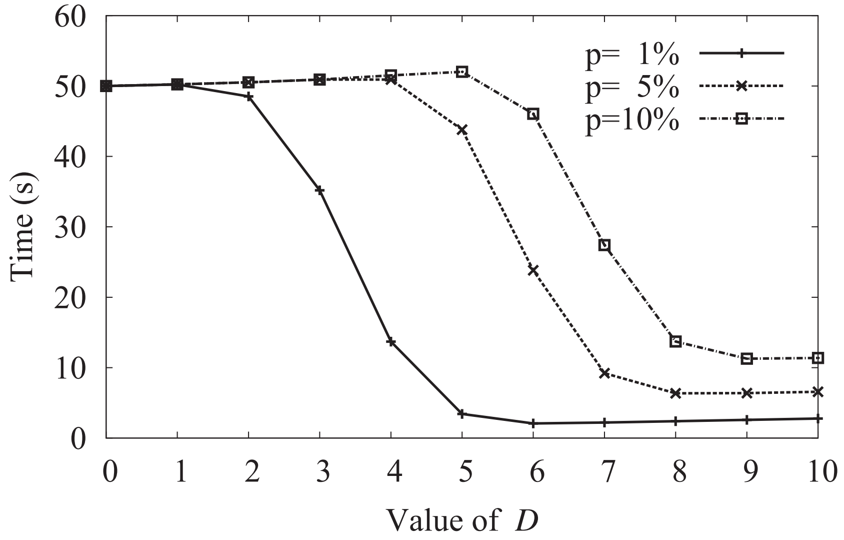


(a) The change of expected Δ_s.



(b) The change of expected Δ_a.

Figure 3.6: The change of Δ_{s}, Δ_{a}, and Δ_{t} when the value of D changes in each case where the value of p is different.



(c) The change of expected Δ_t. ©2013IEEE

Figure 3.6: The change of Δ_{s}, Δ_{a}, and Δ_{t} when the value of D changes in each case where the value of p is different. ©2013IEEE

From Fig. 3.6a, it may be understood that Δ_{s} increases when the value of D is small and starts to decrease after the value of D increases to some value. Since the number of the remaining groups increases by dividing in the searching phase when the value of D is small, Δ_{s} initially increases. However, the number of the remaining groups starts to decrease after that because some groups begin to be detected as groups having just one (or even no) sensor terminal having data to send. Due to the fact that the number of the sensor terminals included in each group becomes small, the probability that the groups are detected as including just one or no sensor terminal having data to send increases. Moreover, the timing that Δ_{s} starts to decrease is earlier in the case where the value of p is small in contrast with the case where the value of p is large. This is because that the probability that the groups are detected as including just one or no sensor terminal having data to send becomes large earlier when the value of p is small.

In a similar way as shown in Fig. 3.6b, Δ_a decreases with the increase of the value of D and the timing to start to decrease is earlier in the case where the value of p is small. It is the same reason why Δ_a starts to decrease when the value of D increases to some extent.

Fig. 3.6c demonstrates the expected total operating time in our proposed method. From this figure, the existence of the optimal value of D which minimizes the total operating time is confirmed. For example, when the value of p is 1%, D_opt is confirmed as 6 from the figure. In addition, the optimal value of D becomes larger with the higher values of p. It is because that the value of D when Δ_a starts to decrease is larger value when the value of p is larger. If the timing that Δ_a starts to decrease is late, Δ_s takes a significantly smaller value than Δ_a over relatively long periods of time. Moreover, it is understood that the value of Δ_t slightly increase when the value of D changes from 0 to 6. This is because Δ_t includes the value of Δ_s which increases at that time.

Secondly, Fig. 3.7 depicts the change of the value of D_opt when the number of sensor terminals in the system is different while the value of p is 1%, 5% and 10%, respectively. Here, the change of the value of D_opt denotes the change of the value of D, which minimizes the total operation time by avoiding unnecessary searching in each case. As shown in Fig. 3.7, the value of D_opt takes a substantially larger value when the number of all the sensor terminals is large or the value of p is large. This happens because the timing that Δ_a starts to decrease becomes late. Thus, the number of times to repeat the searching phase becomes large. In the actual implementation, the satellite sets D_opt equal to D when $\Delta_\mathrm{s}(D) > \Delta_\mathrm{a}(D)$.

In the following section, we turn the focus on analyzing the waiting time affected by our proposal from the perspective of the sensor terminals.

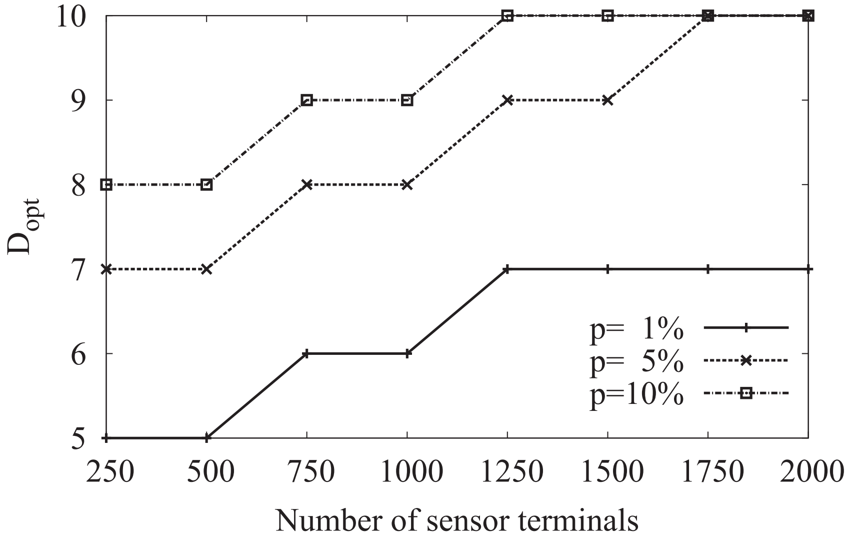


Figure 3.7: The change of D_{opt} when the number of sensor terminals in the system is different. ©2013IEEE

3.3.3 Analysis on Waiting Time of Each Sensor Terminals in Proposed Reactive Approach

In this section, we analyze the expectation value of the waiting time after generating data at each sensor terminal before the sensor completes transmitting its data to the satellite. In addition, we validate the effectiveness of our proposed method in contrast with traditional approaches, namely, slotted ALOHA and TDMA-based fixed assignment scheme.

3.3.3.1 Waiting time formulation

First, we formulate the expectation value of the waiting time of each sensor terminal in the case slotted ALOHA is used as a access control method in SRSS.

It is described as follows:

$$\begin{aligned} EW_{\mathrm{s}} &= \frac{t}{2}\left(\frac{3+\omega}{p_s}-\omega\right)+\{rtt\cdot p_s\cdot(1-p_s) \\ &+ 2\cdot rtt\cdot p_s\cdot(1-p_s)^2+3\cdot rtt\cdot p_s\cdot(1-p_s)^3+\cdots\} \\ &= \frac{t}{2}\left(\frac{3+\omega}{p_s}-\omega\right)+\frac{1-p_s}{p_s}\cdot rtt. \end{aligned} \tag{3.20}$$

The first term of Eq. 3.20 is introduced in [36] as the expectation value of the waiting time in slotted ALOHA under a *uniform backoff* (UB) policy, where ω indicates the range of the random waiting time after a collision occurs in the scheme. In other words, each sensor terminal, which fails to send data due to collision, chooses the waiting time in the range $[1, \omega]$ in the UB policy. In addition, p_s is defined as the transmission success probability, which is expressed as the combination of the new and re-transmitted packet arrival rates G (packets/t) in a Poisson process as follows.

$$p_s = e^{-G}. \tag{3.14}$$

However, in [36], a round trip propagation time between the sender of the data and the corresponding receiver is assumed as a smaller value than a single slot time. However, in the SRSS, the propagation distance between the sensor terminals and the satellite is large. Thus, we add the expectation value of the round trip time in the process as the second term in Eq. 3.20. In the slotted ALOHA technique, whenever a collision occurs, the sensor terminals which already sent data have to wait until a message is returned to them informing the collision event. Hence, the expectation value of the round trip time is expressed with the transmission success probability, p_s, the transmission failure probability, $1-p_s$, and the round trip time, rtt.

