Effective Data Collection via Satellite-Routed Sensor System (SRSS) to Realize Global-Scaled Internet of Things

Citation:

Yuichi Kawamoto, Hiroki Nishiyama, Zubair Md. Fadlullah, and Nei 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.

URL:

http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6515307

Effective Data Collection via Satellite-Routed Sensor System (SRSS) to Realize Global-Scaled Internet of Things

Yuichi Kawamoto, Hiroki Nishiyama, Zubair Md. Fadlullah, and Nei Kato

Graduate School of Information Sciences, Tohoku University, Sendai, Japan
E-mails: {youpsan, bigtree, zubair, kato}@it.ecei.tohoku.ac.jp

***Abstract*—Recently, the concept of Internet of Things, referred to as IoT, has drawn a great deal of research attention for realizing an intelligent society. The IoT is expected to comprise millions of heterogeneous smart "things" having sensor terminals, which may collect various types of information. By sending these collected information via IoT, it is possible to construct many smart systems, e.g., automatic prevention of traffic jam and so on. However, the coverage of IoT and the capacity of its ground networks are, still, not capable enough to connect the numerous devices and terminals deployed all over the world. Therefore, there is an urgent need for effective data collection in such systems. In this work, we focus on effective data collection by Satellite-Routed Sensor System (SRSS), which makes it possible to gather data from wide areas arbitrarily yet efficiently. However, multiple accesses from the numerous things to a satellite result in data collisions and increase the delay. For effectively resolving the problem of data collisions, we envision a new method, which utilizes a "divide and conquer" approach to collect data from the numerous things based upon demand. Also, we mathematically demonstrate how to optimize the operating time of our proposed. The effectiveness of our proposal is evaluated through numerical results.**

***Index Terms*—Divide and conquer, data collection, Internet of Things (IoT), and satellite-routed sensor system (SRSS).**

I. INTRODUCTION

The remarkable development of network environment and communication technologies 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 [1], [2]. 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) [3], [4]. The IoT is expected to comprise millions of heterogeneous smart things, having sensor terminals deployed over home appliances, cars, buildings, and so on [5]. Data collection from these sensor terminals via IoT can improve our lives and help build an intelligent society [6]. 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 [7].

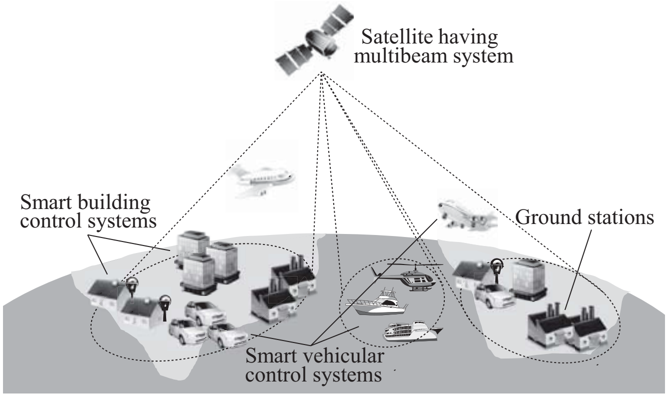


Fig. 1. An example of an SRSS used for facilitating the IoT.

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 [8]. 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 [9].

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 as depicted in Fig. 1. 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 [10], [11]. 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 [12]. 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.

In this paper, we propose a method to efficiently collect data from a large number of things, which have sensor terminals attached, 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 in IoT and minimizes the delay for the operating time in the system.

The remainder of this paper is organized as follows. The assumed network configuration of SRSS is presented in Section II. In addition, the existing access control method and their shortcomings are introduced in this section. Section III describes our proposed method to effectively collect data from numerous things by using a satellite. Section IV contains an analysis of the operating time in our proposed method. An analysis on waiting time of each sensor terminal is presented in Section V. Finally, concluding remarks are provided in Section VI.

