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A Divide and Conquer Approach for Efficient Bandwidth Allocation in Next Generation Satellite-Routed Sensor System (SRSS)

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***Abstract*—Next generation satellite-routed sensor system (SRSS) is expected to provide disaster detection system with high real-time performance. By using satellite networks, SRSS realizes data collection from multiple sensor terminals deployed in a wide area. However, an efficient access control scheme is needed to achieve multiple access from numerous sensor terminals to the satellite with its limited bandwidth. Conventional research works propose a countermeasure to avoid data collisions at the satellite. However, they do not consider the situation that a significantly large number of sensor terminals communicate with the satellite anytime, which cause data collisions and decrease real-time performance. Therefore, in order to efficiently resolve these problems, we propose a new scheme which utilizes a divide and conquer approach for efficient bandwidth allocation. The effect of the scheme on the amount of time for allocating satellite bandwidth is also analyzed. The analysis clearly shows the advantage of our proposed scheme. Furthermore, numerical results demonstrate the effectiveness of our proposal.**

***Index Terms*—Satellite-based sensor networks, Divide and conquer, TDMA, and Real-time performance.**

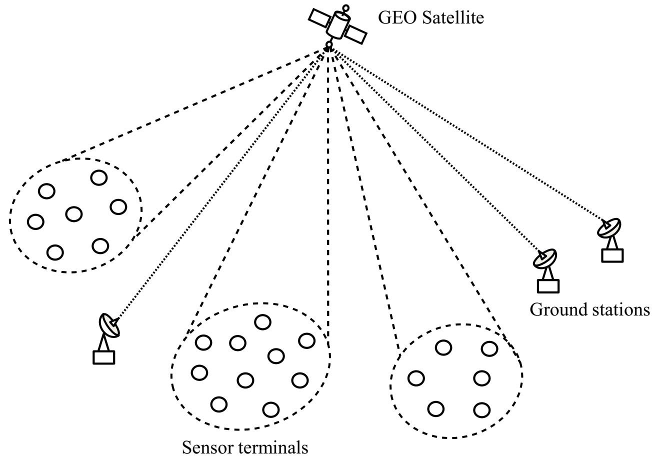

Fig. 1. An example of network configuration of satellite-routed sensor system.

I. INTRODUCTION

Recently, designing disaster detection systems by using wireless sensor networks has attracted much attention. Especially, after East-Japan Catastrophic Disaster in March 2011, many people have suggested a better focus on this kind of systems to quickly provide accurate disaster information. Thus, it is needed to establish a large-scale system to detect disaster at an early date [1]. In order to collect data early from wide areas, Satellite-Routed Sensor System (SRSS) is expected as the next generation system to efficiently collect data from wireless sensor terminals [2]. SRSS is constructed by satellite(s), sensor terminals, and ground stations as shown in Fig. 1. In the SRSS, each sensor terminal sends data of disaster information such as tsunami, earthquake, and volcano to satellite(s) when they detect the emergence of disaster [3]. Satellite(s) receive(s) the data from sensor terminals and send(s) them to ground stations which deliver these information to wherever necessary. This system also collects data from remote areas such as sea or mountain where ground networks cannot communicate with sensor terminals [4].

Conventional satellite network systems use random access control scheme to communicate with sensor terminals on the ground [5]. However, data collisions may occur at the satellite receiving the data from many different sensor terminals at the same time. It is because numerous sensor terminals are deployed in a next generation SRSS, and each sensor terminal can send data to the satellite anytime. Data collisions cause long delay and/or lack of disaster information data, which is fatal problem for the disaster detection system. Moreover, real-time performance is one of the most important factors of the system because we need to deliver the evacuation and disaster prevention information as soon as possible. Thus, an efficient access control scheme is necessary for the system. On the other hand, although fixed bandwidth assignment scheme such as Time Division Multiple Access (TDMA) can avoid the collisions, bandwidth allocation in such scheme causes long waiting time and wastes the bandwidth if there are numerous sensor terminals.

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Therefore, a method to allocate bandwidth efficiently on-demand is needed for the system. In this paper, we propose a new method using both TDMA and searching sensor terminals having request to send in order to allocate bandwidth in minimum operation time. Additionally, the efficiency of the system is analyzed with some mathematical expressions and numerical results.

