Sustainable Wildlife DTN: Wearable Animal Resource Optimization through Intergenerational Multi-hop Network Simulation

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***Abstract*—The Green Internet of Things (IoT) is studied for environmental monitoring, including ecological surveys of wild environments with insufficient electricity, transportation, and communication infrastructure. However, an environmental monitoring method that does not require human intervention is needed because of the inability of replacing batteries during a long-term operation. We focus herein on a carrier pigeon-like sensing system (CPSS) for wildlife monitoring without human intervention. Its agent can be used for any animals and centralize wildlife in the system. This method requires the regular input of animal carriers; hence, the population growth through reproduction may affect the ecosystem during a long-term operation. In particular, a trade-off exists by maintaining system availability and minimizing impact on biodiversity. This study aims to solve the trade-off issue by comparing multiple input scenarios considering intergenerational multi-hop networks. "Intergenerational" is defined when individuals of different release periods encounter each other, and the communication devices wake up to transfer the sensing data of each individual. In the simulation performed herein, the probability of intergenerational multi-hop networks is high, even in the scenario where the number of input animal carriers is high while the number of breeding individuals is suppressed. In this study, we solve the trade-off issue on the animal-to-animal data sharing mechanism, which is important in sustainable wildlife monitoring in terms of the availability of the Green IoT system and impact on biodiversity.**

***Index Terms*—green internet of things, delay-tolerant networks, wildlife, animal, sustainability, monitoring, simulation**

I. Introduction

Monitoring methods in wild environments are poorly studied, and such harsh environments hinder human access, leading to insufficient infrastructure of electricity, transportation, and communication. A wild environment is deficient of such infrastructures; thus, special monitoring devices are required in the actual operation. The device size and weight, in which most of the weight comes from its battery, should be considered to maintain service considering, for instance, the lack of transportation.

In an urban environment, various objects are connected to the Internet under the concept of the Internet of Things (IoT), and environmental information have been retrieved by several studies [1], [2]. In the contrary, retrieving wild environmental information by connecting objects to the Internet (Green IoT [3]) has been rarely studied compared with the urban environment. Providing electricity and communication in a wild environment (e.g., vast national parks, forests, mountainous areas, and under the sea) is very expensive, demanding both research budget and human resources.

Regardless of the implementation difficulty of the Green IoT [3], this technology is essential. In March 2011, the Great East Japan Earthquake affected the Fukushima Daiichi Nuclear Power Plant (F1NPP). The succeeding nuclear accident led to the spread of a huge radioactive contamination around the plant. The evacuation zone remains inaccessible to the public; however, environmental monitoring in the zone must somehow be conducted.

This paper is structured as follows: Section I describes the challenges and necessity of environmental monitoring methods in wild environments; Section II describes the existing research on environmental monitoring methods using the delay-tolerant networks (DTN) and an animal-to-animal data sharing mechanism that solves the unique challenges of wild environments; Section III presents the proposed animal release method for individuals wearing wearable devices that focus on an intergenerational multi-hop network; Section IV describes the setup of the simulation for experiments and experimental results; Section V discusses the effect of the individual survival rate, animal-to-animal data sharing mechanism, availability of time-sensitive network systems, and design of a wild environment monitoring system with effective use of natural resources;

978-1-6654-2854-5/21/$31.00 ©2021 IEEE

finally, Section VI concludes the research contributions.

This paper is a series of studies focusing on solving the problems for the realization of the animal-to-animal data sharing mechanism. Therefore, our previous studies must be cited as long as to explain the background and the history of this research.

II. Related Study

A. Previous research on environmental monitoring methods using the DTN technology

This study focuses on a method of wild environment monitoring technology using the DTN [4]. The DTN realizes reliable data transfer, even in "weak" communication environments consisting large transmission delays. It also uses a store-and-forward method for data transfer. Several previous studies have already been conducted for wild environment monitoring using the DTN technology. In [3], Shaikh et al. defined the Green IoT as a data collection attempt for monitoring forest fires using the IoT sensors. In addition, Tovar et al. [5] also used the message ferry method using wild deer, whereas Toldov et al. [6] improved multi-hop communication in a wild environment. With these circumstances, we attempt herein to monitor a wild environment using the DTN technology.