II. NETWORK MODEL AND EXISTING ACCESS CONTROL METHODS

In this section, we introduce assumed network model for data collection. In this model, SRSS is utilized for realizing efficient data collection in IoT. In addition, the traditional access control methods which have been used for multiple-access communications are introduced. Moreover, the shortcomings of these existing methods when they are adopted to the supposed environment are described.

A. Network model for data collection in SRSS for IoT

We focus on the data collection in IoT by using SRSS. 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 [13], 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 [14], 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 paper, 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 [15]. In these types of generated data, we cannot 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 [16]. Therefore, we consider the system whereby numerous sensor terminals randomly access the satellite.

B. 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 2012 [17].

The conventional access control methods are classified into two groups, namely contention-based schemes and fixed assignment schemes. As a contention-based scheme, ALOHA [18] 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

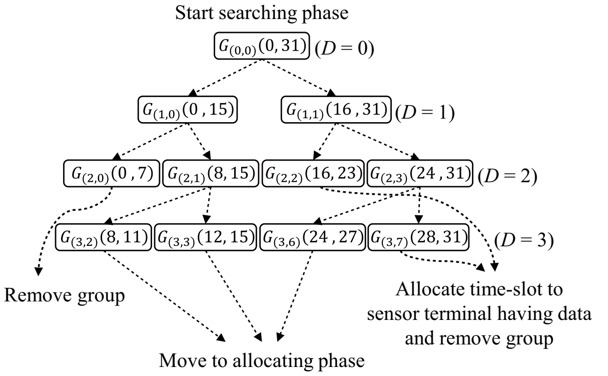


Fig. 2. An example of the flows to divide a number of sensor terminals into some groups (like a binary partition tree).

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 [19].

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.

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 in IoT.

III. AN EFFECTIVE DATA COLLECTION WITH A DIVIDE AND CONQUER APPROACH

In this section, we propose a new method to collect data efficiently in SRSS for the IoT. 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 our proposed method, the satellite collects data from the sensor terminals on-demand by a "divide and conquer" approach to avoid ineffective bandwidth allocation. Fig. 2 shows the example of the process-flow of our proposal in case that there are thirty two sensor terminals. In our proposal, the 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. 2, 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.

Algorithm 1 Proposed data collection algorithm

```
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
```

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 sensor terminals' buffer. We refer to this step as the allocating phase. In Fig. 2, the dividing process terminates at the third iteration, i.e., $D = 3$, and then the allocating phase starts.

The algorithm of our proposal is shown in Algorithm 1. 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

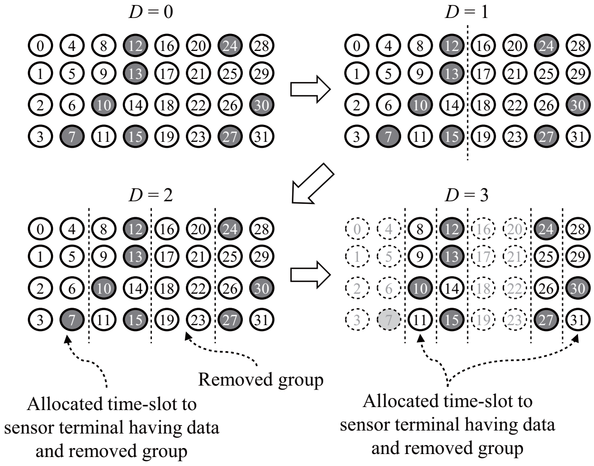


Fig. 3. An example of the processes involved in our proposal.

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. 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, 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 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 our 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 our 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.

IV. ANALYSIS ON OPERATING TIME

In this section, 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 our proposed method is expressed analytically.

A. Formulation of the operating time of our proposal

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 [20], 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.

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

where the rtt is expressed with altitude of satellite, h_sat, and light speed, c, as follows.