Secondly, the expectation value of the waiting time of each sensor terminal in the TDMA-based fixed assignment scheme is introduced. In this scheme, the satellite allocates time-slots to all sensor terminals by a fixed rotation. The sensor terminals, which are allocated time-slots, send data to the satellite if they have data to send at that time. In the case where the waiting time is the shortest value, the waiting time from data generation to completion of the data transmission is just the size of a time-slot, t. Also, in the worst case scenario, the sensor terminal needs to wait until all the other sensor terminals are allocated time-slots. The worst case occurs when the data are generated while a sensor terminal is transmitting previously generated data. Wherein each sensor terminal has to wait N_{all} time-slots until the beginning of the next transmission cycle. Furthermore, an additional time-slot is required to transmit the new data itself. Hence, the worst case waiting time equals to $N_{\mathrm{all}} + 1$ time-slots. As mentioned above, the sensor terminals wait for a certain number of time-slots according to the timing of the data generation. Since the average data generating rate is constant, the expected waiting time in a TDMA-based fixed assignment scheme can be expressed as follows.

$$\begin{aligned} EW_{\mathrm{f}} &= \frac{1}{\{(N_{\mathrm{all}}+1)\cdot t\} - t} \cdot \int_{t}^{(N_{\mathrm{all}}+1)\cdot t} x dx \\ &= \frac{N_{\mathrm{all}}^2 - 1}{2 \cdot N_{\mathrm{all}}} \cdot t. \end{aligned} \tag{3.15}$$

Now, we express the expectation value of the waiting time of each sensor terminal in our proposed scheme. For simplicity, we assume that data generation at the midstream of the operating process in the proposed scheme is collected to satellite at the next operating process as a whole. Thus, we consider the required time for collecting data which the sensor terminals have at the start of operating process a part of the operating process time. In the case where the waiting time is the shortest value, the sensor terminal can send data after the first searching phase in the proposed scheme. In this case, the sensor terminal has to wait for $\Delta_{\mathrm{s}}(0)$ time units. Additionally, the probability that this case occurs can be expressed as $P_{(N_{\mathrm{RM}}=1)}(0)$. Thus, the expected waiting time of each sensor terminal in this case can be expressed as the product of $\Delta_{\mathrm{s}}(0)$ and $P_{(N_{\mathrm{RM}}=1)}(0)$. For a sensor terminal detected as having data to send while time-slots are being allocated in one of the repeated searching phases, it sends data after the current searching phase finishes. Additionally, the shortest waiting time of each sensor terminal after the current searching phase finishes is t and the longest one is $|\mathbb{S}(D)| \cdot t$. Thus, the expected waiting time can be expressed as $\{(1 + |\mathbb{S}(D)|) \cdot t\}/2$. Therefore, the total expected waiting time in this case can be expressed as the product of the probability that the case occurs and the sum of the waiting time to repeat searching phase and $\{(1+|\mathbb{S}(D)|)\cdot t\}/2$. On the other hand, the sensor terminals, which are not detected in the searching phase, send data during the allocating phase. Since the satellite allocates time-slots to all the sensor terminals in each of the remaining groups by using TDMA, regardless of them having data to send or not, the expected time to send data in the allocating phase can be calculated similarly to the previous case.

On the other hand, the sensor terminals, which are not detected in the searching phase, send data during the allocating phase. Since the satellite allocates time-slots to all the sensor terminals in each of the remaining groups even when they do not have data to send, by using TDMA, the expected time to send data in the allocating phase can be calculated similarly to the previous case. Therefore, the expectation value of the waiting time of each sensor terminal in our proposed scheme is expressed as follows:

$$
\begin{aligned}
EW_{\mathrm{p}} &= \Delta_{\mathrm{s}}(0) \cdot P_{(N_{\mathrm{RM}}=1)}(0) \\
&+ \left\{\Delta_{\mathrm{s}}(0) + \Delta_{\mathrm{s}}(1) + \frac{(1+|\mathbb{S}(1)|)\cdot t}{2}\right\} \\
&\cdot P_{(N_{\mathrm{RM}}\geq 2)}(0) \cdot P_{(N_{\mathrm{RM}}=1)}(1) \\
&+ \left\{\Delta_{\mathrm{s}}(0) + \Delta_{\mathrm{s}}(1) + \Delta_{\mathrm{s}}(2) + \frac{(1+|\mathbb{S}(2)|)\cdot t}{2}\right\} \\
&\cdot P_{(N_{\mathrm{RM}}\geq 2)}(0) \cdot P_{(N_{\mathrm{RM}}\geq 2)}(1) \cdot P_{(N_{\mathrm{RM}}=1)}(2) + \cdots \\
&+ \left\{\sum_{D=0}^{D_{\mathrm{opt}}} \Delta_{\mathrm{s}}(D) + \frac{(1+|\mathbb{S}(D_{\mathrm{opt}}-1)|)\cdot t}{2}\right\} \\
&\cdot \prod_{D=0}^{D_{\mathrm{opt}}-1} P_{(N_{\mathrm{RM}}\geq 2)}(D) \cdot P_{(N_{\mathrm{RM}}=1)}(D_{\mathrm{opt}}) \\
&+ \left\{\sum_{D=0}^{D_{\mathrm{opt}}} \Delta_{\mathrm{s}}(D) + \frac{(1+n(D)\cdot G_{\mathrm{r}}(D_{\mathrm{opt}}))\cdot t}{2}\right\} \\
&\cdot \prod_{D=0}^{D_{\mathrm{opt}}} P_{(N_{\mathrm{RM}}\geq 2)}(D). \qquad (3.16)
\end{aligned}
$$

3.3.3.2 Numerical results of the Waiting time

Fig. 3.8 demonstrates the results of the expectation value of the waiting time of the TDMA-based fixed assignment scheme, slotted ALOHA, and our proposed method while the value of p is changed from 1% to 10% and the number of considered sensor terminals is set to 1,000. Furthermore, to calculate the waiting time of the slotted ALOHA technique, we set ω to 600 since the value of ω needs to be large enough to avoid repetitions of data collision events. Moreover, to compare the slotted ALOHA technique and our proposed method in the same

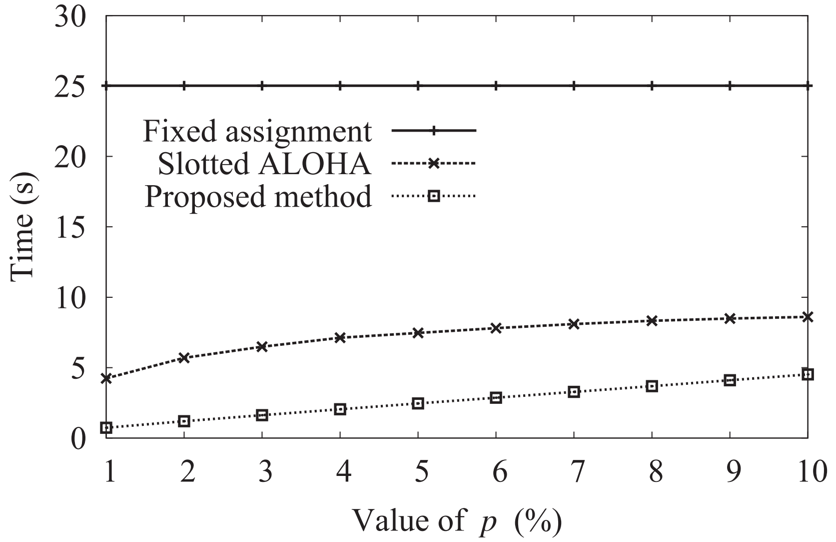


Figure 3.8: The expectation value of the waiting time of TDMA-based fixed assignment scheme, slotted ALOHA, and our proposed method. ©2013IEEE

environment, the value of p_s is calculated from the value of G, which is defined by using the value of p, N_{all}, t, and Δ_t (the total operating time of our proposed method). The value of G is expressed as follows.

$$G = \frac{p \cdot N_{\mathrm{all}} \cdot t}{\Delta_t}. \tag{3.17}$$

As shown in Fig. 3.8, our proposed method achieves a significantly smaller expectation value of the waiting time than the two other existing schemes at any time when the value of p increases. It means that the satellite can collect data from numerous sensor terminals with a substantially high real-time performance in our proposed method.

3.4 Summary

In this chapter, we focused upon using satellites to communicate with numerous sensor terminals. Since the satellites have many advantages such as wide coverage and they are disaster-resistant, they can be considered as a good candidate to constructs networks facilitating a world-wide sensor networks. Toward this end, we proposed two methods to collect data efficiently from an arbitrary wide area by means of SRSS. One is proactive approach and the other is reactive approach. From the numerical analysis, it is confirmaed that in the environment where numerous sensor terminals exist and they generate data at any time, our proposed methods make it possible to collect data from them by avoiding ineffective bandwidth allocation and to decrease the operating time. Therefore, our proposed method achieves the efficient data gathering with small operation time in the SRSS.

Chapter 4

Data Aggregation in Superdense Sensor Terminals to Improve Real-time Performance

4.1 Introduction

In this chapter, we propose two data aggregation methods in superdense sensor termianls to improve the real-time performance in the data collection. The first proposal aims to collect fresh data with hith throughput. The purpose of the second proposed method is to gather uniform amount of fresh data from areas with varying density of the data sending sensor terminals.

The parts of contents in this chapter are refered to the following papers that are written based on our own researches.

- Y. Kawamoto, H. Nishiyama, N. Kato, Y. Shimizu, A. Takahara, and T. Jiang, "A Novel Access Control Scheme to Construct Fresh Database of Ambient Information in Internet of Things," IEEE Wireless Communications and Networking Conference (WCNC 2015), New Orleans, USA, Mar.