Existing methods are not suitable for the wild environment targeted in this study. For example, in [5] after collecting the environmental information served by wild deer, the sensing nodes should be picked up by human entry of patrolling in the wild environment to retrieve data. This human intervention poses a high demand to researchers, as described in Section I. In addition, even when human intervention is not presumed, as in the case in [6], the connection between the nodes should always be maintained. This limits the system to operate in wide and vast areas as nodes can rarely be in proximity to each other. Insufficient electrical and communication infrastructures cannot compensate for this disadvantage; thus, using such a system in a wide land for a long time is hopeless.

Based on the abovementioned existing research, the technical requirements for a sustainable system free from human intervention during the system operation should be clarified.

B. Power Saving Research for the Data Sharing Function

In a DTN research, the technical requirements meet those of a sustainable system free from human intervention during the operation. The research includes an animal-to-animal data sharing mechanism or a carrier pigeon-like sensing system (CPSS) [7]. In the CPSS, an animal carrier with a wearable environmental sensor serves as a terminal node, and the nodes consist of a peer-to-peer connection. Figure 1 presents the detailed system descriptions and shortly describes the CPSS, in which the following processes are described:

1) Sensing: collecting environmental information at a solo trip;
2) Data sharing: wireless multi-hop data transfer between individuals at group activities; and
3) Touch'n Go at Home: uploading data to a server when an individual returns the communication range of a mobile carrier network.

The combination of these three methods enables the collection of environmental information in the wild environment for a long period of time without human intervention. Therefore, this system is idealistic in terms of sustainability, as defined in Section I.

However, an issue must be solved to realize the system in operation.The system is completely autonomous; hence, once the system is activated, there is little way to intervene with the released nodes; that is, the energy consumption should be extensively considered for the nodes to be active. The data sharing function requires the near-field communication to be constantly energized to transfer the collected data between the animal carriers, which increases the power consumption and inhibits the devices to operate for a long time, considering that the battery replacement is unexpected. In our previous research [8], we proposed animal-to-animal data sharing process using animal behavior (Figure 2) for power saving and conducted field experiments using four dogs raised at Azabu University [9] and domestic cattle around the F1NPP to verify the method effectiveness [8].

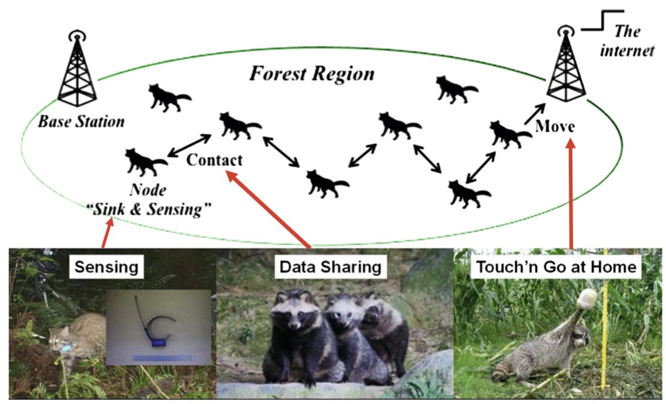

Fig. 1. Concept image of the carrier pigeon-like sensing system (CPSS) [7].

C. Wearable animal resource optimization for sustainable long-term monitoring to overcome the life span of animal carriers

However, the long-term operation of the CPSS cannot only be achieved by focusing on power saving. The duration in which a node is active depends on the life span of the animal carriers. Wild environments are less hygienic, and carriers are more susceptible to temperature and climate changes and more frequently exposed to dangers not found in urban environments, such as the presence of predators. As a result, for example, the life span of a raccoon in captivity is reported to be approximately 10 years [10], whereas this is reported to be approximately 2–3 years only in the wild [11], which is about a quarter shorter. Consequently, the life span of a wild animal is sometimes shorter than the battery life. In such a