The remainder of this paper is organized as follows. Section Ⅱ describes the assumed network configuration of SRSS. In addition, the existing access control schemes and their shortcomings are introduced. Section Ⅲ demonstrates an efficient way to allocate satellite bandwidth to sensor terminals. Moreover, the operation time for allocating bandwidth in our proposed model is analyzed in this section. The results of numerical analysis are presented in Section Ⅳ. Finally, concluding remarks are provided in Section Ⅴ.

II. NETWORK CONFIGURATION AND ACCESS CONTROL SCHEMES FOR SRSS

A. Assumed network configuration of SRSS

In this paper, we assume the SRSS constructed by a satellite, sensor terminals, and ground terminals as a simple SRSS model to validate the efficiency of the communication between the satellite and sensor terminals. A Geostationary Earth Orbit (GEO) satellite [6] is considered as a good candidate for collecting data from a large number of sensor terminals due to the wide coverage. For example, Engineering Test Satellite Ⅷ (ETS-Ⅷ), which was launched by Japan Aerospace Exploration Agency (JAXA) in 2006, was conducted for various experiments including the communication with sensor terminals in Japan and its surrounding areas. The satellite provides the communication environment by using the multi-beam system. The system can efficiently utilize the frequency because sensor terminals deployed on separate areas can use the same frequency range. Moreover, since the satellite can concentrate the transmission power to a narrow area, it becomes possible to increase the transmission capacity. The frequency range is divided into some channels to permit multiple access without interference. By using these systems, new systems where a satellite can collect data from numerous sensor terminals will appear in the near future.

On the other hand, many sensor terminals are currently used for multiple purposes. For example, there are about 4,200 sensors for earthquake and about 1,300 sensors for monitoring weather events in Japan. Thus, as a next generation system, hundreds or thousands of sensor terminals are supposed to be deployed in the wide area densely to realize the real-time disaster detection system. Therefore, a satellite needs to communicate with hundreds or thousands of sensor terminals in each channel.

B. Existing access control schemes and their shortcomings

In the above mentioned network, an appropriate access control scheme is needed to achieve the communication between multiple sensor terminals and a satellite without collisions at the satellite. For the common terrestrial networks, many access control schemes are developed such as Carrier Sense Multiple Access/Collision Detection (CSMA/CD) and Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). However, in the SRSS, it is difficult to detect radio waves from neighbor sensor terminals because the distance between these sensor terminals is too long. Thus, conventional schemes are supposed to be used in the satellite networks even in 2012 [8]. Here, we introduce the conventional schemes, which are classified to two groups as contention-based schemes and fixed assignment schemes.

As a contention-based scheme, ALOHA [9] or slotted ALOHA [10] is commonly used in satellite networks. In the case of ALOHA, each sensor terminal sends data to a satellite when the data is required to send. If collisions at the satellite occur due to the data received from multiple sensor terminals, each sensor terminal waits a random time and sends the data again. By using the random time of waiting, they can avoid the further collisions. The slotted ALOHA achieves higher throughput than ALOHA by controlling the timing of data sending from all sensor terminals. In addition, many schemes which improve ALOHA or slotted ALOHA are developed [11]. However, in the environment where numerous sensor terminals are deployed, continuous collisions might occur. As a results, throughput and real-time performance decrease drastically because the increase of sensor terminals causes the increase of probability that more than one sensor terminal send data to a satellite at the same time.

On the other hand, TDMA is well known as a fixed assignment scheme. In this scheme, sensor terminals are assigned 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 regular intervals, it is possible to avoid the time overlapping of data sending. Although fixed assignment schemes achieve higher performance in limited environments such as when sensor terminals generate data constantly, fruitless time-slots assignment might happen when the data is arbitrarily generated at sensor terminals. Moreover, if many sensor terminals are deployed, each sensor terminal might have to wait for long time until the time-slots are assigned in the fixed assignment schemes, and thus, they cannot guarantee the real-time performance.

Therefore, the increase of deployed sensor terminals causes the decrease of performance in both contention-based schemes and fixed assignment schemes. Especially, in the disaster detection system, real-time performance is one of the most important factors because the disaster information should be sent to ground stations as soon as possible after the disaster happened. Hence, a method to assign bandwidth on-demand to sensor terminal which detects the event with small operation time is required for real-time detection of disaster.