2015.

- Y. Kawamoto, T. Nakazawa, H. Nishiyama, N. Kato, Y. Shimizu, and T. Jiang, "A Method for Collecting Uniform Amount of Fresh Data from Areas with Varying Population Density," IEEE International Conference on Communications (ICC 2015), London, UK, Jun. 2015.

4.2 Proposed Data Aggregation Method to Collect Fresh Data

4.2.1 Assumed network model and access control scheme

In this section, we show the network model assumed in this section. In the assumed network, each AP collects data from the sesor terminals covered by the AP and sends them to satellite. Indeed, since the ambient environment of each sensor terminal changes continuously, the freshness of the collected data decreases momentarily. In order to keep the freshness, the collected data is updated regularly by the uploaded data from the APs. Thus, each AP needs to periodically collect the data of the sensor terminals with a certain interval.

On the other hand, as the access control scheme used between the APs and sensor terminals in the assumed network, CSMA/CA is supposed to be used. Additionally, it is assumed that the sensor terminals covered by the same AP are close enough to each other to succeed the carrier sense. In the process of CSMA/CA, each sensor terminal checks the usage condition of the channel and starts sending data if the sensor terminal does not sense the usage of the channel for a random period of time called "backoff time". On the other hand, if the sensor terminal senses the other sensor terminal's usage of the channel, it stops the data sending process and wait until next interval. After waiting, the sensor terminal starts retransmitting if the channel is free at that time. In the case where the data collision occurs by the data sending from multiple sensor terminals at the same time, the sensor terminal chooses the random backoff time again. At this time, the range of the chosen backoff time is increased in the process of CSMA/CA. By increasing the range in an exponential fashion each time when the sensor terminal, it decreases the probability that the collision occurs again. In this process, the backoff time, BT, is calculated as the following expression:

$$BT = r \cdot t, \tag{4.1}$$

where r and t represent a random number and the length of a time slot. Additionally, the value of r is chosen from the range between 0 and CW, which is called contention window. The value of CW is decided from the following expression.

$$CW = (CW_{\min} + 1) \cdot 2^m - 1, \tag{4.2}$$

where $CW_{\min}$ and m shows the minimum value of the contention window and the number of retransmissions. The value of contention window increases along with the number of retransmission as shown in Eq. 4.24, and stops when the value exceeds the value of $CW_{\max}$, which denotes the maximum value of the contention window. After that, the random value, r, is chosen from the range between 0 and $CW_{\max}$ repeatedly.

4.2.2 Proposed access control scheme

In this subsection, at first, the summary of the proposed scheme, where the timings of sending traffic from sensor terminals are optimized by considering the freshness of the collected data, is represented. Secondly, the optimization problem described by using mathematical expressions. Thirdly, the freshness of the collected data by using the proposed scheme and existing scheme, respectively, is analyzed.

4.2.2.1 Summary of the proposed scheme

At first, we introduce the summary of the proposed access control scheme. As mentioned in previous section, keeping the freshness of the collected data is very important. However, in order to keep the freshness, it is necessary to periodically collect the data from many sensor terminals with a short interval, which causes heavy traffic congestion in the existing communication networks. Thus, in our proposal, the timing of sending traffic is controlled by considering the difference in the changing rapidity of each sensor terminal's ambient environment. Actually, the changing rapidity of each sensor terminal's ambient environment is considered to be totally different from that the other sensor terminals. For example, the ambient environment around the sensor terminals to observe the users' density in crowded places may change continually. However, they usually do not change much in areas with sparse population of users. Thus, in the case of crowded places, the data should be repeatedly collected to keep the database constructed by the collected data fresh while it is not necessary to collect very often in uncrowded places. Therefore, we set the data sending interval of each sensor terminal dynamically according to the rapidity of change of the sensor terminal's ambient environment.

To decide the data sending timing, each sensor terminal regularly checks the changed ratio between its current ambient environment and the data that the terminal sent to the AP last time. We define the status of the current sensor terminal's ambient environment as l_i where i denotes the identification number of each sensor terminal. l_i satisfies the following formulation:

$$0 \leq l_i \leq 1. \tag{4.3}$$

When the data is sent to the AP, l_i equals to 1. It decreases with the changing ratio of the sensor terminal's ambient environment, and becomes 0 when the data of the ambient environment becomes totally different from the data that the sensor terminal sent to the AP. Additionally, we define changing rapidity of the sensor terminal's ambient environment as x_i per slot.

In our proposal, each sensor terminal starts the data sending process when l_i falls below a predetermined threshold, denoted by θ. The value of θ is set for each AP according to the condition of the area where the AP covers such as the number of sensor terminals and the changing rapidity of the ambient environment. Additionally, the value of θ is broadcasted from each AP to the sensor terminals covered by the AP. Moreover, the value of θ needs the following condition:

$$0 \leq \theta < 1. \tag{4.4}$$

Thus, the interval from the previous data sending to the start of the next data sending process, Δ_i, is expressed as follows:

$$\Delta_i = \frac{1-\theta}{x_i}. \tag{4.5}$$

If θ is set to a high value, the sensor terminals have to periodically send its ambient information with a short interval, and thus traffic congestion may occur. On the other hand, the freshness of the collected data may decrease with the lower value of θ. Therefore, it is required to optimize the value of θ to keep the collected data fresh while avoiding traffic congestion.

4.2.2.2 Optimizing the value of θ

We analyze the optimal value of θ to keep the collected data as fresh as possible by using mathematical expressions. In this analysis, nonpersistent CSMA [36] is assumed to be used in the network. Additionally, the number of sensor terminals in the area, which is covered by an AP, is defined as N. Then, we have following expression.

$$1 \leq i \leq N. \tag{4.6}$$

As noted previously, each sensor terminal, i, starts the data sending process according to the interval Δ_i. Thus, when the proposed method is used, the rate of occurring traffic including the retransmission data from the sensor terminals in to an AP, G (packets/slot), is expressed as follows:

$$G = \sum_{i=0}^{N} \frac{1}{\Delta_i}. \tag{4.7}$$

When the proposed method is not used, the value of G may be set by considering other network conditions such as throughput and delay.

On the other hand, the probability that the data sending of a terminal succeed, p_s, is introduced in [39] as follows:

$$p_{\mathrm{s}} = \frac{e^{-aG}}{G \cdot (1 + 2a) + e^{-aG}}, \tag{4.8}$$

where a denotes the ratio of propagation delay to packet transmission time. Additionally, the traffic occurring rate G is assumed to follow a Poisson distribution. Moreover, the throughput, S (packets/slot), is expressed as follows:

$$S = G \cdot p_{\mathrm{s}} = \frac{G \cdot e^{-aG}}{G \cdot (1 + 2a) + e^{-aG}}. \tag{4.9}$$

From the analysis on the throughput in previous researches [40, 41], it is shown that the function of S is convex upward with the value of G. Thus, there is the value of G that achieves the maximum value of the throughput. Therefore, we define the optimal value of θ, θ_{opt}, as the value that achieves the maximum throughput. Hence, the value of θ_{opt} is expressed as follows:

$$\theta_{\text{opt}} = \arg\max_{\theta} S. \tag{4.10}$$

4.2.2.3 The freshness of database

The guaranteed freshness of collected data in two cases where the proposed method is used or not is analyzed by using mathematical expressions. Here, we define the freshness of the data of i^{th} sensor terminal in the collected data at the AP when the proposal is used or not as F_i^{prop} and F_i^{exist}, respectively. In addition, these values are needed to satisfy the following expression:

$$0 \leq F_i^{\text{prop}}, F_i^{\text{exist}} \leq 1. \tag{4.11}$$

Since the collected datae at the AP is updated every time when new data is collected from sensor terminals, the freshness depends on the expectation value of the time required to finish sending the data from the previous data sending. Thus, when the proposed method is not used, the expectation value of the required time, E_{exist}, is expressed as follows:

$$E_{\text{exist}} = \frac{N}{G_{\text{random}}} + A, \tag{4.12}$$

where G_{random} and A represent the rate of occurring traffic where the proposed method is not used and the expectation value of the required time when the data sending is missed and the retransmission is carried out in several occasions. On the other hand, $\frac{N}{G_{\text{random}}}$ denotes the average required waiting time from the previous data sending to start next data sending process. Moreover, the value of