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

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.

$$\Delta_\mathrm{d}(D) = |\mathbb{S}(D)|\cdot t. \tag{3}$$

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.

$$P_{(N_\mathrm{RM}=1)}(D) = {}_{n(D)}C_1\cdot p\cdot(1-p)^{n(D)-1}, \tag{4}$$

where

$$n(D) = \frac{N_\mathrm{all}}{2^D}. \tag{5}$$

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

$$|\mathbb{S}(D)| = P_{(N_\mathrm{RM=1})}(D)\cdot G_\mathrm{r}(D). \tag{6}$$

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.

$$\Delta_\mathrm{a}(D) = n(D)\cdot G_\mathrm{r}(D)\cdot t. \tag{7}$$

B. Minimized total operating time of our proposal

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.

$$P_{(N_\mathrm{RM}\geq 2)}(D) = \sum_{k=2}^{n(D)}\left\{{}_{n(D)}C_k\cdot p^k\cdot(1-p)^{n(D)-k}\right\}, \tag{8}$$

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.

$$G_\mathrm{r}(D+1) = 2\cdot G_\mathrm{r}(D)\cdot P_{(N_\mathrm{RM}\geq 2)}(D). \tag{9}$$

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. 9, the number of the remaining groups (when the value of D equals that of D_opt) is expressed as follows.

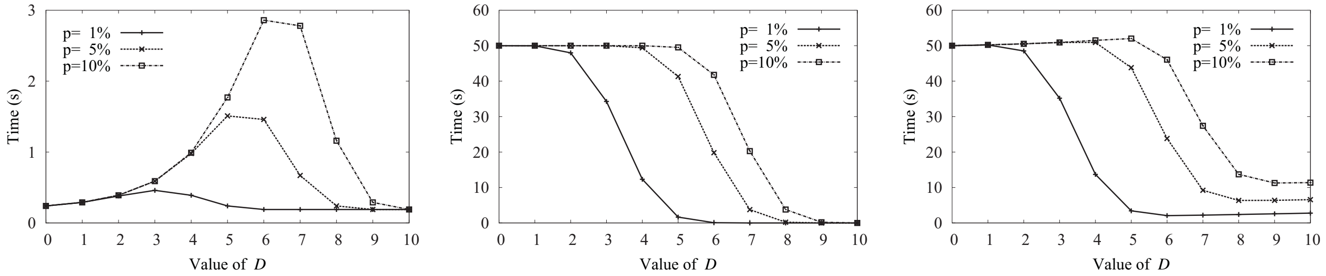
$$G_\mathrm{r}(D_\mathrm{opt}) = \prod_{D=0}^{D_\mathrm{opt}-1}\left\{2\cdot P_{(N_\mathrm{RM}\geq 2)}(D)\right\}. \tag{10}$$

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.

$$\Delta_\mathrm{t}(D_\mathrm{opt}) = \sum_{D=0}^{D_\mathrm{opt}-1}\{\Delta_\mathrm{s}(D)+\Delta_\mathrm{d}(D)\} + \Delta_\mathrm{a}(D_\mathrm{opt}). \tag{11}$$

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.

$$D_\mathrm{opt} = \arg\min_{D}\Delta_\mathrm{t}(D). \tag{12}$$



(a) The change of expected Δ_s. (b) The change of expected Δ_a. (c) The change of expected Δ_t.

Fig. 4. 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. Numerical results of the operating time of our proposal

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. 4 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.

From Fig. 4a, 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.

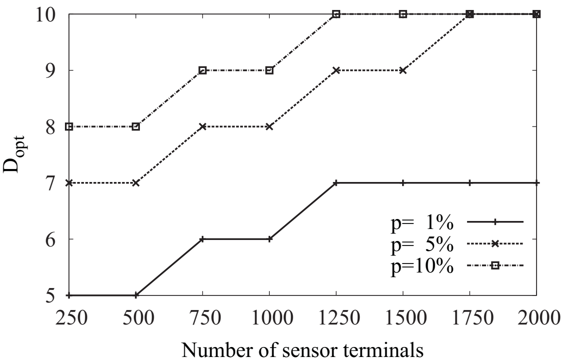


Fig. 5. The change of D_opt when the number of sensor terminals in the system is different.