III. AN EFFECTIVE ON-DEMAND BANDWIDTH ALLOCATION SCHEME

In this section, we propose a scheme to allocate satellite bandwidth to sensor terminals according to their request to send with minimum operation time. In this proposed scheme,

Algorithm 1 Proposed bandwidth allocation algorithm

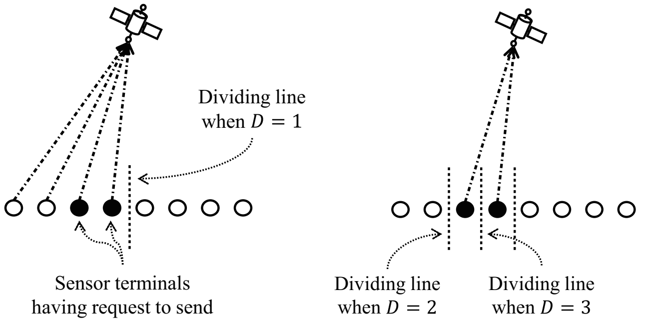
```
Join all sensor terminals into $G_0(0, N_{\text{sensor}})$
while $D < D_{\text{opt}}$ do
    (Start searching phase)
    while $G_i(\alpha, \beta)$ exist do
        Send SM to $G_i(\alpha, \beta)$ in order of $i$
        if $N_{\text{RM}} = 0$ then
            Remove $G_i(\alpha, \beta)$
        else if $N_{\text{RM}} = 1$ then
            Allocate time-slots to the sensor terminal
            Remove $G_i(\alpha, \beta)$
        else if $N_{\text{RM}} \geq 2$ then
            Make $G_{i+1}(\alpha, \frac{\alpha+\beta-1}{2})$ and $G_{i+2}(\frac{\alpha+\beta+1}{2}, \beta)$
            Remove $G_i(\alpha, \beta)$
            $D$++
        end if
    end while
end while
(Start allocating phase)
```

satellite searches the sensor terminals having the request to send by a divide and conquer approach. In this section, the operation time for allocating bandwidth in our proposed model is also analyzed with some mathematical expressions.

A. Proposed algorithm

In this proposal, we aim to allocate satellite bandwidth on-demand to sensor terminals with minimum operation time in the environment where numerous sensor terminals share the same channel and arbitrarily generate data. The proposed algorithm is shown in Algorithm 1. In this algorithm, we define $G_i(\alpha, \beta)$ as the group of sensor terminals having identification number i, with α and β show the smallest and largest identification number in the group, respectively. As shown in Algorithm 1, at first, satellite broadcasts messages to all sensor terminals to search sensor terminals which have a request to send data, and wait the response from sensor terminals. The above flow is called searching phase and the searching message is called SM. If there is no response from sensor terminals, satellite broadcasts the SMs at a regular interval. On the other hand, if sensor terminals have the data, they must return the request messages, namely RMs, to the satellite. The RM includes the identification number of the sensor terminal which has sent the message. After that, the satellite receives RMs. If the number of received RMs is one, the satellite allocates bandwidth to the sensor terminal. Here, TDMA is supposed as the bandwidth allocation method in this system. Additionally, the data size of sensor terminals is assumed to be small because it is enough for sensor terminals to send a few digit data such as temperature, intensity of earthquake, and wave height. Thus, when the satellite allocates bandwidth, a constant size of time-slot is allocated to a sensor terminal.

If the number of RMs is more than one, the satellite detects collision of the RMs. As a result, the satellite cannot individuate the sensor terminals which sent the RMs. In this case, the satellite divides all sensor terminals into two groups according to the identification numbers of them. After dividing, the satellite broadcasts SM to one of the groups, and repeats the above procedures. If the number of RMs is zero, the satellite broadcasts SM to another group. Although it is possible to identify the sensor terminal which sent RM with above mentioned scheme, it might take long time to find the sensor terminal according to circumstances.



(a) The case when searching phase finishes at the first dividing phase.

(b) The case when searching phase is repeated until the sensor terminals sending RMs are individuated.

Fig. 2. An example of the case when the searching phase has finished.

Therefore, in our proposed scheme, the satellite allocates time-slots to all the sensor terminals by using the rotation in the same group, which is called allocating phase, after repeating constant number of dividing times. By using these procedures, the number of searches can be decreased. However, if the number of dividing times is too small, the satellite has to allocate many time-slots to sensor terminals which do not have any data to send. Thus, there is a trade-off relationship between the amount of time for searching phase and that of allocating phase. Therefore, an appropriate number of dividing times needs to be decided for efficient bandwidth allocation.