A is expressed as follows:

$$\begin{aligned}
A &= p_s \cdot (1-p_s)^0 \cdot \frac{2^0 \cdot CW_{\min} \cdot t}{2} + p_s \cdot (1-p_s)^1 \cdot \frac{2^1 \cdot CW_{\min} \cdot t}{2} \\
&+ p_s \cdot (1-p_s)^2 \cdot \frac{2^2 \cdot CW_{\min} \cdot t}{2} + \cdots + p_s \cdot (1-p_s)^{\omega} \cdot \frac{CW_{\max} \cdot t}{2} \\
&+ p_s \cdot (1-p_s)^{\omega+1} \cdot \frac{CW_{\max} \cdot t}{2} + p_s \cdot (1-p_s)^{\omega+2} \cdot \frac{CW_{\max} \cdot t}{2} + \cdots \\
&= \sum_{k=0}^{\omega-1} p_s \cdot (1-p_s)^k \cdot \frac{2^k \cdot CW_{\min} \cdot t}{2} + \sum_{l=\omega}^{\infty} p_s \cdot (1-p_s)^l \cdot \frac{CW_{\max} \cdot t}{2}, \quad (4.13)
\end{aligned}$$

where ω denotes the number of retransmissions when the value of contention window reaches $CW_{\max}$. Using Eq. 4.24, the value of ω can be calculated as follows:

$$\omega = \frac{1}{\log 2} \cdot \log\left(\frac{CW_{\max}+1}{CW_{\min}+1}\right). \quad (4.14)$$

Thus, the average freshness of collected data at the server when the proposal is not used is expressed as follows:

$$\begin{aligned}
F_i^{\text{exist}} &= 1 - \frac{E_{\text{exist}} \cdot x_i}{2} \\
&= 1 - \frac{1}{2} \cdot \left(\frac{N \cdot x_i}{G_{\text{random}}} + A \cdot x_i\right). \quad (4.15)
\end{aligned}$$

On the other hand, when the proposed method is used, each sensor terminal starts the data sending process when the status of the sensor terminal's ambient environment, l_i, falls below the value of θ_{opt}. Thus, the required time depends on the value of the changing rapidity of the sensor terminal's ambient environment, x_i. Therefore, the expectation value of the required time when the proposed method is used, E_i^{prop}, is expressed as follows:

$$E_i^{\mathrm{prop}} = \frac{1-\theta_{\mathrm{opt}}}{x_i} + A. \tag{4.16}$$

Hence, the freshness of the data of each sensor terminals in the collected data, when the proposal is used, is expressed as follows:

$$\begin{aligned} F_i^{\mathrm{prop}} &= 1 - \frac{E_i^{\mathrm{prop}} \cdot x_i}{2} \\ &= \frac{1}{2} \cdot \left(1 + \theta_{\mathrm{opt}} - A \cdot x_i\right). \end{aligned} \tag{4.17}$$

From Eqs. 4.15 and 4.17, it is understood that the freshness of the collected data provided in the case where the existing access control method is used depends on the data occurring rate from the sensor terminals. On the other hand, when the proposed method is used, it is controlled by the value of θ_{opt} which is calculated in the proposed method. Thus, it is clearly shown that we can control the freshness of the collected data of ambient environment of sensor terminals by adequately setting the value of the threshold in our proposal.

4.2.3 Analysis on Freshness of Collected Data

In this section, we confirm the existence of the optimal value of θ by analyzing the relationship between the throughput and the value of θ. The numerical calculation results are provided to verify the analysis. Additionally, the effectiveness of the proposed method is also shown in the analysis on the minimum guaranteed freshness of the collected data from the sensor terminals and the standard deviation of the freshness.

Table 4.1: Parameter settings

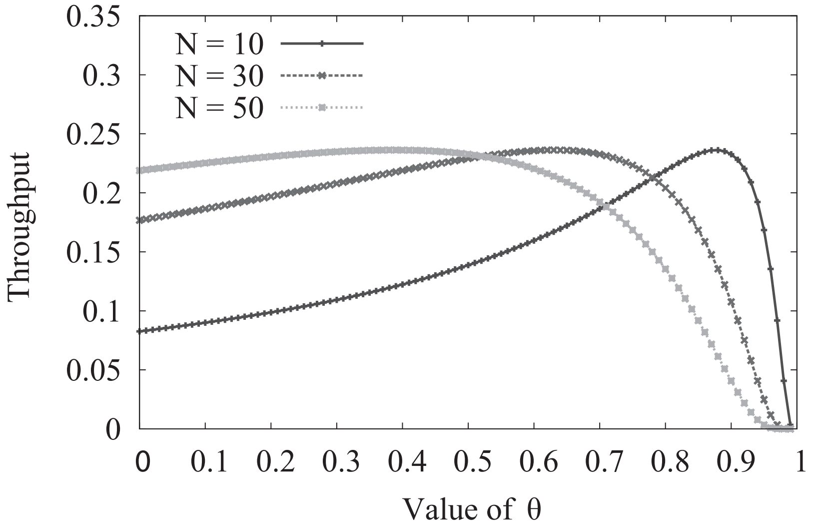
Number of sensor terminals (N)	10, 30, 50
Maximum value of contention window (CW_{max})	15
Minimum value of contention window (CW_{min})	1023
Length of a time-slot (t)	$20\mu s$
Ratio of propagation delay to packet transmission time (a)	0.5

4.2.3.1 Parameter settings

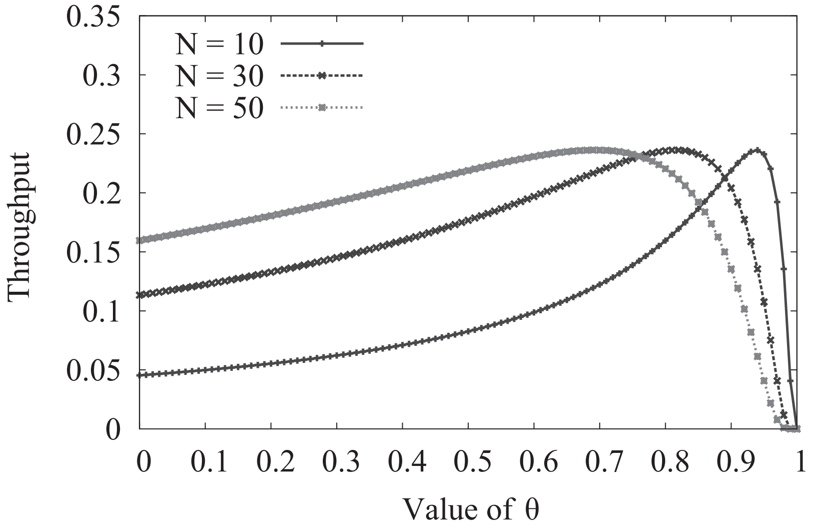
The parameter settings are summarized in Table 4.2. In this numerical analysis, for the simplicity, it is supposed that an AP collects the data from the sensor terminals in the coverage of the AP. The number of the sensor terminals in the coverage of an AP is set to 10, 30, and 50, respectively, to evaluate multiple situations where the number of sensor terminals are different. Additionally, the sensor terminals are deployed randomly in the coverage of the AP. The AP collects the data from the sensor terminals by using CSMA/CA with or without the proposed method. As the parameters used in the process of CSMA/CA, the maximum and minimum values of the contention window are set to 15 and 1023, respectively. Moreover, the length of a time-slot and the ratio of propagation delay to packet transmission time are set to $20\mu s$ and 0.5, respectively. On the other hand, three situations to reflect the difference in the changing rapidity of ambient environment are supposed in this numerical analysis. In the three situations, the average value of the changing rapidity of ambient environment, x_{ave}, is set to 0.01, 0.005, and 0.001, respectively. Additionally, in each case, the changing rapidity of ambient environment is randomly chosen from the value at up to 5% above or below the average value. Furthermore, we assumed that the retransmission from the sensor terminals can only occur maximum three times.

4.2.3.2 Existence of the optimal value of θ

At first, the existence of optimal value of θ which maximizes the freshness of the collected data is proved. Fig. 4.4 shows the change of throughput at the AP in the network when the value of θ is changed. Fig. 4.1a, 4.1b, and 4.1c show the different cases where the changing rapidity of ambient environment is set to different values. Additionally, each figure shows the case where the number of sensor terminal is set to 10, 30, and 50, respectively. From Fig. 4.4, it is clearly shown that there is an optimal value of θ which maximizes the throughput in each case where the changing rapidity of ambient environment and the number of sensor terminals are different. This is because the set value of θ has an effect on the interval of data sending in the network. If the value of θ is set to a high value, data from each sensor terminal will occur often, which causes traffic congestion at the AP. On the other hand, a low value of θ avoids the traffic congestion but decreases the throughput. Since the high throughput can help to update the collected data at each sensor terminal with a short interval, it can increase the freshness of the collected data. Moreover, it is understood that the optimal value of θ should be set to a high value when the changing rapidity of ambient environment is low and the number of sensor terminals in the network is few.