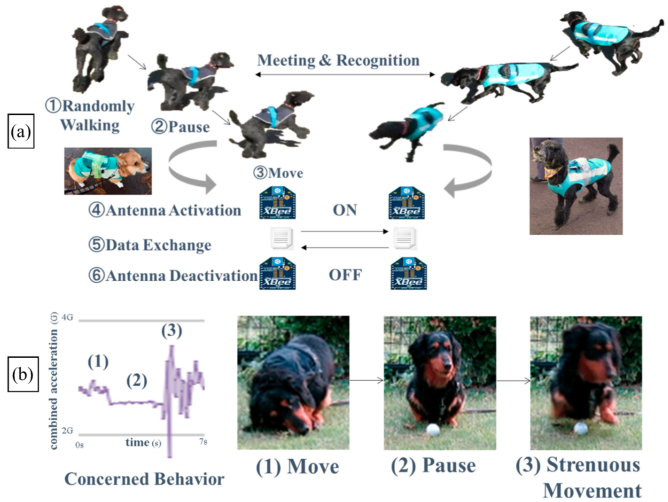

Fig. 2. (a) Animal-to-animal data sharing process (1–6). (b) Reaction state of dogs to the peripheral stimuli ((1)–(3)) [8].

case, when the device is still active, the interaction between animal carriers still occurs, but data transfers may no longer be anticipated. To compensate for this inevitable dropout, researchers must complement the nodes into the targeted area.

In our previous study [12] [13], we proposed a node employment model for a sustainable communication platform using Green IoT devices (Figure 3). We simulated the release of the same number of agents per time and compared them to determine the most encountered model in different release numbers. In the existing simulation, we applied the reproductive information obtained from the raccoon ecology yielded at a national park in Ontario, Canada. The properties include life span, linear distance, speed, and population density. Thus, the most effective release scenario for sustainable monitoring is concluded.

D. Motivation: Long-term operation of the system and impacts on biodiversity

As described in Section II-C, continuously releasing multiple animal carriers in the targeted area is necessary to realize a sustainable data sharing mechanism for a long-term operation. However, the number of compensatory released nodes should be ecologically and operationally minimized. In this study, the targeted animal was assumed to be a vermin, like a raccoon, with a very high reproduction ratio.

If excessive number of animal nodes are released, the population could exponentially grow and significantly affect the surrounding biodiversity. The number of released animal nodes cannot simply be reduced because of the following reasons: i) it diminishes the number of encounters with other animal nodes and ii) it diminishes the number of released animals that return to the base station.

As described in this section, a trade-off exists between the long-term operation of the system and the impact on biodiversity. Therefore, a method that achieves the data sharing function must be achieved (Figure 1: center), with the minimum population growth of the released animal species. We focus herein on the data sharing function.

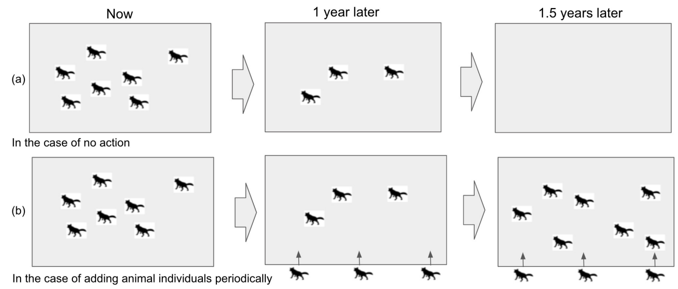

Fig. 3. State transition of the density of wild animals in the cases of (a) no action and (b) periodically adding animal carriers [12].

III. Proposed Method

We propose a minimum recruit model of animal carriers, including multiple raccoon generations. This model considers intra- and intergenerational multi-hop networks under the minimum population growth. This study aims to solve the trade-off problem for sustainable data sharing from an ecological perspective.

To solve this trade-off problem, we focus on the intergenerational multi-hop network, with which the batteries on the animal carriers and the carrier animals themselves have a limited lifetime, albeit the data on the network being persistently contrasting. In this paper, the term "intergenerational" is used to define the state when individuals of different release periods encounter each other, and the communication devices wake up to transfer the sensing data of each individual; "intragenerational" on the other hand refers to that when individuals of the same release periods encounter and successfully communicate with each other (Figure 4). When data are transferred to a longer life span carrier, such as a young animal, it enables the sustainment of the sensing data for a longer time and makes it feasible to share the data over generations.

