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A Centralized Multiple Access Scheme for Data Gathering in Satellite-Routed Sensor System (SRSS)

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***Abstract*—Satellite-Routed Sensor System (SRSS) has attracted attentions as a next generation sensor network system to realize data gathering from a large scale sensors deployment. In this system, a large number of sensor terminals send sensed data to the monitoring stations which are located in the different area via a satellite. With the help of satellite, it is possible to collect data from sensor terminals that are located in an area that has no physical infrastructure. Thus, SRSS is expected to provide many services such as real-time traffic control system and disaster detection systems by utilizing gathered data from large area. However, an efficient access control method is required to accommodate a large number of sensor terminals trying to transmit their sensed data to the satellite. Therefore, this paper proposes a novel data gathering method that can efficiently allocate bandwidth to the sensor terminals in need to transmit their sensed data. Additionally, an optimization to improve the efficiency of our proposed method is provided with mathematical expressions. The effectiveness of our proposal is evaluated through numerical results.**

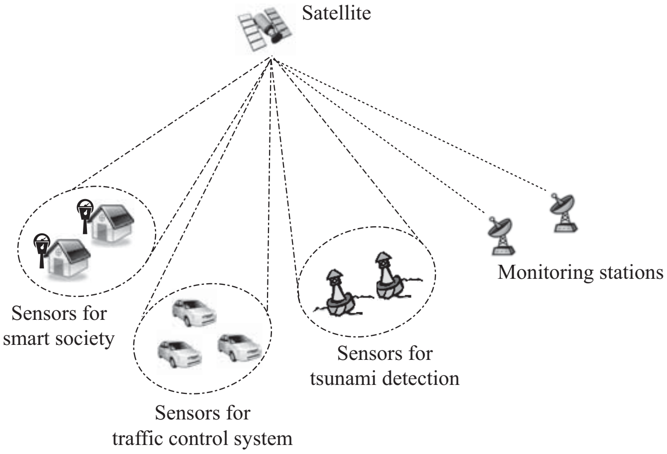


Fig. 1. An example of SRSS.

I. INTRODUCTION

In recent years, the development of sensor terminals and communication technologies has made our lives more convenient [1]. 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 [2]. Additionally, disaster prediction systems that utilize wireless sensor networks have attracted attention, especially, after East-Japan Catastrophic Disaster in March 2011 [3]. 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. However, since the network infrastructure on the surface cannot cover a very large area, existing systems suffer from limited coverage area. In particular, it is very hard to deploy a new network infrastructure on remote areas such as mountain or sea area [4].

Therefore, we focus on Satellite-Routed Sensor System (SRSS) to gather data from sensor terminals deployed in a large area [5]. Fig. 1 shows an example of SRSS composed of a satellite, monitoring stations, and sensor terminals. By utilizing satellite, SRSS is able to communicate with a large number of sensor terminals deployed in a large area concurrently. Moreover, since satellites are not affected by disaster on the surface, it can continue to provide communications service even during or after disaster [6]. The SRSS have a great potential as a next generation sensor network architecture that can provide many services to improve the quality of our lives. However, in an environment where a large number of sensor terminals are deployed, and each terminal can send data to the satellite at any given time, data collision may occur at the satellite. Thus, in order to realize efficient and accurate data gathering method, an efficient access control method is required for SRSS.

In this paper, we propose a new method to gather data efficiently from numerous sensor terminals for SRSS. In our proposed method, the satellite partition sensor terminals into nonoverlapping groups and allocate time-slots to sensor terminals that have data to send by using a combination of random access control technique and fixed assignment scheme in an on-demand fashion. Moreover, the total number of groups is optimized to minimize the operation time by using the efficient allocation method along with mathematical expressions.

The remainder of this paper is organized as follows. The assumed network model of SRSS is presented in Section II. Additionally, the existing access control method and their drawbacks are introduced in this section. Section III provides our proposed method to gather data from deployed sensor terminals by using a satellite. Section IV contains the results of numerical analysis. Finally, concluding remarks are provided in Section V.

II. NETWORK MODEL AND ACCESS CONTROL METHODS FOR SRSS

In this section, we introduce assumed network model for data gathering in SRSS. Additionally, existing access control methods in satellite networks are presented along with their drawbacks in the situation where numerous sensor terminals send data to a satellite at any time are discussed.

A. Network model for data gathering in SRSS

In this paper, we consider the SRSS composed of satellite, monitoring stations, and a large number of sensor terminals for data gathering. In the SRSS, sensor terminals gather various data such as wave length for tsunami detection, earthquake intensity for earthquake detection, and amount of traffic for traffic control systems. They send the data to the monitoring stations via the satellite at regular interval or when needed. In order to realize prompt and precise network systems, it is necessary to deploy a large number of sensor terminals to wide area. For example, about 4,200 sensor terminals for earthquake and about 1,300 sensor terminals for monitoring weather events are deployed in Japan. So, as a next generation SRSS, a satellite is required to communicate with thousands of sensor terminals. On the other hand, Geostationary Earth Orbit (GEO) satellite is considered to be a suitable candidate of the satellite in SRSS. GEO satellite has high altitude of about 36,000km above the surface and appear as stationary with respect to an arbitrary point of the surface due to the characteristic of the orbit [7]. Thus, it is suitable for data gathering from wide area over a long term [8], [9]. Additionally, high real-time performance is needed to construct disaster warning system because the system has to provide the information of the disaster to people as early as possible. Therefore, we consider the method to gather data which can be generated at any time from numerous sensor terminals within the shortest possible time.