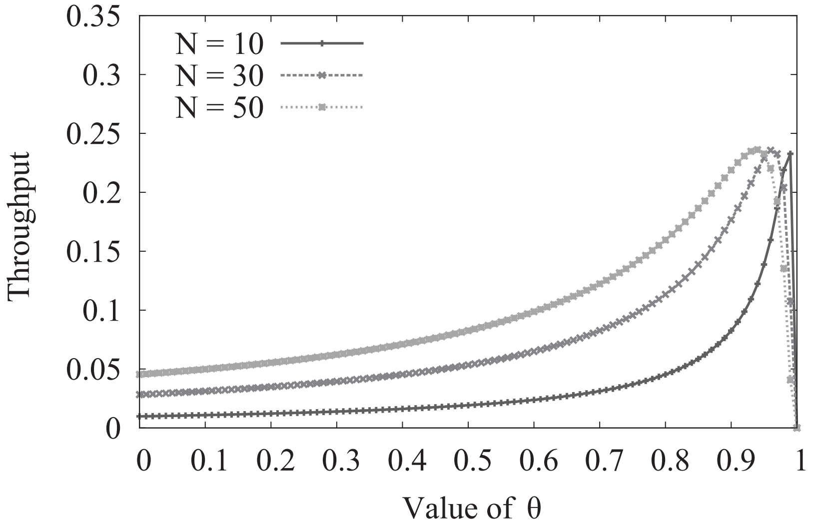


(a) x = 0.01.



(b) x = 0.005.

Figure 4.1: Value of θ vs. throughput.

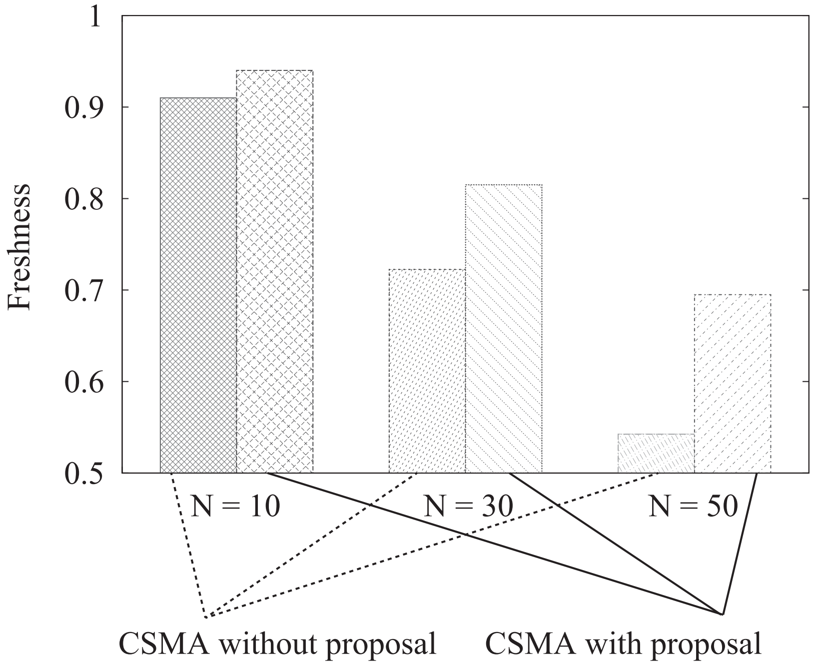


(c) x = 0.001.

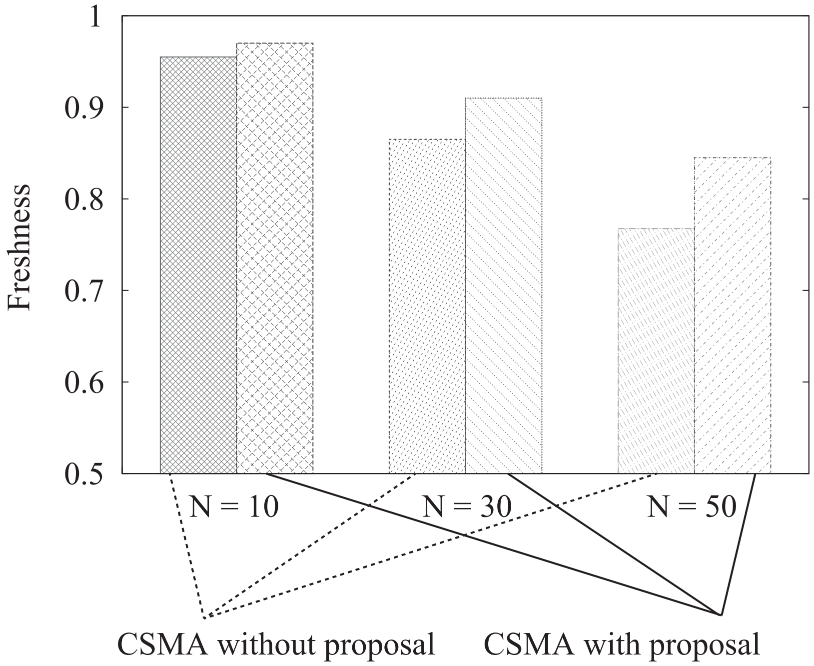
Figure 4.1: Value of θ vs. throughput. ©2015IEEE

4.2.3.3 The minimum guaranteed freshness of ambient information

Fig. 4.2 shows the result of the minimum guaranteed freshness of collected data from each sensor terminals in the two cases where the proposed method is used or not. Fig. 4.2a, 4.2b, and 4.2c show the different cases where the value of the changing rapidity of ambient environment is set to different values. From Fig. 4.2, it is understood that the proposed method achieves higher freshness of the collected data than when the proposal is not used. Additionally, the proposed method provides a significant improvement when the changing rapidity of ambient environment and the number of the sensor terminals are high. In such situations, existing access control scheme cannot avoid traffic congestion, which causes lower freshness of the collected data.

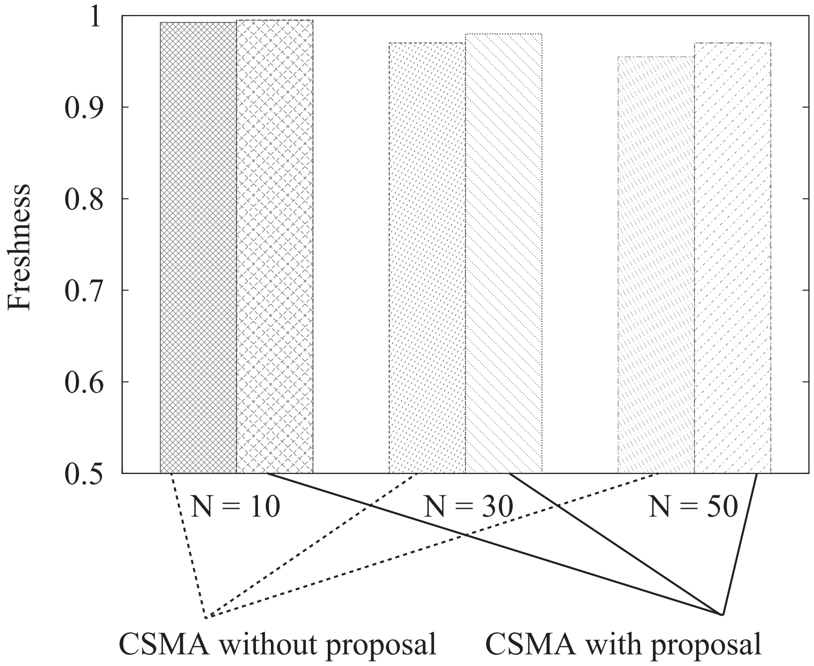


(a) x = 0.01.



(b) x = 0.005.

Figure 4.2: The minimum guaranteed freshness of collected data from each sensor terminals.



(c) x = 0.001

Figure 4.2: The minimum guaranteed freshness of collected data from each sensor terminals. ©2015IEEE

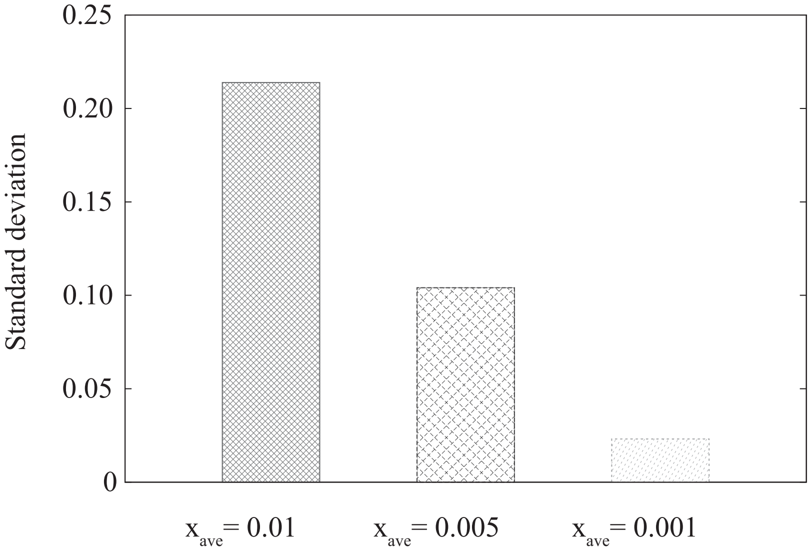
4.2.3.4 Standard deviation of the freshness of database

Furthermore, we show the results of standard deviation of the freshness of collected data in the two cases where the proposed method is used or not. The standard deviation of the freshness of database is expressed as follows:

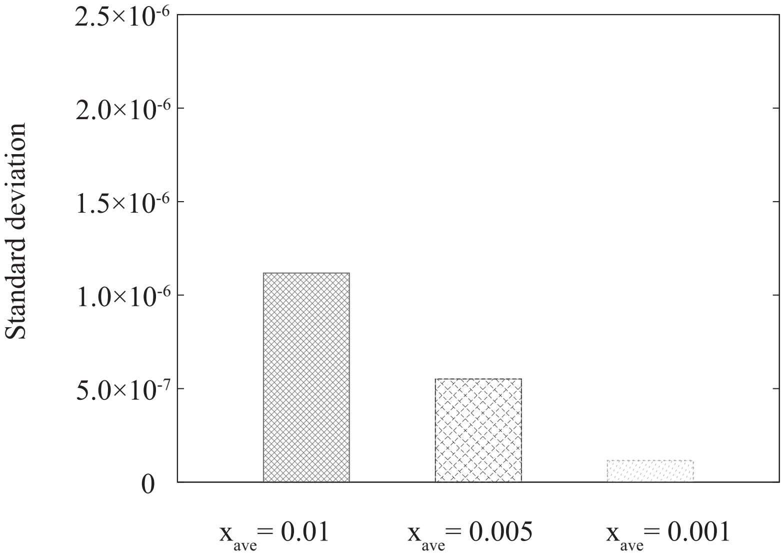
$$\sigma = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (F_i - \overline{F})^2}, \tag{4.18}$$

where $\overline{F}$ denotes the average value of F_i.

From Fig. 4.3a and Fig. 4.3b, it is clearly shown that when the proposed method is used, the standard deviation of the freshness is significantly lower than when our proposal is not used. This is because in the proposal, each sensor terminal sends its data while considering the freshness of the ambient environment of itself. A low standard deviation of the freshness implies that the provided collected data is stable.



(a) Without the proposed method. ©2015IEEE



(b) With the proposed method. ©2015IEEE

Figure 4.3: Standard deviation.

4.3 Proposed method to collect uniform amount of data

In this section, we propose a method for collecting uniform amount of fresh data from areas with varying density of the data sending sensor terminals. In this proposal, by considering the network condition and the requirements from the system, we aim to collect same amount of data from both areas where many data sending sensor terminals are and fewer data sending sensor terminals are with keeping the highest throughput.

4.3.1 Algorithm of proposed data collection method

As mentioned above, the density of data sending sensor terminals is different depending on the place. Additionally, the data sending sensor terminals inside the coverage always change from time to time. Thus, we propose a data collection method which dynamically adjusts to the network and data sending sensor terminals' conditions based on the CSMA/CA scheme. In our proposal, each AP which collects the data from the sensor terminals decides the amount of data sending sensor terminals which will execute the data transmission and the time period during which the sensor terminals are allowed to transmit according to the requirements of the density of the collected data. To decide the number of sensor terminals which will execute the data transmission during the determined time period, we set the rate of the number of sensor terminals sending data in the group of all sensor terminals inside the coverage of the AP as α. Additionally, the time period is denoted as T. By controlling the values of α and T dynamically, our proposal achieves to collect uniform amount of data from areas with varying density of data sending sensor terminals and high throughput which results into a fresh data collection and also satisfies the requirements of the density of the collected data.

α and T are calculated by the AP at the end of each time period and broadcasted to the sensor terminals. Each sensor terminals receiving the message including these parameters from the APs decides whether or not they send the data during the time period randomly according to the value of α. Next, the sensor terminals which decide to send the data choose an amount of time to wait before starting the data transmission randomly between 0 and T. By choosing the waiting time randomly, wasteful data collision is avoided. The value of T is calculated to optimize the expected throughput with the expected amount of sensor terminals transmitting data, which depends on the value of α. However, since it is difficult for each AP to determine how many data sending sensor terminals are inside its coverage, it is impossible to determine the value of α adequately. Thus, in our proposal, each AP sets the value of α according to Algorithm 3. In this algorithm, the AP dynamically changes the value of α after the end of each time period according to the throughput and number of collisions occurred during that time period, n_{c}. In our consideration, APs can identify data collision by observing changes to the signal level. So, when the throughput is lower than the expected value, the AP estimates whether the value of α was set lower or higher than the optimal value through the number of collisions. Since it can be calculated with the behavior of data transmission in CSMA/CA and observation of actual network, we skip the introduction of the number of occurred data collisions when the throughput is maximized, namely ϕ. In the case where the value of α was set too low, there was some period during which no data was received, which results in no data collision and n_{c} becoming lower than ϕ. On the other hand, in the case where a high value of α is set, data collision occurs many times, which results in the lower throughput and n_{c} becoming higher than ϕ. Therefore, each AP determines whether the value of α should be changed to

Algorithm 3 Proposed data collection algorithm

```
AP broadcasts the set of $\alpha$ and $T$ to all of users
Each user decides whether to send data or not randomly according to $\alpha$
AP receives data during $T$ and counts the number of data collisions
/* After the time period $T$ */
if $n_{\mathrm{c}} > \phi$ then
    $\alpha = \alpha - \Delta$
else
    $\alpha = \alpha + \Delta$
end if
Recalculate the optimal value of $T$ according to the new $\alpha$
```

higher or lower than the value which was used at the previous interval. Here, we define the amount of increment / decrement as Δ. Actually, the value of Δ has an effect on the capability of staying close to the optimal value in the proposal, but, we use it as a constant value in this section. On the other hand, the value of T can be optimized to maximize the throughput during the time period after the value of α is fixed as expressed in the following explanation. In this way, the proposed method controls the number of sensor terminals sending data during a interval and the length of the interval, which causes efficient data collecting based on CSMA/CA.

4.3.2 Optimization of the value of T

In our proposal, CSMA/CA is supposed to be used as the access control scheme. Additionally, each sensor terminals chooses a random amount of time to wait before starting the data transmission during the time period of T. Thus, the throughput is calculated by the existing analysis of CSMA/CA. Therefore, we use this analysis to optimize the value of T in this section. In this analysis, we assume that all of the data transmitted from the sensor terminals is that collects ambient information.

From the research in [36], the probability that data transmission succeeds in a network using CSMA/CA is expressed as follows:

$$p_{\mathrm{s}} = \frac{e^{-aG}}{G \cdot (1+2a) + e^{-aG}}, \tag{4.19}$$

where a denotes the ratio of propagation delay to packet transmission time. Here, we suppose that each sensor terminals sends a packet to AP when data occur at the sensor terminals. Additionally, the traffic occurring rate inside the coverage of the AP, G (packets/slot), is assumed to be in a Poisson process. Moreover, in the assumed network that the proposed method is adopted, the value of G is expressed as follows:

$$G = \frac{N \cdot \alpha \cdot t}{T}, \tag{4.20}$$

where N and t denote the total number of sensor terminals in the coverage of the AP and the length of a time-slot, respectively. At this time, the throughput, S (packets/slot), is expressed as follows:

$$S = G \cdot p_{\mathrm{s}} = \frac{G \cdot e^{-aG}}{G \cdot (1+2a) + e^{-aG}}. \tag{4.21}$$

It is presented that there is a value of G which maximizes S in researches [40, 41]. Therefore, we define the optimal value of T, T_{opt}, as the value that achieves the maximum throughput. The value of T_{opt} is expressed as follows:

$$T_{\mathrm{opt}} = \arg\max_{T} S. \tag{4.22}$$

4.3.3 Analysis on the expected performance of the proposal

At last, we analyze that how much the requirement of data collection density is satisfied with the proposed data collection method. Here, we represent the value of p_{s} in the case where the proposed method is adopted in the assumed network as $p_{\mathrm{s}}^{\mathrm{prop}}$. Then, the probability that the data transmission from the sensor terminals which decides to execute the data sensing according to the value of α succeeds with the proposal during the time period, P, is expressed as follows:

$$P = 1 - (1 - p_{\mathrm{s}}^{\mathrm{prop}})^{M+1}, \tag{4.23}$$

where M denotes the maximum number of attempted retransmissions during one time period. In the process of CSMA/CA, contention window, CW, is used to determine the backoff time. A random number is chosen from the range between 0 and CW, and the product between this random number and the length of a time slot is set as the backoff time. Additionally, the value for the contention window stops increasing when it exceeds the value of CW_{max}. After that, the random value is chosen from the range between 0 and CW_{max} repeatedly. Moreover, the value of the contention window increases along with the number of retransmissions according to the following expression:

$$CW = (CW_{\mathrm{min}} + 1) \cdot 2^m - 1. \tag{4.24}$$

Then, M is expressed as follows:

$$M = \begin{cases} \dfrac{T - \displaystyle\sum_{m=0}^{k} \{(CW_{\min} + 1) \cdot 2^m - 1\} \cdot t}{\left\{(CW_{\min} + 1) \cdot 2^{k+1} - 1\right\} \cdot t} + k \\ \qquad \left(CW_{\min} \cdot t < T < t \cdot \displaystyle\sum_{m=0}^{\omega} \{(CW_{\min} + 1) \cdot 2^m - 1\} \right) \\ \dfrac{T - \displaystyle\sum_{m=0}^{\omega} \{(CW_{\min} + 1) \cdot 2^m - 1\} \cdot t}{CW_{\max} \cdot t} + \omega \\ \qquad \left(t \cdot \displaystyle\sum_{m=0}^{\omega} \{(CW_{\min} + 1) \cdot 2^m - 1\} \leq T \right) \end{cases} \tag{4.25}$$