We describe the efficiency of sensing data collection in intergenerational multi-hop network. Assuming that the number of animal carrier released during the study period is n times and the number of animal carriers released per release is m individuals, the total number of animal carriers released during the study period is mn individuals. To collect the sensing data of the released animal carriers, it is necessary for the released animal carriers to return to the communication area of the mobile network as described in Section II. Here, we calculate the theoretical minimum number of returning individuals required to collect all the data from mn released individuals. The following is a comparison of the minimum number of returning individuals in a scenario where only intragenerational data transfer occurs and a scenario where intragenerational and intergenerational data transfer occur.

1) Intragenerational multi-hop network: n individuals
2) Intragenerational and intergenerational multi-hop network: 1 individual

In the scenario of intragenerational multi-hop network, sensing data cannot be transferred to animal carriers at different release times, so it is necessary for one of the animal carriers at each release time to return. In particular, if the number of times the animal carriers are released is n during the study period, then n individuals must return. On the contrary, in the scenario of intragenerational and intergenerational multi-hop network, sensing data can be transferred to young animal carriers at different release times; hence, sensing data can be collected if at least one animal carrier returns regardless of the number of releases. From the above scenario, intragenerational and inter-generational multi-hop network will result in $1/n$ times the number of returning animal carriers compared to intra-generational multi-hop network. Therefore, intergenerational multi-hop network can improve the efficiency of sensing data collection.

Based on these considerations, the resource optimization model with a low population growth and a high intergenerational data transfer probability is examined in Section IV. We prioritize the low population growth relevant to ecological damage.

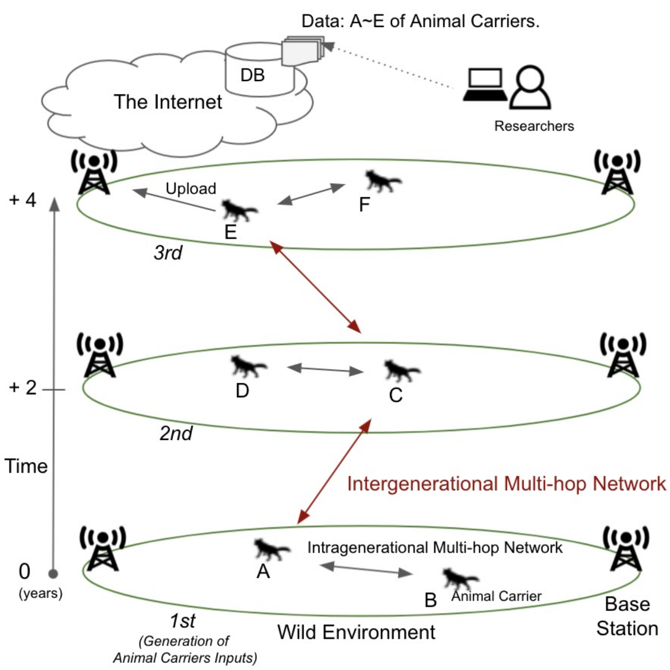

Fig. 4. System overview using the intergenerational multi-hop network.

IV. Experiments and Results

A. Simulation Setup

We used the multi-agent simulation platform Artisoc version 4.2 (5.0) created by Kozo Keikaku Engineering, Inc. [14]. Tables I and II present the simulation parameters following those in [13].

We prepared two types of agents: Agents A and B (Table I). Agent A simulated the animal carrier at the time of capture; hence, its age was set to 18 months. On the contrary, Agent B denotes breeding individuals in nature; thus, the age was set to 0 month. The other properties were common between the two agents. In this model, the two agents simultaneously coexisted in the field. Note that only the number of Agent B increases over time because it simulates the breeding dynamics of a natural raccoon. Agent A decreases over time until a new release because it represents the animal attached to the sensor, which cannot inherit its sensor for the next generation. In other words, if Agent A could reproduce the next generation, her children should be treated as Agent B. While only Agent A carries the information, the existing number of Agent A has a greater interest.

TABLE I
Parameters of the agent used in the simulation based on the biological studies of a raccoon.

	Agent parameters	
	Agent A	Agent B
Age (month)	18	0
Max. remaining life (month)	42	60
Speed (m/h)	55.9	
Distance of encounter	Less than 50 m	
Walking direction	Randomly changed per 1.54 km	

The evaluation period was set to 10 years. The number of breeding sessions was set to once at the end of year. The reproduction ratio per female individual was set to 2. The considered reproductive rate was 66% in the yearling individual and 96% in adults. For the litter size, it was 3.6 in yearlings and 3.9 in adults [15]. The reproduction ratio taken at this experiment was justified as 3.6×0.66 of a yearling individual. Note that the reproduction session happened once in this experiment; thus, the litter size was equal to the reproduction ratio. The male/female ratio was 1:1 (Table II).