B. Existing access control methods and their drawbacks

As mentioned earlier, an appropriate method to provide communication between numerous sensor terminals and a satellite is required. In the traditional satellite networks, various access control methods have been considered [10], [11]. Here, we introduce these methods by classification them into two groups, namely contention-based schemes and fixed bandwidth assignment schemes.

As the contention-based scheme, ALOHA is a famous method used in satellite communication [12]. In ALOHA, each terminal on the surface sends its data at any time when the data is generated. In the case where data collision occurs when multiple terminals transmit at the same time, each terminal waits for a random time before retransmitting the data. By utilizing the random waiting time, further collisions can be avoided. Moreover, slotted ALOHA which is developed by improving the ALOHA is generally used in satellite networks [13]. In the slotted ALOHA, each terminal control the data transmission timing at regular interval. By controlling the timing, it decreases the probability of data colliding. Thus, the slotted ALOHA achieves higher throughput performance than ALOHA. Furthermore, many methods which improve the ALOHA and the slotted ALOHA are proposed in the past. However, in the case where large number of terminals are deployed, the probability of data collisions increase drastically in ALOHA or slotted ALOHA. It is common for these schemes to have data collision especially with a large number of terminals. Data collision required the data to be retransmitted which decrease the overall throughput and real-time performance of the network.

On the other hand, Time Division Multiple Access (TDMA) is very well known fixed bandwidth allocation method. In the case where TDMA is adopted in satellite networks, satellite allocates time-slots which are the smallest logical units for bandwidth allocation to each terminal. Each terminal sends its data during the allocated time-slots. In TDMA, each terminal can avoid data collisions because they only send their data during their own allocated timing. However, in the case where numerous terminals are allocated time-slots one by one in TDMA, the total data transmission interval becomes very long. Thus, the real-time performance decrease with the increase of the number of terminals.

Therefore, as mentioned above, in the situation where numerous sensor terminals are deployed, it is difficult to provide adequate communication environment for existing access control methods. In order to avoid data collisions while keeping high real-time performance in SRSS which is constructed by a satellite and numerous sensor terminals, a new methods to control the access and assign bandwidth on-demand to sensor terminals with a small operation time.

III. AN EFFICIENT DATA GATHERING TECHNIQUE

In this section, we propose the new satellite bandwidth allocation method to gather data from numerous sensor terminals in an on-demand fashion within a small operation time. Additionally, to increase real-time performance, the operation time of our proposal is optimized with mathematical analysis.

A. Proposed algorithm

In our proposed method, 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 1. In this proposal, satellite partitions sensor terminals into groups with respect to their identification number. 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 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

Algorithm 1 Proposed data gathering algorithm

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

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, $N_{\rm RM}$ 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 $N_{\rm RM}$. 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.

B. 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 $T_{\rm cp}$, 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.

$$T_{\rm cp}(N_{\rm g}) = rtt + N_{\rm g} \cdot t, \tag{1}$$

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

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

From Eq. 1, it is clearly shown that the expected operation time in classification phase increase with the increase of the total number of groups.

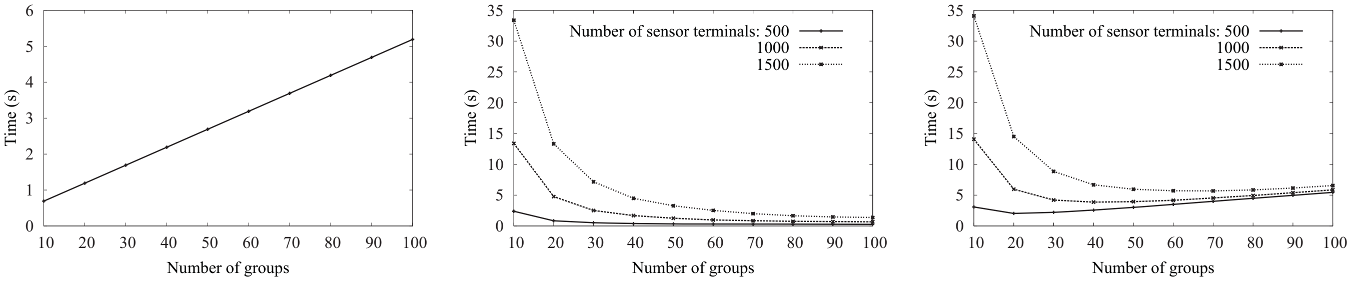
Secondly, we express the expected operation time in allocation phase. It is determined by how many groups are classified as *Category-1* or *Category-2* and it depends on the probability that each sensor terminal has data to send when the sensor terminal receives SM. Here, we define average of the probability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

$$P_{(N_{\rm RM}=1)}(N_{\rm g}) = {}_{\frac{N_{\rm s}}{N_{\rm g}}}C_1 \cdot p \cdot (1-p)^{\frac{N_{\rm s}}{N_{\rm g}}-1}. \tag{3}$$

