On Real-Time Data Gathering in Next Generation Satellite-Routed Sensor System (SRSS)

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Yuichi Kawamoto†, Hiroki Nishiyama†, Nei Kato†, Shinichi Yamamoto§, Naoko Yoshimura§, and Naoto Kadowaki§
†Graduate School of Information Sciences, Tohoku University, Sendai, Japan
§Wireless Network Research Institute,
National Institute of Information and Communications Technology, Tokyo, Japan
E-mails: †{youpsan, bigtree, kato}@it.ecei.tohoku.ac.jp

Abstract—**Recently, satellite-routed sensor systems are expected to be used as early disaster detection systems. The networks efficiently provide data collected from wide areas with small sensor terminals and satellites. In this system, each sensor terminal collects and sends data to monitoring stations on the ground via satellites. Although the future major disaster detection systems require high capacity to manage numerous sensor terminals, it is difficult to collect data from a large number of sensor terminals simultaneously since the bandwidth of each satellite is limited. Hence, an efficient system to allocate the bandwidth to each sensor terminals is required. Moreover, for early disaster detection, the real-time performance is very important. Therefore, in this paper, we discuss an appropriate bandwidth allocation model to construct a next generation satellite-routed sensor system while considering the real-time performance. In the new model, we particularly focus on the relationship between throughput of each sensor terminal and real-time performance, and introduce a method to allocate bandwidth. A numerical analysis is used to validate the new system model.**

I. INTRODUCTION

In recent years, the development of communication technology has accelerated the development of sensor networks [1],[2]. Moreover, sensor networks for disaster prediction and environmental observation have improved regularly [3],[4]. Since sensor networks make it possible to collect many information, they have been used in many situations such as earthquake early warning systems and weather forecasting systems. However, sensor networks need to deploy a lot of sensor terminals widely. Thus, it is difficult to collect data from all sensor terminals with only the infrastructure on the ground. Particularly, monitoring stations on the ground have difficulties in gathering data from sensor terminals at remote areas such as sea or mountain.

Therefore, using satellites to collect data from the sensor terminals has attracted attention in recent days [5]. Since satellites have large coverage area, they can communicate with sensor terminals which are deployed in a wide area at the same time. Additionally, they have the advantage of providing network environment even during disasters, because they are not affected by disasters on the ground [6].

In satellite-routed sensor system, each sensor terminal collects data and sends them to monitoring stations via satellites as shown in Fig. 1. By using satellites, the networks also achieve the collected data from remote areas. However, there have been some research issues such as how to use satellite bandwidth effectively and improve real-time performance of data collection. The real-time performance is considered as a very important parameter for early detection of disasters such as earthquake, volcano eruption, and tsunami. Therefore, we consider a new system model with an efficient approach to allocate satellite bandwidth to sensor terminals which improves the real-time performance.

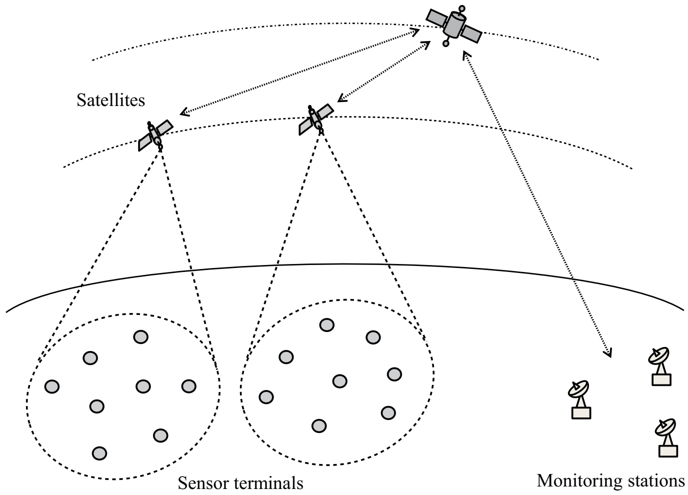


Fig. 1. An example of satellite-routed sensor system.

In this paper, we analyze the relationship between throughput of each sensor terminal and real-time performance when the allocated bandwidth changes. Consequently, an appropriate number of the slots for one sensor is expressed with mathematical formulations.

The remainder of this paper is organized as follows. Section II describes the existing systems of sensor networks, satellite-routed sensor systems, and their shortcomings. Section III demonstrates an efficient way to allocate satellite bandwidth to sensor terminals. Additionally, the throughput of each sensor terminal and real-time performance are analyzed in this section. The results of numerical analysis are presented in Section IV. Finally, concluding remarks are provided in Section V.