To identify the optimal resource model described in Section III, we compared the proposed scenarios shown in Table III. The release was executed once in every 2 years because the life span should overlap between the animal carriers of the current release and those of the preceding release. In addition, the release period cannot be shorter or longer than 2 years to prevent the agent from experiencing multiple breeding periods.

Using the proposed method, we released four individuals once in every 2 years for Scenario 1, 6 individuals for Scenario 2, 8 individuals for Scenario 3, and 10 individuals for Scenario 4. The simulation was conducted thrice and averaged over those three ensemble members to conclude the study.

B. Experimental results

Table IV shows the total population and intergenerational data transfer probability. While the existing population of animal carrier differed, the number of intergenerational encounters between the scenarios cannot be directly compared. Thus, the number of such encounters was normalized over existing individuals. The total population after 10 years contained Agents A and B.

Consequently, when comparing the ensemble average of each scenario, Scenario 2 resulted in an average number of in-

TABLE II
GENERAL ENVIRONMENTAL PARAMETERS USED IN THE MULTI-AGENT SIMULATION.

	General parameters
Area	$100\,\mathrm{km}^2$
Evaluation period	10 years
Step size (in Artisoc)	10 min
Breeding frequency	Once in every end of year
Reproduction ratio	Two per female
Sex ratio (M/F)	1/1

TABLE III
PARAMETERS OF EACH INPUT SCENARIO.

	Inputs of animal carriers (per 2 years)	(10 years)
Scenario 1	4	20
Scenario 2	6	30
Scenario 3	8	40
Scenario 4	10	50

tergenerational encounters that was approximately 1.85 times higher than that of Scenario 1. The total number of individuals at the end of 10 years was approximately 0.97 times lower than that in Scenario 1. On the contrary, the average number of intergenerational encounters was approximately 2.5 times higher than that for Scenarios 3 and 4 compared with Scenario 1. Furthermore, the total number of individuals at the end of 10 years was approximately 1.77 (Scenario 3) and 2.11 (Scenario 4) times higher than that for Scenario 1. The simulation results indicated that Scenario 2 was the best resource model with a low population growth rate and a high probability of the intergenerational multi-hop network for individual wildlife species during a long-term operation.

V. DISCUSSION

A. Effect of the individual survival rate

As shown in Figure 5, Scenarios 1 and 2 exhibited cases that active transmission nodes dropped to zero in nature. This means that no active nodes existed in the field at the time of the next release of the sensor node. This result illustrates the possibility that the monitoring data cannot be recovered 10 years after starting the experiment. Once such a case happens, even if the researcher releases new animal carriers after the time of extinction, there would be no chance to recover the preceding monitoring data because the carrier with the previous data is no longer active in the wild. In short, the survival rate of individuals is critical in this long-term operating system, as well as the number of inputs of the animal carriers described in Section II-D. This simulation proved to force a very conservative choice of scenarios.

This simulation proved that the survival rate of individuals is a factor affecting the intergenerational transfer and population growth ratio. Thus, to realize a long-term intergenerational multi-hop network, gentle care of the subject at the capture and release is specially required to increase the survival rate of the subject and the possibility of data recovery.

TABLE IV
RESULT OF EACH SCENARIO.

	Intergenerational encounters (per capita)		Individuals after 10 years	
Scenario 1	9.6	(1.00)	162.3	(1.00)
Scenario 2	17.8	(1.85)	157.7	(0.97)
Scenario 3	24.6	(2.56)	287.3	(1.77)
Scenario 4	24.2	(2.52)	344.0	(2.12)

The numbers in parentheses depict the ratio per scenario 1.