In a similar way as shown in Fig. 4b, 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. 4c 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. 5 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. 5, 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.

V. ANALYSIS ON WAITING TIME OF EACH SENSOR TERMINALS

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.

A. *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 Eq. 13. The first term of Eq. 13 is introduced in [18] 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.

$$p_s = e^{-G}. \tag{14}$$

However, in [18], 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. 13. 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.

$$\begin{aligned} EW_{\mathrm{f}} &= \frac{1}{\{(N_{\mathrm{all}}+1)\cdot t\} - t} \cdot \int_{t}^{(N_{\mathrm{all}}+1)\cdot t} x dx \\ &= \frac{N_{\mathrm{all}}^2 - 1}{2 \cdot N_{\mathrm{all}}} \cdot t. \end{aligned} \tag{15}$$

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

$$\begin{aligned} EW_{\mathrm{s}} &= \frac{t}{2}\left(\frac{3+\omega}{p_s} - \omega\right) + \{rtt \cdot p_s \cdot (1-p_s) + 2 \cdot rtt \cdot p_s \cdot (1-p_s)^2 + 3 \cdot rtt \cdot p_s \cdot (1-p_s)^3 + \cdots\} \\ &= \frac{t}{2}\left(\frac{3+\omega}{p_s} - \omega\right) + \frac{1-p_s}{p_s} \cdot rtt. \end{aligned} \tag{13}$$

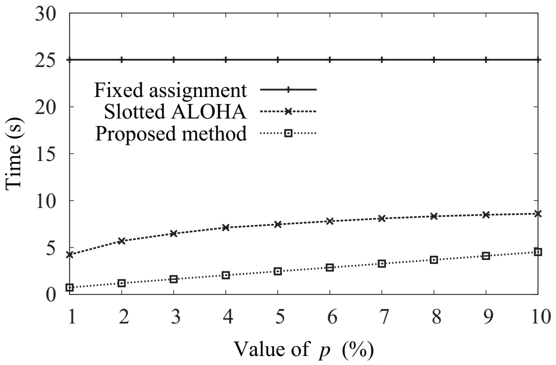


Fig. 6. The expectation value of the waiting time of TDMA-based fixed assignment scheme, slotted ALOHA, and our proposed method.

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 Eq. 16.

B. Numerical results of the Waiting time

Fig. 6 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 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.

$$G = \frac{p \cdot N_{\mathrm{all}} \cdot t}{\Delta_t}. \tag{17}$$

As shown in Fig. 6, 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.

VI. CONCLUSION

In order to realize the IoT 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 paper, we focused upon using satellites to communicate with many kind of things. 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 IoT. Toward this end, we proposed a new method to collect data efficiently from an arbitrary wide area in the IoT by means of SRSS. In our 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 our 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 like IoT, our proposed method makes it possible to collect data from them by avoiding ineffective bandwidth allocation and to decrease the operating time. Therefore, our proposed method realizes