II. Existing Systems

In this section, 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. We describe the shortcomings of their systems and discuss the requirements for the next generation satellite-routed sensor system.

A. 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 [7]. The system includes about 1,300 stations and collects weather data from each station [8]. 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.

B. Argos system

Argos system is one of the most popular data collecting systems for environmental research and conservation by using sensor terminals and satellites [9]-[11]. 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 [12]. 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 [13].

Since the Argos system uses Low Earth Orbit (LEO) satellites [14] and Doppler location capability, it is possible to communicate with downsize sensor terminals using low power consumption [15],[16]. 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.

C. 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.

Since Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) are used in existing satellite networks as bandwidth allocation methods, they are expected to be used in the satellite-routed sensor system. As the bandwidth of each satellite is limited, the combination of TDMA and FDMA is needed to achieve efficient bandwidth allocation. In this research, we assume that frequency channels are assigned to different groups of sensor terminals, and each frequency is shared in the allocated group based on TDMA mechanism. In this paper, we focus on the method of allocating bandwidth to each sensor terminal with TDMA because the bandwidth allocation with TDMA has a significant effect on the real-time performance in data collecting in the satellite-routed sensor system. In the next section, we describe the system model to allocate bandwidth and analyze the effect of bandwidth allocation on the real-time performance with some mathematical expressions.

III. System Model

In this section, we introduce the model of bandwidth allocation in TDMA and its problem in the satellite-routed sensor system with considering real-time performance. Secondly, the throughput of each sensor terminal in different bandwidth allocations is formulated. Additionally, the efficient way to allocate bandwidth while considering real-time performance is presented at the end.

A. Bandwidth allocation model and real-time performance

In satellite-routed sensor systems, satellites distribute time-slots, which are the smallest logical units for bandwidth allocation. Sensor terminals sharing the same bandwidth of the satellite get some slots by rotation. In this research, we define the size of slot as s and the number of slots concurrently allocated to a sensor as N_{slot}. Thus, each sensor terminal sends data in a duration of time equal to $\mathrm{s} \cdot N_{\mathrm{slot}}$. Fig. 2 shows an example of slot allocation to each sensor terminal by rotation, where the number of sensor terminals in the system is defined as N_{sensor}.

In the Fig. 2, α is the size of guard time, which is necessary to avoid interference between sensor terminals [17]. The size of the guard time depends on the accuracy of the synchronism capability between sensor terminals. If all sensor terminals have a perfectly synchronized clock, the guard time is unnecessary. However, it is difficult to achieve perfectly synchronism because many sensor terminals are deployed widely. Moreover, since the switching of the slot allocation between their sensor terminals often occurs in the environment where numerous sensor terminals share the same bandwidth, the overhead of the guard time is considered to be bigger than that of the existing systems.

In Fig. 2, the transmission interval, T_{interval}, is equal to the sum of the size of time-slots allocated to other sensor terminals and their guard times as follows,

$$T_{\mathrm{interval}} = (N_{\mathrm{sensor}} - 1) \cdot (\mathrm{s} \cdot N_{\mathrm{slot}} + \alpha). \quad (1)$$

From Eq. 1, it is understood that increasing the number of slots allocated to each sensor terminal causes the increase of the transmission interval. If the interval becomes long, the repetition of data collecting from each sensor terminal will decrease. Increasing the number of slots for each sensor terminal results in the increase of the transmission interval, which causes the decrease of the real-time performance.

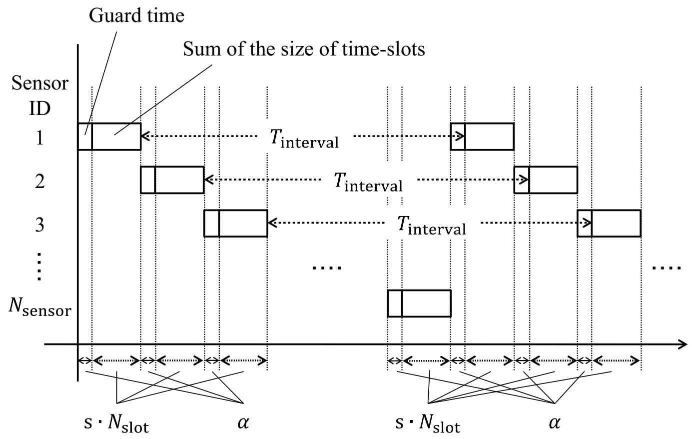


Fig. 2. An example of TDMA based on the fixed size time-slot.