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

$$\begin{aligned} & P_{(N_{\rm RM}\geq 2)}(N_{\rm g}) \\ = & \sum_{k=2}^{\frac{N_{\rm s}}{N_{\rm g}}} \left\{ {}_{\frac{N_{\rm s}}{N_{\rm g}}}C_k \cdot p^k \cdot (1-p)^{\frac{N_{\rm s}}{N_{\rm g}}-k} \right\}. \end{aligned} \tag{4}$$

Since only the sensor terminal having data to send in *Category-1* group and all sensor terminals in *Category-2* group



(a) The operation time for classification phase. (b) The operation time for allocation phase. (c) The total operation time.

Fig. 2. Operation time for searching phase and allocation phase, and the total time of them.

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.

$$\begin{aligned} T_{\mathrm{ap}}(N_{\mathrm{g}}) &= N_{\mathrm{g}} \cdot P_{(N_{\mathrm{RM}}=1)}(N_{\mathrm{g}}) \cdot t \\ &+ N_{\mathrm{g}} \cdot P_{(N_{\mathrm{RM}}\geq 2)}(N_{\mathrm{g}}) \cdot \frac{N_{\mathrm{s}}}{N_{\mathrm{g}}} \cdot t. \end{aligned} \tag{5}$$

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

$$\begin{aligned} T_{\mathrm{total}}(N_{\mathrm{g}}) &= T_{\mathrm{cp}}(N_{\mathrm{g}}) + T_{\mathrm{ap}}(N_{\mathrm{g}}) \\ &= rtt + N_{\mathrm{g}} \cdot t + \Bigg[p \cdot (1-p)^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}-1} \\ &+ \sum_{k=2}^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}} \left\{ {}_{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}}C_k \cdot p^k \cdot (1-p)^{\frac{N_{\mathrm{s}}}{N_{\mathrm{g}}}-k} \right\} \Bigg] \cdot N_{\mathrm{s}} \cdot t. \end{aligned} \tag{6}$$

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.

$$N_{\mathrm{optg}} = \arg\min_{N_{\mathrm{g}}} T_{\mathrm{total}}(N_{\mathrm{g}}). \tag{7}$$

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, our proposed method achieves to efficiently allocate bandwidth to sensor terminals with minimal operation time.

IV. NUMERICAL ANALYSIS

In this section, we confirm the relationship between the operation times of classification phase and allocation phase in our 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 I. 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

A. Parameter settings

The parameter settings are summarized in Table I. 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.

B. Numerical results

First, we evaluate the operation time for classification phase, allocation phase, and the sum of both. Fig. 2(a) shows the operation time for classification phase when the number of groups increase. Since Eq. 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. 2(a), 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. 2(b). 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. 2(c) 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.

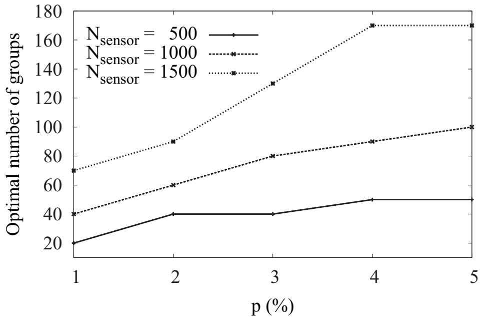


Fig. 3. The change of optimal number of groups.

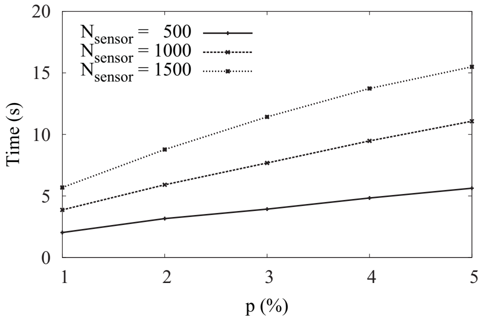


Fig. 4. The change of total operation time when the number of groups is optimized.

Secondly, we study the change of the optimal number of groups and total operation time when the number of groups is optimized. Fig. 3 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, 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. 4 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.

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.

V. CONCLUSION

In this paper, we proposed the new bandwidth allocation method to gather data from numerous sensor terminals in the next generation Satellite-Routed Sensor System (SRSS). In the SRSS, an appropriate schemes to gather data from large number of sensor terminals with small operation time is necessary. Thus, in this proposal, satellite partitions the sensor terminals into groups and allocate bandwidth by using both random access control scheme and fixed assignment scheme efficiently. Additionally, the number of dividing groups is optimized to minimize the operation time of the proposed method with mathematical analysis. Numerical results represent the existence of optimal total number of groups and show the effect of the data generation from sensor terminals on the proposed method. From the results, we confirmed that the optimal number of the groups is decided to minimize the operation time of our proposal. Therefore, our proposed method achieves the efficient data gathering with small operation time in the SRSS.

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