In Eq. 4.25, k is the maximum value which satisfies the following expression:

$$t \cdot \sum_{m=0}^{k} \{(CW_{\min} + 1) \cdot 2^m - 1\} \leq T, \tag{4.26}$$

where $CW_{\max}$, $CW_{\min}$, and ω denote maximum and minimum value for the contention window and the number of retransmissions when the value of contention window reaches $CW_{\max}$, respectively. Furthermore, by using Eq. 4.24, the value of ω can be calculated as follows:

$$\omega = \log_2 \left(\frac{CW_{\max} + 1}{CW_{\min} + 1} \right). \tag{4.27}$$

4.3.4 Performance evaluation

4.3.4.1 Parameter settings

Table 4.2 shows the parameter settings. In this performance evaluation, the radius of the AP which collects the data from the sensor terminals is set to 30m. Additionally, we suppose that the sensor terminals are deployed randomly in

Table 4.2: Parameter settings

Radius of the coverage of AP	30m
Maximum value of contention window ($CW_{\max}$)	15
Minimum value of contention window ($CW_{\min}$)	1023
Length of a time-slot (t)	20μs
Ratio of propagation delay to packet transmission time (a)	0.5

the coverage of the AP and that CSMA/CA is used as the based access control scheme. The maximum and minimum values for the contention window are set to 15 and 1023, respectively, as the settings used in the process of CSMA/CA. Moreover, a time-slot length and the ratio of propagation delay to packet transmission time are set to 20μs and 0.5, respectively. To make evaluations in different situations, the required density (number of sensor terminals per square meter) of collected data, D, is set to 0.004, 0.008, 0.011, respectively. To simplify the analysis, it is supposed that the data collection in the proposal is executed after the value of α is set to an adequate value. It means that the data collection begins after the value of n_{c} becomes ϕ.

4.3.4.2 Numerical results

At first, we investigate the relationship between the throughput and the length of the time period to confirm the existence of an optimal value for the time period. Fig. 4.4 shows the results of throughput with the change of the time period. From these results, it can be seen that an optimal value of the time period which maximizes the throughput exists for each required density of collected data. Thus, in our proposal, by calculating the throughput with the required density, the optimal value of T is set and broadcasted repeatedly.

Secondly, we evaluate the efficiency of the proposed method by contrast with

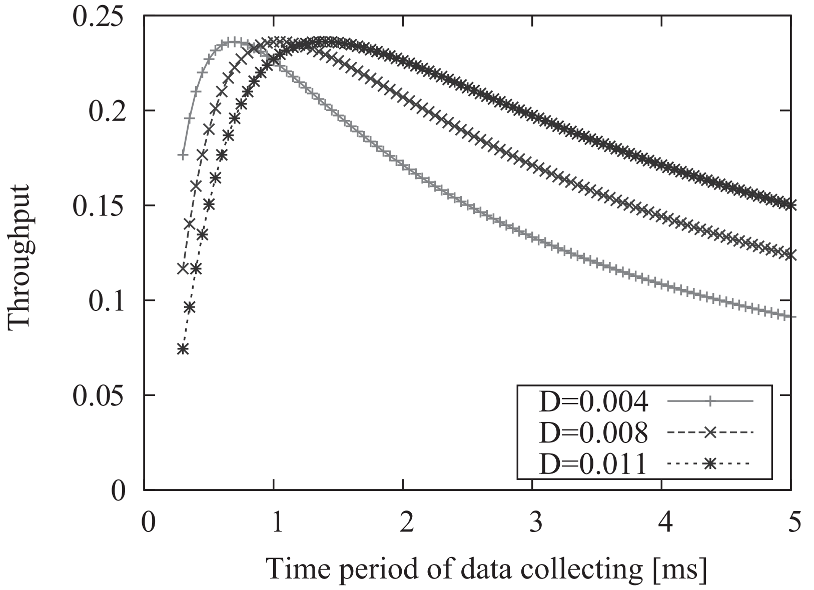


Figure 4.4: Throughput vs. Time period of data collecting. ©2015IEEE

the case where a fixed value for the data collecting time period is adopted. Fig. 4.5 shows the difference between the rate of achieved and required density of collected data in each case where the required density is set to 0.004, 0.008, 0.011, respectively. For comparison, the time period is set to 0.70, 1.05, and 1.40, respectively. The reason why these values were picked up is that they are the same value of the optimal value of T in each case where the required density is set to 0.004, 0.008, 0.011, respectively. From the results, it is shown that the proposed method achieved the minimum value of the evaluation index. By comparing with the case where a fixed value for the time period is adopted, it is understood that the proposed method always uses the optimal value of T, even if the required density is different. Therefore, it is confirmed that the proposal achieves an effective data collection according to the requirement from the system.

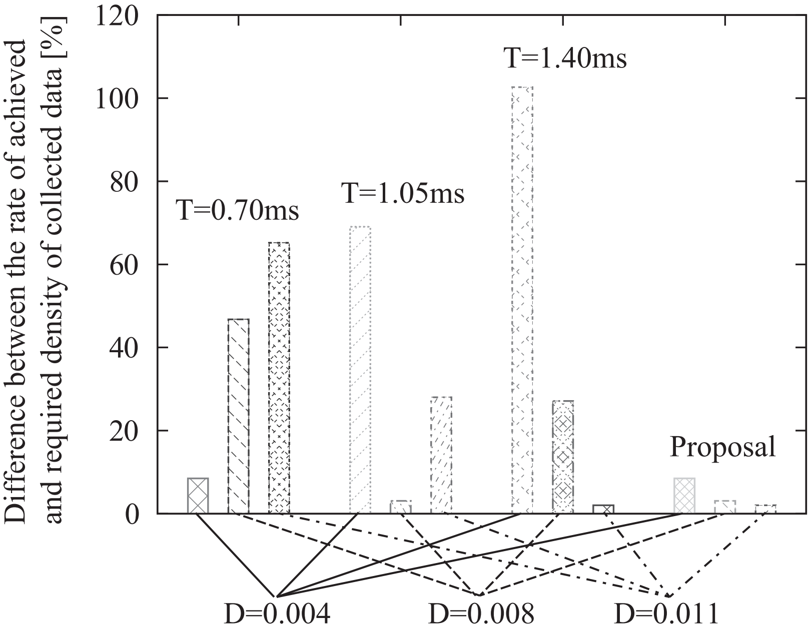


Figure 4.5: Difference between the rates of achieved and required density of collected data with or without our proposal. ©2015IEEE

4.4 Summary

In this chapter, we proposed two access control schemes to collect fresh data from sensor terminals. To keep the freshness of the collected data, it is needed to collect the data from many sensor terminals adequately while avoiding traffic congestion. In the proposed methods, the freshness and the density of the collected data is considered as important factors for the data collection. Our proposed methods make it possible to collect fresh data from sensor terminals by avoiding congestion and to increase the throughput. Therefore, our proposed methods achieves the efficient data collection with high throughput.

Chapter 5

Conclusion

In order to realize the smart society all over the world, providing network environment not only to urban areas but also to areas lacking adequate infrastructure (e.g., disaster-affected zones, rural areas, and so on) is essential. In this vein, in this thesis, we focused upon using satellites to collect data from many kind of sensor terminals. Since the satellites have many advantages such as wide coverage and they are disaster-resistant, they can be considered as a good candidate to constructs networks all over the world. However, there are some problems remained to realize the efficient data collection via SRSS. Since the number of the sensor terminals increase day by day, the satellite bandwidth is not enough to communicate with all the sensor terminals at the same time. Additionally, to improve the real-time performance of the systems for the smart society, data collection in real-time is required. For each of those problems, we provide novel contributions, which are supported with intensive analysis and numerical simulation. Precisely, our contributions as listed as follows:

In Chapter 2, the overview of supposed SRSS is introduced. Additionally, the existing data collection method in SRSS and their shortcomings are described. In this chapter, we made it clear that the efficient data collection method from sensor terminals to satellite and data aggregation method in sensor networks to improve the real-time performance of the system are needed.