B. Throughput of each sensor terminal

Firstly, we study the impact on the throughput of the number of time-slots allocated to each sensor terminal at once. Fig. 3 shows the example of different time-slot allocation where each of (a), (b), and (c) represents the case that the number of slots allocated is 1, 2, and 3, respectively. In the case of (a), the ratio of guard time in a constant time is higher than the cases of (b) and (c). As a result, data transfer time in (a) is shorter than that in (b) and (c). Thus, the throughput in (a) is also lower. Hence, the smaller number of slots allocated is, the lower throughput will be.

Secondly, we consider the throughput of each sensor terminal. Each sensor terminal is allocated to send data only within the allocated time-slots. The amount of data, d , which a sensor terminal can send at that time is formulated as follows,

$$d = \mathrm{s} \cdot N_{\mathrm{slot}} \cdot \mathrm{TR}, \quad (2)$$

where TR refers to the transmission rate of the sensor terminal. Since each sensor terminal sends the amount of data equal to d by rotation, the total amount of data collected in a cycle is $d \cdot N_{sensor}$. We define the throughput as the amount of data which can be transferred per unit time. Therefore, the throughput of each sensor terminal, θ, is expressed as follows,

$$\begin{aligned} \theta &= \frac{d}{N_{\mathrm{sensor}} \cdot (\mathrm{s} \cdot N_{\mathrm{slot}} + \alpha)} \\ &= \frac{\mathrm{s} \cdot \mathrm{TR}}{N_{\mathrm{sensor}} \cdot (\mathrm{s} + \frac{\alpha}{N_{\mathrm{slot}}})}. \end{aligned} \quad (3)$$

As implied in Eq. 3, increasing N_{slot} also increase each sensor terminal throughput. This is because many slots are allocated at the same time, the ratio of guard time in total time decreases. Thus, data transmission time for each sensor terminal increases, and the throughput of each sensor terminal also increases.

(a) One time-slot is allocated once.
(b) Two time-slots are allocated once.
(c) Three time-slots are allocated once.

Fig. 3. Different time-slots allocation methods.

C. Optimal number of time-slots allocated to a sensor terminal

From the analysis on the real-time performance and the throughput of each sensor terminal in the satellite-routed sensor system, it is understood that the real-time performance decreases, and throughput of each sensor terminal increases with the increase of the number of slots allocated to each sensor terminal. Hence, the real-time performance and the throughput of each sensor terminal are in a trade off relationship for different number of slots to each sensor terminal. Based on the given requirement of real-time performance, we can calculate the optimal number of the slots allocated to a sensor terminal to achieve the highest throughput.

IV. Result of Numerical Analysis

In this section, we aim to verify the relationship between the real-time performance and throughput of each sensor terminal in the satellite-routed sensor system. We describe how the number of slots allocated to each sensor terminal affects the real-time performance and throughput of each sensor terminal with some numerical calculation results.

A. Parameter settings

The parameter settings which define a satellite network managing numerous sensor terminals, are summarized in Table I. Suppose that the bandwidth allocation method is a TDMA-based system where the size of guard time is fixed to one fifth of that of a time-slot. Moreover, the number of time-slot allocated to each sensor terminal varies from 1 to 10, and the number of sensor terminals varies from 1,000 to 2,000 with a step size of 250.

B. Numerical results

Firstly, we study the relationship between the number of slots allocated to each sensor terminal and the throughput of each sensor terminal. Fig. 4(a) shows the throughput of each sensor terminal when the number of slots changes from 1 to 10 with different numbers of sensor terminals. From the Fig. 4(a), it is clear that the throughput of each sensor terminal increases with the increase of the slot number in the case of any number of sensor terminals. This is because the ratio of guard time within a constant time decreases when the number of the slots allocated to each sensor terminal increases. In addition, since more sensor terminals in a system needs more number of guard times, the throughput of each sensor terminal decreases when the number of sensor terminals increases.

Secondly, the length of the transmission interval of each sensor terminal is shown in Fig. 4(b). The longer transmission interval is, the worse the real-time performance will be. As shown in Fig. 4(b), the transmission interval increases with the increase of the number of slots. Consequently, the real-time performance decreases in that circumstance. This is because the increase of the number of slots for one sensor terminal gives long time to send data to each sensor terminal and increases the total time of one cycle to collect data from all sensor terminals. Moreover, the transmission interval becomes longer when there are more sensor terminals deployed in the network.