In order to simply express the effect of changing the number of dividing times, we suppose a simple model of SRSS constructed by a satellite and eight sensor terminals which share one channel to communicate with the satellite in the Fig. 2. In this figure, there are two sensor terminals having data to send. Fig. 2(a) shows the case when searching phase finishes after the sensor terminals are divided once. In this case, the amount of time for searching phase is small. However, since there remains four sensor terminals to be allocated time-slots, the amount of time for allocating phase becomes long due to the needless time-slot allocations. On the other hand, Fig. 2(b) shows the worst case when searching phase is repeated until the sensor terminals sending RMs are individuated. In this case, since it needs to divide three times to individuate these sensor terminals having data to send, the sensor terminals sending RMs are identified when $D = 3$. In this case, it is considered that the searching phase needs long time because only one time of searching also takes a big amount of time due to the long propagation distance between the satellite and sensor terminals [12]. In contrast, the amount of time for allocating time is small because satellite has already identified the sensor terminals which have data to send. Therefore, it is considered that the trade-off relationship between the amount of time for searching phase and allocating phase exists. Although Fig. 2 shows a simple model for explanation, similar phenomena can occur in the case many sensor terminals are deployed. In the worst case, the searching phase repeats until all sensor terminals having data to send are individuated.

B. Optimal number of dividing times

In this subsection, we analyze the optimal number of maximum dividing times in our proposed scheme with some mathematical expressions. In this analysis, the number of satellites is set to one, and the number of sensor terminals which share the same channel is N_{sensor}. In order to clarify the existence of the optimal number of dividing times, for simplicity, we consider the case where the number of sensor terminals, which send RMs at the same time, is equal to 2.

Firstly, we formulate the amount of time for searching phase. In our proposed scheme, it is one cycle that satellite broadcasts SMs and then receives RMs from sensor terminals. One cycle takes the time equal to $(2 \cdot h_{\text{sat}})/c$, where the altitude of satellite and light speed are defined as h_{sat} and c, respectively. The satellite repeats the cycle on several occasions to divide sensor terminals when the data collision occurs due to the multiple RMs. We define the maximum number of dividing times as D. Thus, the amount of time with the cycle equal to D, namely T_{search}, is expressed as follows:

$$T_{\text{search}}(D) = \frac{2 \cdot h_{\text{sat}}}{c} \cdot (2 \cdot D + 1). \quad (1)$$

Secondly, we formulate the amount of time for allocating phase. After searching phase, the satellite allocates time-slots to each sensor terminal which remains as a candidate of sensor terminals having data to send. The size of a time-slot is defined as t. Since the number of the remaining sensor terminals is expressed as N_{sensor}, the amount of time to allocate time-slots to these sensor terminals, namely T_{allocate}, is formulated as follows:

$$T_{\text{allocate}}(D) = \frac{N_{\text{sensor}}}{2^D} \cdot t. \quad (2)$$

From Eq. 1, it is understood that the amount of time for searching phase increases with the increase of the value of D. In contrast, from Eq. 2, it is clear that the amount of time for allocating phase decreases with the increase of the value of D. Thus, there is a trade-off relationship between the amount of time for searching phase and allocating phase when deciding the number of maximum dividing times in our proposed method. Therefore, the optimal number of maximum dividing times, D_{opt}, to minimize the total amount of time of searching phase and allocating phase exists. D_{opt} is expressed as follows:

$$D_{\text{opt}} = \arg\min_{D} T_{\text{total}}(D) \quad (3)$$

TABLE I
PARAMETER SETTINGS

Number of satellites	1
Altitude of satellite (h_{sat})	36,000km
Number of sensor terminals (N_{sensor})	500-2,000
Time-slot (t)	5ms
Light speed (c)	300,000km/s

IV. NUMERICAL ANALYSIS

In this section, we aim to verify the trade-off relationship between the amount of time for searching and allocating phases. Moreover, we declare the existence of the optimal number of maximum dividing times in SRSS with some numerical calculation results.