$$\begin{aligned}
EW_{\mathrm{p}} =& \Delta_{\mathrm{s}}(0) \cdot P_{(N_{\mathrm{RM}}=1)}(0) \\
&+ \left\{ \Delta_{\mathrm{s}}(0) + \Delta_{\mathrm{s}}(1) + \frac{(1+|\mathbb{S}(1)|)\cdot t}{2} \right\} \cdot P_{(N_{\mathrm{RM}}\geq 2)}(0) \cdot P_{(N_{\mathrm{RM}}=1)}(1) \\
&+ \left\{ \Delta_{\mathrm{s}}(0) + \Delta_{\mathrm{s}}(1) + \Delta_{\mathrm{s}}(2) + \frac{(1+|\mathbb{S}(2)|)\cdot t}{2} \right\} \cdot P_{(N_{\mathrm{RM}}\geq 2)}(0) \cdot P_{(N_{\mathrm{RM}}\geq 2)}(1) \cdot P_{(N_{\mathrm{RM}}=1)}(2) + \cdots \\
&+ \left\{ \sum_{D=0}^{D_{\mathrm{opt}}} \Delta_{\mathrm{s}}(D) + \frac{(1+|\mathbb{S}(D_{\mathrm{opt}}-1)|)\cdot t}{2} \right\} \cdot \prod_{D=0}^{D_{\mathrm{opt}}-1} P_{(N_{\mathrm{RM}}\geq 2)}(D) \cdot P_{(N_{\mathrm{RM}}=1)}(D_{\mathrm{opt}}) \\
&+ \left\{ \sum_{D=0}^{D_{\mathrm{opt}}} \Delta_{\mathrm{s}}(D) + \frac{(1+n(D)\cdot G_{\mathrm{r}}(D_{\mathrm{opt}}))\cdot t}{2} \right\} \cdot \prod_{D=0}^{D_{\mathrm{opt}}} P_{(N_{\mathrm{RM}}\geq 2)}(D).
\end{aligned} \tag{16}$$

global-scaled IoT effectively with a significantly high real-time performance. 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.

ACKNOWLEDGEMENT

Part of this research belongs to "Research of communication control techniques in next generation satellite-routed sensor system," supported by National Institute of Information and Communications Technology (NICT).

REFERENCES

[1] I. F. Akyildiz, T. Melodia, and K. R. Chowdury, "Wireless multimedia sensor networks: A survey," *Wireless Communications, IEEE,*" vol. 14, no. 6, pp. 32–39, Dec. 2007.

[2] J. Pan, Y. Hou, L. Cai, Y. Shi, and X. Shen, "Topology control for wireless sensor networks," *Proc. ACM Int'l Conf. on Mobile Comp. and Netw. (MobiCom'03),* pp. 286–299, San Diego, California, USA, Sep. 14–19, 2003.

[3] L. Xu, L. Rongxing, L. Xiaohui, S. Xuemin, C. Jiming, L. Xiaodong, "Smart community: an internet of things application," *Communications Magazine, IEEE,* vol. 49, no. 11, pp. 68–75, Nov. 2011.

[4] L. Atzori, A. Iera, G. Morabito, "SIoT: Giving a Social Structure to the Internet of Things," *Communications Letters, IEEE,* vol. 15, no. 11, pp. 1193–1195, Nov. 2011.

[5] M. Zorzi, A. Gluhak, S. Lange, A. Bassi, "From today's INTRAnet of things to a future INTERnet of things: a wireless- and mobility-related view," *Wireless Communications, IEEE,* vol. 17, no. 6, pp. 44–51, Dec. 2010.

[6] H. Sungmin, K. Daeyoung, H. Minkeun, B. Sungho, J. P. Sang, J. Wooyoung, K. Jae–Eon, "SNAIL: an IP-based wireless sensor network approach to the internet of things," *Wireless Communications, IEEE,* vol. 17, no. 6, pp. 34–42, Dec. 2010.

[7] Shibo He, Jiming Chen, Yau, D. K. Y. Youxian Sun, "Cross-Layer Optimization of Correlated Data Gathering in Wireless Sensor Networks," *Mobile Computing, IEEE Transactions on,* vol. 11, no. 11, pp. 1678–1691, Nov. 2012.

[8] L. Jing, X. Yang, C.L.P. Chen, "Authentication and Access Control in the Internet of Things," *Distributed Computing Systems Workshops (ICDCSW), 2012 32nd International Conference on,* pp. 588–592, 18–21 Jun. 2012.

[9] 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),* 25–27, Oct. 2012.

[10] H. Nishiyama, Y. Tada, N. Kato, N. Yoshimura, M. Toyoshima, and N. Kadowaki, "Toward Optimized Traffic Distribution for Efficient Network Capacity Utilization in Two-Layered Satellite Networks," *IEEE Transactions on Vehicular Technology,* to appear.