In Chapter 3, we proposed new methods to collect data efficiently from an arbitrary wide area by means of SRSS. In the first proposal, by utilizing the history of data generating, it achieves to efficiently collect data from sensor terminals. Moreover, the second proposal realize efficient data collection without the history of data generating. In the sencond proposal, the satellite allocates time-slots on-demand to the sensor terminals, which have some data to send, by a divide and conquer-based approach, which consists of two steps, namely the searching and allocation phases. In the searching phase, the satellite finds the sensor terminals having data to send by repeating the process of dividing the sensor terminals into groups and removing some groups which do not include any sensor terminal having data to send. In addition, the searching phase stops on some level and moves to the allocation phase whereby the satellite allocates time-slots to all the remaining sensor terminals to minimize the total operating time. Moreover, the operating time of the searching and allocation phases are mathematically analyzed, and the total operating time is minimized. By using the proposed method, the satellite collects data from the sensor terminals deployed arbitrarily in a wide area. Thus, in the environment where numerous sensor terminals exist and they generate data at any time, our proposed method makes it possible to collect data from them by avoiding ineffective bandwidth allocation and to decrease the operating time. Also, it has been clearly demonstrated that in contrast with existing methods (such as slotted ALOHA and TDMA-based fixed assignment schemes), our proposal is capable of achieving higher efficiency of utilizing the satellite's bandwidth.

In Chapter 4, we proposed two access control schemes to collect fresh data from sensor terminals. To keep the collected data fresh, it is needed to collect data from many sensor terminals adequately while avoiding traffic congestion. In the first proposals, the interval for sending data by each sensor terminal is controlled with the changing rapidity of the ambient environment surrounding the sensor terminal. By considering the changing rapidity of the ambient environment, it is possible to keep the difference between the realtime information and the collected information as small as possible while avoiding traffic congestion. Additionally, an optimization was introduced to improve the efficiency of the proposed access control scheme by setting a threshold to control the timing of sending data. Mathematical analysis and numerical results represented the existence of the optimal threshold and show the effectiveness of the proposed method on keeping the freshness of the collected data in the assumed network. Therefore, the proposed method can be considered to achieve the efficient data collecting from the sensor terminals while avoiding traffic congestion. As the second method, we proposed a method for collecting uniform amount of fresh data from areas with varying density of data sending sensor terminals. To achieve an efficient collection of the data from the sensor terminals, in our proposal, the difference of the network condition between different places is considered. Additionally, we propose an algorithm to accommodate the change of the network condition dynamically. Numerical results represent the effect on the data collection from the sensor terminals on the proposed method. From the results, we confirmed that the proposed method achieves an efficient data collection that satisfies the required density of the data collection.

In Chapter 5, as a conclusion, we summarized this thesis.

As explained above, in this research, we proposed the methods to aggregate data in sensor networks and collect data efficiently from the sensor terminals via satellite networks. It is considered that the results of this research contribute the development of the next generation SRSS to realize future smart society.

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Appendix
Copyright Permissions

In this appendix, we inclose the permissions that were used to write this thesis. Please see the attached documents for a detailed description of permissions. The used publications that were used to write this thesis are listed as follows:

- Y. Kawamoto, H. Nishiyama, N. Kato, S. Yamamoto, N. Yoshimura, and N. Kadowaki " On Real-Time Data Gathering in Next Generation Satellite-Routed Sensor System (SRSS)," *2012 International Conference on Wireless Communications and Signal Processing (WCSP 2012),* Huangshan, China, Oct. 2012.

- Y. Kawamoto, H. Nishiyama, Z. Md. Fadlullah, and N. Kato, "Effective Data Collection via Satellite-Routed Sensor System (SRSS) to Realize Global-Scaled Internet of Things," *IEEE Sensors Journal,* vol. 13, no. 10, pp. 3645-3654, Oct. 2013.

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- Y. Kawamoto, H. Nishiyama, N. Kato, Y. Shimizu, A. Takahara, and T. Jiang, "A Novel Access Control Scheme to Construct Fresh Database of Ambient Information in Internet of Things," IEEE Wireless Communications and Networking Conference (WCNC 2015), New Orleans, USA, Mar. 2015.

- Y. Kawamoto, T. Nakazawa, H. Nishiyama, N. Kato, Y. Shimizu, and T. Jiang, "A Method for Collecting Uniform Amount of Fresh Data from Areas with Varying Population Density," IEEE International Conference on Communications (ICC 2015), London, UK, Jun. 2015.

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Publications

Journals

[1] Yuichi Kawamoto, Hiroki Nishiyama, Nei Kato, Yoshitaka Shimizu, Atsushi Takahara, and Tingting Jiang, "Effectively Collecting Data for the Location Based Authentication in Internet of Things", IEEE Systems Journal, Accepted.

[2] Ko Togashi, Yuichi Kawamoto, Hiroki Nishiyama, and Nei Kato, "A Cooperative ONU Sleep Method for Reducing Latency and Energy Consumption of STA in Smart-FiWi Networks," IEEE Transactions on Parallel and Distributed Systems, Accepted.

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Refereed Conference Papers

[11] Keisuke Sato, Yuichi Kawamoto, Hiroki Nishiyama, Nei Kato, Yoshitaka Shimizu, “A Modeling Technique Utilizing Feedback Control Theory for Performance Evaluation of IoT System in Real-Time”, 2015 International Conference on Wireless Communications and Signal Processing (WCSP 2015) , Nanjing, China, Oct. 2015. (Best Paper Award)

[12] Chi-Wei Tseng, Rubbens Boisgueney, Chih-Wei Huangy, Phone Lin, and Yuichi Kawamoto, "A Scheduled Grouping Scheme for MTC Device ID Sharing," International Wireless Communications & Mobile Computing Conference (IWCMC 2015) M2M & IoT Workshop, Dubrovnik, Croatia, Accepted.

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Non-Refereed Conference Papers

[24] Yuichi Kawamoto, ”A Study on A Centralized Multiple Access Scheme for Data Gathering in Satellite-Routed Sensor System (SRSS)” Annual Workshop on A3 Foresight Program, Gyeongju, Korea, Jul. 2014.

[25] Yuichi Kawamoto, ”Effective Data Collection via Satellite-Routed Sensor System (SRSS),” Annual Workshop on A3 Foresight Program, Sapporo, Japan, July 2013.

[26] Yuichi Kawamoto, Hiroki Nishiyama, and Nei Kato, ”A Study on Real-Time Data Gathering in Next Generation Satellite-Routed Sensor System (SRSS),” Annual Workshop on A3 Foresight Program, Jeju, Korea, Feb. 2013.

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[29] Yuichi Kawamoto, Keisuke Sato, Hiroki Nishiyama, Nei Kato, ”IoT から見たネットワークの課題,” 2015 IEICE Society Conference, Japan, Sep. 2015.

[30] Yuichi Kawamoto, Hiroki Nishiyama, Nei Kato, ”衛星センサネットワークにおけるリアルタイムデータ収集のための回線割り当て方式,” 2013 IEICE Society Conference, Japan, Sep. 2013.（学術奨励賞受賞）

[31] Yuichi Kawamoto，Hiroki Nishiyama，Nei Kato，Shinichi Yamamoto，Naoko Yoshimura，Naoto Kadowaki，“次世代衛星センサネットワークにおけるデータのリアルタイム性を考慮した帯域割り当て方法に関する一考察，”電子情報通信学会技術研究報告，vol. 112，no. 191，SAT2012-26，pp. 49-54，Aug. 2012.

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Awards

[33] 平成 27 年度（第 5 回） RIEC Award 東北大学学生賞

[34] 2015 International Conference on Wireless Communications and Signal Processing (WCSP 2015) Best Paper Award “A Modeling Technique Utilizing Feedback Control Theory for Performance Evaluation of IoT System in Real-Time ”

[35] 第 38 回 丹羽保次郎記念論文賞 ”Effective Data Collection via Satellite-Routed Sensor System (SRSS) to Realize Global-Scaled Internet of Things”

[36] IEEE Wireless Communications and Networking Conference (WCNC 2014) Best Paper Award ”An Efficient Traffic Detouring Method by Using Device-to-Device Communication Technologies in Heterogeneous Network “

[37] IEICE ソサイエティ大会 2013 学術奨励賞 ”衛星センサネットワークにおけるリアルタイムデータ収集のための回線割当方式”

[38] IEEE Global Communications Conference (GLOBECOM 2013) Best Paper Award ”A Centralized Multiple Access Scheme for Data Gathering in Satellite-Routed Sensor System (SRSS) “

[39] The 9th IEEE International wireless Communications and Mobile Computing Conference (IWCMC 2013) Best Paper Award “A Divide and Conquer Approach for Efficient Bandwidth Allocation in Next Generation Satellite-Routed Sensor System (SRSS) ”

[40] IEEE VTS Japan 2013 Student Paper Award ”Packet Transfer Delay Minimization by Network-Wide Equalization of Unbalanced Traffic Load in Multi-Layered Satellite Networks”

[41] 第8回 情報処理学会東北支部 野口研究奨励賞 ”Assessing Packet Delivery Delay in Multi-Layered Satellite Networks”

[42] 電気情報通信学会 2011 年度衛星通信研究賞 ”階層型衛星ネットワークの構成と通信遅延の関係に関する一考察” IEEE Wireless Communications and Networking Conference 2012 Student Travel Grant ”Assessing Packet Delivery Delay in Multi-Layered Satellite Networks ”