B. Animal-to-animal data sharing mechanism

To collect a wide range of environmental information in the wild environment over a long period of time, an animal-to-animal data sharing mechanism [8] was proposed, in which individual wild animals are equipped with wearable sensors to collect a large amount of data over a long period of time. This section describes the details of the animal-to-animal data sharing mechanism, which was already outlined in Sections I I-B and II-C. Specifically, after a collar-type wearable sensor is attached to a captured wild animal, and the animal is returned to the wild environment, the collar-type wearable sensor is used to sense the environmental information when the wild animal is acting alone. This is mutually done. When one of the animal carriers enters an area where humans can enter (within the communication range of the base station), the data of the animal carriers are uploaded to the server by a mechanism called Touch'n Go at Home. This method makes it possible to acquire extensive and long-term data in the wild environment, which is difficult because of the high workload of researchers.

C. Availability of time-sensitive network systems

When evaluating the availability of access in monitoring data through an end-to-end transfer via the DTN, only the spatial node distribution was discussed in the previous studies [13]. As described in Section II-A, the DTN technology was used in a weak communication environment and did not presume the establishment of an end-to-end connection, thus being robust to a big time lag in data transfer.

This study discusses the long-term operation of the CPSS with a very limited number of animal carriers similar to the realistic monitoring environment due to biodiversity concerns, with which the monitoring nodes should be minimized. As mentioned in Section V-A, with the existence of a small number of transferring nodes, the system availability critically depends on the single individual because no data recovery should be anticipated afterward once the existing nodes are completely lost throughout the monitoring period. Thus, to evaluate the system availability depending on the end-to-end communication, only studies from spatial perspectives are insufficient, but studies from a temporal perspective are required. We describe the following factors affecting the system availability described in Section V-A, as originally discussed in [13]:

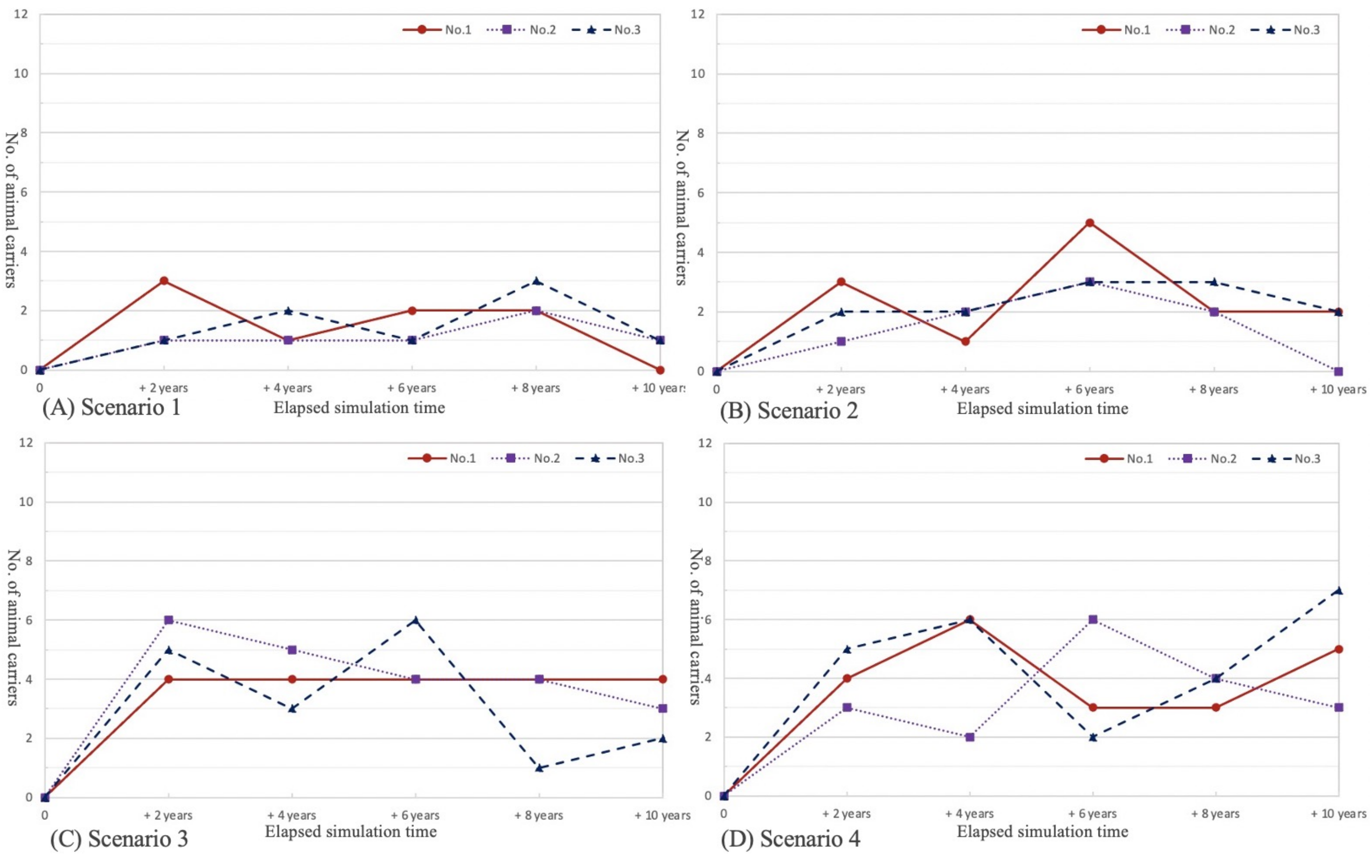

Fig. 5. Number of Agent A existing in the wild just before the release of new node; (A) Scenario 1, (B) Scenario 2, (C) Scenario 3, and (D) Scenario 4 are the experimental results on each scenario. Lines represent the experimental results on each ensemble member.

1) Individual encounter probability;.
2) Communication success probability; and
3) Data transfer efficiency.

As discussed in [13], we omitted items 2) and 3) and discusses item 1) here. Item 1) includes intra- and intergenerational encounter probability. The higher the number of nodes released at a time, the higher the chance of an intragenerational encounter. Furthermore, the more frequent the nodes are released, the higher the chance of an intergenerational encounter. We have mentioned herein the minimum of releasing nodes by a probabilistic study.

Maintaining the system availability and minimizing the impact to the ecosystem are the trade-offs explained in Section II-D. This probabilistic research illustrates the minimum sufficient number of releasing nodes to maintain the system availability, which minimizes ecological impact.

D. Design of the wild environment monitoring system with effective use of natural resources

The Green IoT has been used in various fields; however, as described in Section I, it is typically used in the field of wild life monitoring because studies have faced various issues, regardless of technological advances, caused by the extremely different environment compared with urban cities. The primary reasons are communication, battery capacity, and power supply sources for recharging the battery.

This study focuses on the CPSS or animal-to-animal data sharing mechanism. The mechanism works regardless of human intervention from data collection and data recovery, because animals wear a data collection device, and the wild animal carriers autonomously act for the data transfer between nodes and the base station and for the battery recharge. Although some issues still exist in the data sharing function, existing studies [13] and the present paper have provided a solution, making sustainable long-term environmental monitoring available, even in areas where human access is limited and power and communication infrastructure is poor.

As a new direction for the Green IoT, we proposed herein a wild environment-friendly monitoring method that effectively uses wild resources. The previous environmental monitoring methods introduced with fixed sensors and fixed-point cameras were suitable for use in urban environments regularly maintained by humans. Once these systems are operated in nature, they result in a variety of problems, as discussed with relevance to battery or power issues and device maintenance issues. The automated device recapturing technique is being considered. In the first place, we have proposed herein the CPSS to realize a long-term and effective research.

VI. Conclusion

This study solves the trade-off issue (i.e., availability of the system and impact on biodiversity) using the proposed animal release scenarios for wearable device-wearing individuals, focusing on intergenerational multi-hop network in Section III. In Section IV, we simulated and validated the four methods shown in Table III in terms of the probability of the intergenerational multi-hop network and the number of breeding individuals. The results showed that Scenario 2 resulted in an average number of intergenerational encounters, which was approximately 1.85 times higher than that in Scenario 1. The total number of individuals at the end of 10 years was approximately 0.97 times lower than that in Scenario 1. The abovementioned results illustrated that the issue of the trade-off between the system availability and the impact on biodiversity, which is an issue in the existing research, was solved by the animal release scenario of the wearable device-wearing individuals, focusing on the intergenerational multi-hop network.

Acknowledgment

This study was supported by JSPS KAKENHI Grants (18H04089 and 21H04886) and Tateisi Science and Technology Foundation.

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