[11] M. Shimada, T. Tadono, and A. Rosenqvist, "Advanced Land Observing Satellite (ALOS) and Monitoring Global Environmental Change," *Proceedings of the IEEE,* vol. 98, no. 5, pp. 780–799, May 2010.

[12] I. Bisio and M. Marchese, "Efficient Satellite-Based Sensor Networks for Information Retrieval," *Systems Journal, IEEE,* vol. 2, no. 4, pp. 464–475, Dec. 2008.

[13] H. Nishiyama, D. Kudoh, N. Kato, and N. Kadowaki, "Load Balancing and QoS Provisioning Based on Congestion Prediction for GEO/LEO Hybrid Satellite Networks," *Proceedings of the IEEE*, no. 99, pp. 1–10.

[14] R. Miura, T. Tanaka, I. Chiba, A. Horie, Y. Karasawa, "Beamforming experiment with a DBF multibeam antenna in a mobile satellite environment," *Antennas and Propagation, IEEE Transactions on,* vol. 45, no. 4, pp. 707–714, Apr. 1997.

[15] S. Tozlu, M. Senel, M. Wei, A. Keshavarzian, "Wi-Fi enabled sensors for internet of things: A practical approach," *Communications Magazine, IEEE,* vol. 50, no. 6, pp. 134–143, Jun. 2012.

[16] R. D. Gaudenzi, O. R. Herrero, "Advances in Random Access protocols for satellite networks," *Satellite and Space Communications, 2009. IWSSC 2009. International Workshop on,* pp. 331–336, 9-11, Sep. 2009.

[17] H. H. Choi, S. H. Lee, D. H. Cho, "Hybrid access scheme based on one-phase preamble and channel monitoring/assignment for satellite communications," *Communications Letters, IEEE,* vol. 8, no. 2, pp. 96–98, Feb. 2004.

[18] Y. Yang, T. S. P. Yum, "Delay distributions of slotted ALOHA and CSMA," *Communications, IEEE Transactions on,* vol. 51, no. 11, pp. 1846–1857, Nov. 2003.

[19] E. Casini, R. D. Gaudenzi, O. R. Herrero, "Contention Resolution Diversity Slotted ALOHA (CRDSA): An Enhanced Random Access Scheme for Satellite Access Packet Networks," *Wireless Communications, IEEE Transactions on,* vol. 6, no. 4, pp. 1408–1419, Apr. 2007.

[20] Y. Kawamoto, H. Nishiyama, N. Kato, N. Yoshimura, N. Kadowaki, "Assessing packet delivery delay in multi-layered satellite networks," *Communications (ICC), 2012 IEEE International Conference on,* pp. 3311–3315, 10–15, Jun. 2012.

Yuichi Kawamoto received his B.E. in Information Engineering from Tohoku University, Japan, in 2011. Currently, he is pursuing M.S. degree in the Graduate School of Information Science (GSIS) at Tohoku University. He was awarded the Satellite Communications Research Award in the fiscal year of 2011 from the Institute of Electronics, Information and Communication Engineers (IEICE). He is recipient of Japan Society for the Promotion of Science (JSPS) in 2013. His research interests are in the areas of satellite networks and sensor networks. He is a student member of IEEE.

Hiroki Nishiyama received his M.S. and Ph.D. in Information Science from Tohoku University, Japan, in 2007 and 2008, respectively. He was a Research Fellow of the prestigious Japan Society for the Promotion of Science (JSPS) until the completion of his PhD, following which he went on to become an Assistant Professor at the Graduate School of Information Sciences (GSIS) at Tohoku University. He was promoted to his current position of an Associate Professor at GSIS in 2012, when he was just 29 years old. He was acclaimed with the Best Paper Awards in many international conferences including IEEE's flagship events, namely the IEEE Wireless Communications and Networking Conference in 2012 (WCNC'12) and the IEEE Global Communications Conference in 2010 (GLOBECOM'10). He is a young yet already prominent researcher in his field as evident from his valuable contributions in terms of many quality publications in prestigious IEEE journals and conferences. He was also a recipient of the IEICE Communications Society Academic Encouragement Award 2011 and the 2009 FUNAI Foundation's Research Incentive Award for Information Technology. He received the Best Student Award and Excellent Research Award from Tohoku University for his phenomenal performance during the undergraduate and master course study, respectively. His research covers a wide range of areas including traffic engineering, congestion control, satellite communications, ad hoc and sensor networks, and network security. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), and he is also an IEEE senior member.

