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A Power-Aware Air Interface Scheduling Scheme for Improving Network Connectivity in Solar Powered Wireless Mesh Networks

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***Abstract*—Recently, many large-scale natural disasters, such as earthquake and tsunami occur all over the world. One of the major problems after a disaster is the damage caused to the communication and power infrastructure, such as damaged base station and power grid. As a result, disaster victims are unable to communicate with outside area for an extended period of time. Therefore, it is essential to deploy a communication network, which can operate even without power supply or infrastructure. In this paper, we focus on Wireless Mesh Networks (WMNs), which consists of Solar Powered Base Station (SPBS) equipped with air interfaces. These WMNs can be promptly setup. However, because the power generated from solar panel is easily affected by weather condition, it is insufficient and unstable. Additionally, because the power consumption is affected by the distance between the SPBSs and the number of wireless links in each SPBS, it is difficult to maintain network connectivity in the WMNs that are consisted of SPBSs. Therefore, to address the network connectivity problem in the assumed network, we aim to reduce the power consumption of the wireless links by controlling the on-off cycle of air interfaces. We first analyze the network connectivity issue in disaster area and formulate this problem, and propose the on-off scheme of controlling the wireless links of air interfaces based on graph theory. Simulation results of our proposal show that our proposed scheme can ensure the network connectivity.**

I. Introduction

In recent years, large-scale natural disasters, such as the Great East Japan Earthquake and Tsunamis on March 11, 2011, has devastated the telecommunication infrastructure and power grid, caused scarcity in electricity, and limited the ability to communicate with outside areas [1] [2]. As a result, a large number of people who were left behind in the disaster area could not communicate with the others outside the area for over an extended period of time. Therefore, it is necessary to setup some temporary telecommunication network in the disaster area. The Wireless Mesh Network (WMN) is suitable for the disaster areas due to its flexibility [3] [4]. The WMN consists of many base stations, which connect wirelessly with each other using mesh topology. Moreover, in order to power such networks, researchers' attention have been focused on renewable energy from environmental sources, such as sun and wind. As an example, authors in [5] have focused on developing disaster resilient regional platform WMNs, named NerveNet. NerveNet is a regional wireless access platform comprised of base stations powered by renewable energy sources, in which multiple service providers provide their services by sharing the use of the network, enabling a range of context-aware services. It acts like a human nervous system, which enables a reliable and managed WMN. The assumed network consists of the base stations equipped with a solar panel or the Solar Powered Base Station (SPBS). The SPBSs can operate autonomously with the energy generated from the equipped solar panel. Additionally, the SPBSs are also equipped with air interfaces, making it possible to establish links between the remote SPBSs to send and receive data. Fig. 1 shows an example of WMN consisting of SPBSs, which are equipped with air interfaces. The air interface of each SPBS is directional antenna, and can operate independently. Therefore, each SPBS can reduce power consumption by halting the operation of the unnecessary air interface. There are a lot of shelters in the disaster areas, but it is often found that some shelters are unusable due to the damage caused to the building after a disaster. Therefore, it is possible that there are large distances between the shelters. However, under such situation, disaster victims can communicate between the shelters by using SPBS equipped with directional air interfaces. In Japan, Nippon Telegraph and Telephone (NTT) has developed the Movable and Deployable Resource Unit (MDRU), which is the prototype of SPBSs. The MDRUs are compact unit like car or attache case, which contained equipment necessary to offer

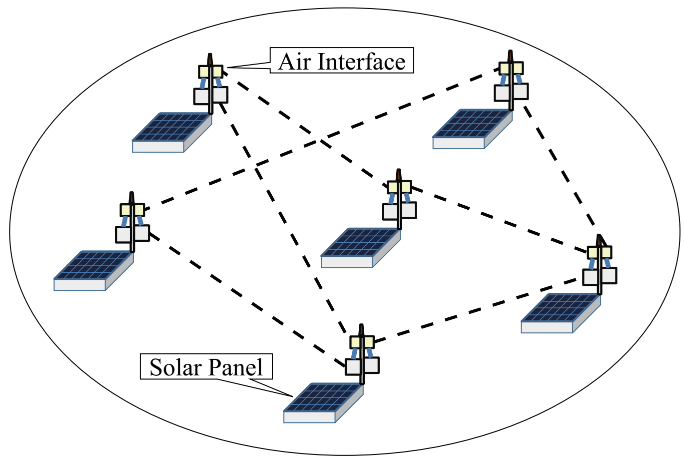


Fig. 1: WMN composed of SPBSs equipped with air interfaces.