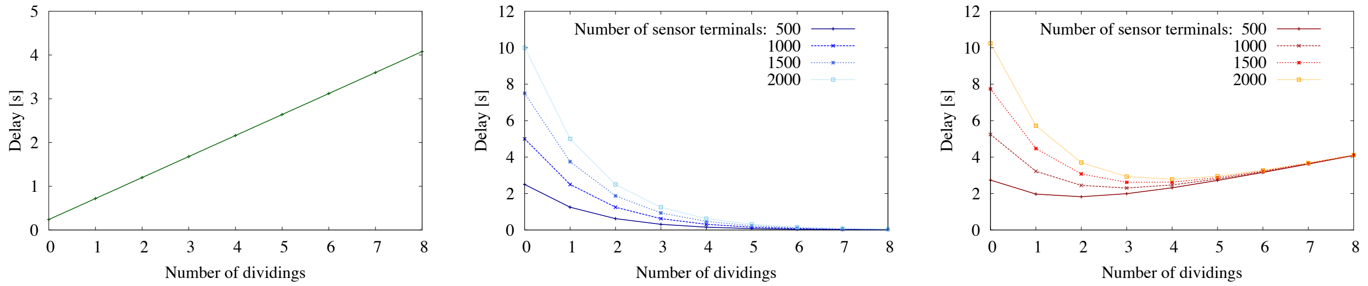
A. Parameter settings

The parameter settings are summarized in Table I. In this numerical analysis, the SRSS constructed by a GEO satellite and sensor terminals sharing a channel is considered as the network configuration. Suppose that a TDMA-based system, where the length of a time-slot is 5ms, is utilized as the bandwidth allocation method. Additionally, the number of sensor terminals varies from 500 to 2,000 with the step of 500.

B. Numerical results

Firstly, we study the relationship between the amount of time for searching and allocating phases. Fig. 3(a) shows the change of the amount of time for searching phase when the number of dividing times varies from 0 to 8. From Fig. 3(a), it is clearly shown that the amount of time for searching phase increases with the increase of the number of diving times. That is because the increase of the number of dividing times causes the increase of the number of times for transmitting and receiving messages between the satellite and sensor terminals. Fig. 3(b) demonstrates the amount of time for allocating phase. From Fig. 3(b), it is understood that the amount of time for allocating phase decreases with the increase of the number of dividing times. Since the increase of the number of dividing times leads to the decrease of the number of the sensor terminals which share the channel at the allocating phase, the amount of time for allocating phase decreases. From Fig. 3(a) and Fig. 3(b), it is confirmed that the amount of time of searching phase increases and the amount of time for allocating phase decreases when the number of dividing times increases. Thus, the trade-off relationship between the amount of time of searching phase and allocating phase exists.

Secondly, Fig. 3(c) shows the total amount of time for searching and allocating phases. We can find the optimal number of dividing times from Fig. 3(c). For example, when the number of sensor terminals is 2,000, the optimal number of dividing times is determined as 4. In addition, the total time when the number of dividing times is set appropriately becomes smaller than the case when the number of dividing



(a) The amount of time for searching phase.

(b) The amount of time for allocating phase.

(c) The total amount of time for searching and allocating phases.

Fig. 3. The amount of time for searching phase and allocating phase, and the total time of them.

times equals to 0, which means that the satellite allocates timeslots to all sensor terminals in the network by rotation. It means that our proposed scheme provides shorter operation time than the bandwidth allocation with only TDMA-based scheme. Moreover, it is understood that the optimal number of dividing times increases with the increase of the sensor terminals. This is because the amount of time for allocating phase increases while the amount of time for searching time is constant when the number of sensor terminals increases.

Although these results are calculated in the environment where there are only two sensor terminals having data to send at the same time, the same phenomenon is considered to occur in the situation that the data is generated at multiple sensor terminals arbitrarily.

V. CONCLUSION

In this paper, we proposed the scheme to allocate satellite bandwidth on-demand to sensor terminals in minimum operation time for the next generation Satellite-Routed Sensor System (SRSS). In the SRSS, real-time performance is one of the most important factors to utilize the system as disaster detection system. However, in the environment where a large number of sensor terminals are deployed and share the same channel to communicate with the satellite, it is difficult to collect data generated arbitrarily from sensor terminals while guaranteeing a certain level of real-time performance. Thus, in our proposal, a satellite searches the sensor terminals which have request to send by repeatedly dividing them into halves. The scheme helps to decrease the total time of searching and allocating by adjusting the number of dividing times. Moreover, the optimal number of maximum dividing times is analyzed with some mathematical expressions. The numerical results demonstrate that there is a trade-off relationship between the amount of time to search sensor terminals and the amount of time to allocate bandwidth to them. We confirmed that the optimal number of maximum dividing times can be determined to achieve minimum operation time when the number of sensor terminals having data to send is two. Considering the case of more than two sensor terminals having data to send is a challenging issue because the derivation of the optimal number of maximum dividing times is not easy, which is one of our next target.

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