Zubair Md. Fadlullah (S'06-M'11) received B.Sc. degree in Computer Science from the Islamic University of Technology (IUT), Bangladesh, in 2003, and M.S. and Ph.D. degrees from the Graduate School of Information Sciences (GSIS), Tohoku University, Japan, in 2008 and 2011, respectively. Currently, he is serving as an Assistant Professor at GSIS. His research interests are in the areas of smart grid, network security, intrusion detection, and quality of security service provisioning mechanisms. Dr. Fadlullah was a recipient of the prestigious Deans and Presidents awards from Tohoku University in March 2011.

Nei Kato (A'03-M'04-SM'05-F'13) received his Bachelor Degree from Polytechnic University, Japan in 1986, M.S. and Ph.D. Degrees in information engineering from Tohoku University, Japan, in 1988 and 1991, respectively. He joined Computer Center of Tohoku University at 1991, and has been a full professor with the Graduate School of Information Sciences since 2003. He became Special Assistant to the President of Tohoku University since 2013. He has been engaged in research on satellite communications, computer networking, wireless mobile communications, smart grid, image processing, and pattern recognition. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He currently serves as the Vice Chair of IEEE Ad Hoc & Sensor Networks Technical Committee, the Chair of IEEE ComSoc Sendai Chapter, the steering committee member of WCNC and a voting member of GITC, an editor of IEEE Wireless Communications(2006-), IEEE Wireless Communications(2006-), IEEE Network Magazine(2012-), IEEE Transactions on Wireless Communications(2008-), IEEE Transactions on Vehicular Technology(2010-), and IEEE Trans. on Parallel and Distributed Systems(TPDS). From 2013, he also serves as an Associate Editor-in-Chief of TPDS. He has served as the Chair of IEEE Satellite and Space Communications Technical Committee(2010-2012), the Chair of IEICE Satellite Communications Technical Committee(2011-2012), guest-editor of many IEEE transactions/journals/magazines, a symposium co-chair of GLOBECOM'07, ICC'10, ICC'11, ICC'12, Vice Chair of IEEE WCNC'10, WCNC'11, ChinaCom'08, ChinaCom'09, Symposia co-chair of GLOBECOM'12, ICC'14, and workshop co-chair of VTC2010. His awards include Minoru Ishida Foundation Research Encouragement Prize(2003), Distinguished Contributions to Satellite Communications Award from the IEEE Communications Society, Satellite and Space Communications Technical Committee(2005), the FUNAI information Science Award(2007), the TELCOM System Technology Award from Foundation for Electrical Communications Diffusion(2008), the IEICE Network System Research Award(2009), the IEICE Satellite Communications Research Award(2011), the KDDI Foundation Excellent Research Award(2012), IEICE Communications Society Distinguished Service Award(2012), IEEE GLOBECOM Best Paper Award(twice), IEEE WCNC Best Paper Award, and IEICE Communications Society Best Paper Award(2012). Besides his academic activities, he also serves on the expert committee of Telecommunications Council, Ministry of Internal Affairs and Communications, and as the chairperson of ITU-R SG4 and SG7, Japan. Nei Kato is a Distinguished Lecturer of IEEE Communications Society(2012-2014) and the co-PI of A3 Foresight Program(2011-2014) funded by Japan Society for the Promotion of Sciences(JSPS), NSFC of China, and NRF of Korea. He is a fellow of IEEE and IEICE.