Information and Communication Technology (ICT) services, such as the Internet or information processing. With WMN deployed, people within the disaster area can communicate even though the existing communication networks and energy infrastructures are unavailable. In disaster areas, a WMN can be easily setup using multiple SPBSs. After the WMN is setup, it is possible to attempt safety confirmation, make a phone call (VoIP), exchange disaster information, send e-mail, and share the location information by using the disaster victims' mobile devices, such as smartphones or personal computers. Additionally, people within the disaster area can browse the Web and exchange e-mail through the internet from their device by connecting their devices to one of the SPBSs that has connectivity to the Internet. One critical issue is the simultaneous desire of users to communicate with others outside the area through real-time applications. Moreover, in disaster areas where the majority of the population are worried about the safety of the family and friends, users focus more on real-time application such as voice call in order to connect with users outside their area. However, the energy generated from the equipped solar panel is easily influenced by weather conditions due to the geographic distribution of the SPBSs [6].

With the variation of the amount of energy available from environmental sources, researchers and engineers have focused on various sleep mechanisms of base stations for an efficient use of the available energy resources in WMN powered by renewable energy. Some authors [7] focus on the synchronization-based sleep approach in cases where the traffic pattern is the same in several cells in the network, or in cases where base stations are not densely deployed, such as remote and disaster areas, where communication operator have less incentive to deploy many base stations. Therefore, in order to extend network coverage to disaster areas, we focus on the synchronization-based sleep approach to guarantee a network that enables real-time application such as voice call among users. In our assumption, each SPBS can be 100m-10km away. Therefore, it is difficult to ensure the network connectivity because the transmitting power increase by the distance between SPBSs. In addition, the directional air interfaces equipped in the SPBSs can work independently. However, it is necessary to control how much energy is used in each SPBS, because the power consumption increases with the number of wireless links that are used. From these two reasons, the network is unstable and insufficient. Therefore, the SPBSs have two states, active and sleep state. Thus, to ensure a stable network connectivity, it is necessary to control the number of wireless links depending on the situation. We propose an on-off scheme, which consider the distance between the SPBSs, and the number of wireless links of each SPBS in order to cope with the unstable and inadequate power generation. The remaining sections are organized as follows. Section II describes issues in the assumed network. In Section III, the assumed WMN consisting of the SPBSs and the problem formulation in this research. In addition, our proposed on-off scheme, which focuses on the influence of the power consumption by the distance between the SPBSs and the number of wireless communication links, is introduced in Section IV. In Section V, the simulation results are presented. Finally, the paper is concluded in Section VI.

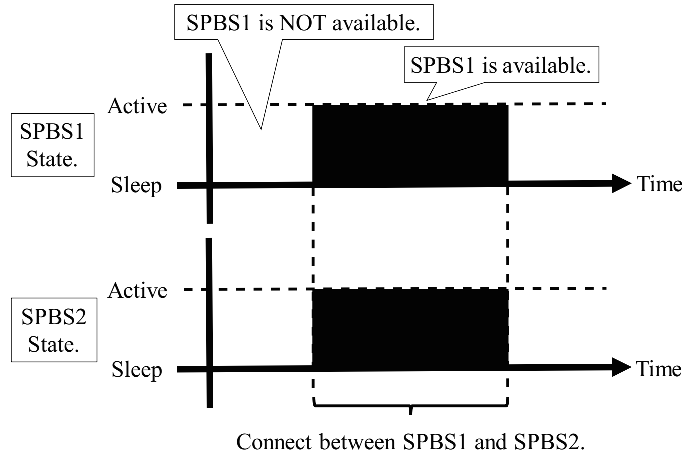


Fig. 2: The change of state of SPBSs.

II. Assumed Network Issues

In a disaster area, users focus more on real time application such as voice call for the safety confirmation of a family and friend. Therefore, it is necessary to provide a network that enables real time application such as voice call among users. However, because there is unevenness in the power that each SPBS has to operate with the power that are generated in the WMN, SPBS's operation time is not balanced, and the network can easily be disconnected. Therefore, we focus on sleep mechanism of base stations for an efficient use of the available energy resources in WMN powered by renewable energy. The sleep mechanism is namely the synchronization-based sleep approach, where all base stations comprising the network are switched to ON or OFF simultaneously. Fig. 2 shows the change of state of SPBSs in the synchronization-based sleep approach. Users can communicate each other in the network between ON by switching ON and OFF of SPBSs simultaneously. However, two critical issues occur by all SPBS operating and constructing the network simultaneously. One is that distance between SPBSs and number of links greatly influences the power consumption in our assumed WMN. The other is that because SPBS always generates the power from solar panel, when the use of the power is controlled, the power that exceeds battery capacity is wasted. Therefore, it is necessary to construct the network considered these issues. We propose a method to improve connectivity of the whole network by controlling the wireless links of air interfaces. In the assumed network, it is necessary to reduce the power consumption by minimizing distance cost in order to maintain connectivity of the whole network. However, number of links do not exceed number of air interfaces. Additionally, it is necessary that SPBS that electricity is beyond, links more. Therefore, each SPBS satisfies the following condition:

1) The number of links from each SPBS do not exceed number of air interfaces.