From these results, it is understood that the throughput of each sensor terminal increases and real-time performance decreases when the number of slots allocated to each sensor terminal at the same time increases. Thus, the trade-off relationship between the throughput of each sensor terminal and real-time performance is observed. Moreover, the optimal number of time-slots is defined so that it achieves the highest throughput while fulfilling the requirement of real-time performance of the system. For example, if the system needs to collect data from 1,000 sensor terminals in every half-second, the optimal number of slots is determined as 5, which keeps about 96 kbps as the throughput. In this way, it is possible to calculate the appropriate number of time-slots for the system to achieve the highest throughput according to the performance requirements.

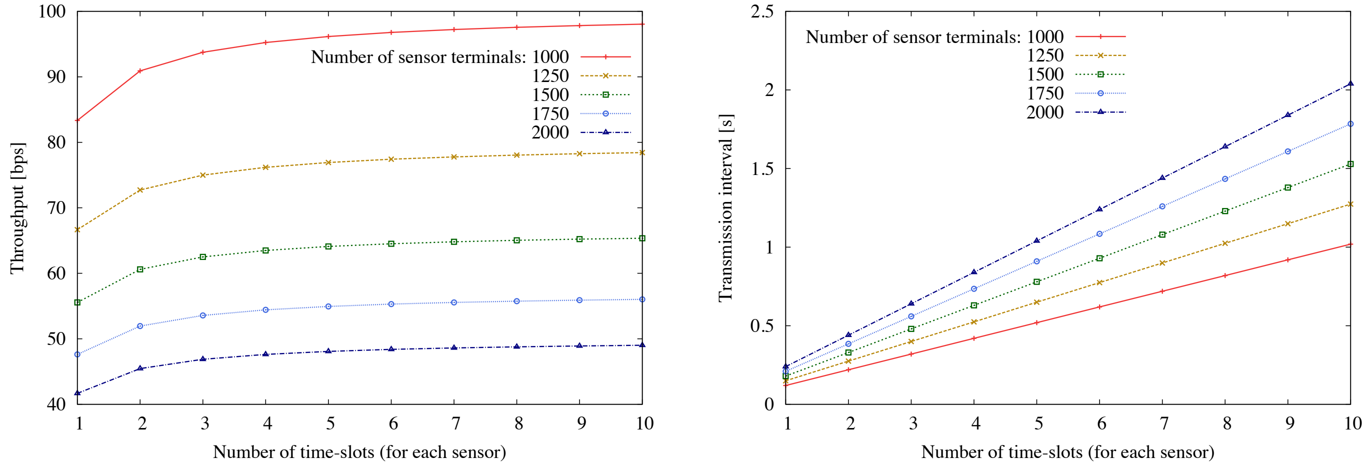
C. Discussion

It is noticed that in this paper we considered a single channel scenario and only the TDMA scheme is adopted for sensor terminal scheduling. Thus, it would be interesting to further extend the theoretical analysis developed in this paper to the multiple channel scenario where the FDMA could be adopted for sensor terminal scheduling.

On the other hand, The satellite network managing numerous sensor terminals is considered as the next generation SRSS. However, since the size of time-slot is set to a very small value to increase the system real-time performance, it is very hard to synchronize clocks of sensor terminals. It is because synchronizing needs to use a certain amount of data including the information of time. Therefore, an efficient way to manage numerous sensor terminals while achieving the synchronization is needed.

V. Conclusion

In this paper, we discussed the bandwidth allocation method for the next generation satellite-routed sensor systems (SRSSs). The SRSSs provide many services such as early disaster detecting and environment monitoring. In this research,



(a) Throughput vs. the number of slots. (b) Transmission interval vs. the number of slots.

Fig. 4. The impact of the number of time-slots on the throughput and transmission interval.

TABLE I
PARAMETER SETTINGS

Number of satellites	1
Number of sensor terminals	1000-2000
Time-slot	100μs
Guard time	20μs
Number of time-slots for each sensor terminals	1-10
Transmission rate of sensor terminals	100kbps

we prioritize real-time performance of data collecting in the networks which are consisting of numerous sensor terminals. Thus, we focus on the way to allocate satellite bandwidth to sensor terminals, and analyze how the number of time-slots allocated to each sensor terminal at the same time affects the throughput of each sensor terminal and real-time performance. The numerical results demonstrate that the throughput of each sensor terminal and real-time performance have a trade-off relationship. We confirmed that the optimal number of the slots can be determined to achieve the highest throughput of each sensor terminal while satisfying the requirement of the real-time performance.

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