2) The remaining energy of each SPBS exceeds threshold value.

It is thought to improve the network connectivity by constructing topology that consider these conditions. Therefore, we

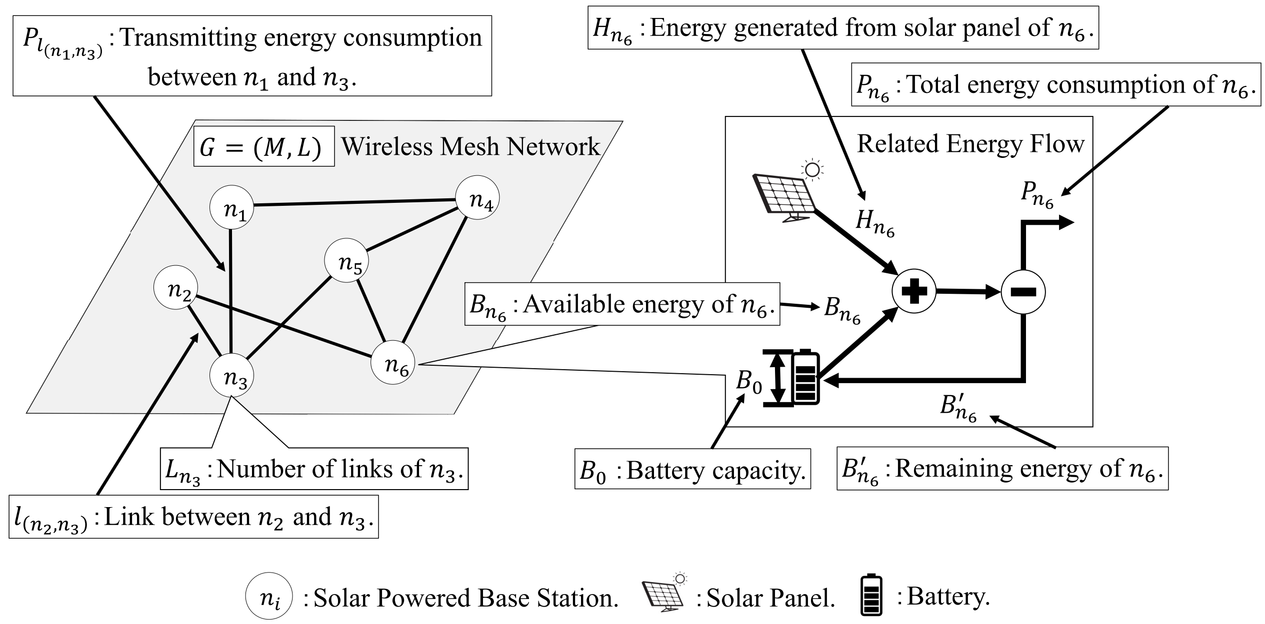


Fig. 3: Model of WMN and related energy flow of SPBSs.

propose the network model and proposed scheme satisfying these conditions.

III. System Model

In this section, we explain the related assumptions about the WMN consisting of the SPBSs. In addition, we describe the considered network model in detail.

A. System Assumption

Our assumed network consists of the SPBSs. In this network, because each SPBS is wirelessly connected and there is a significant distance between the SPBSs geographically, propagation loss by wireless communication is considered. In short, transmission power increases depending on the distance between the SPBSs to maintain the network connectivity. We explain the assumed network and energy relations such as harvesting, consumption, and storage as follows:

1) Network and system structure:
Firstly, we deploy the SPBS equipped in the shelters and construct the WMN in the disaster area. Additionally, SPBSs also work as wireless access points and provide communication service to a number of people within the disaster area. Additionally, all SPBSs are also equipped with solar panels and rechargeable batteries for deployment in disaster area without the need of power infrastructure. Moreover, all SPBSs have several directional air interfaces, which are used to establish communication links between each SPBS. We assume that each SPBS periodically switches between the two states of active and sleep for energy management. The SPBS operates depending on the amount of the generated energy and the energy consumption, or the scheduling policy of the sleep state. Therefore, the SPBSs switch between active and sleep state over time. In active state, the SPBS operates and can wirelessly communicate with other SPBS by enabling several directional air interfaces of which the power consumption of each is independent. On the other hand, because the SPBS shuts down and stops all wireless communication in sleep state, the energy consumption decreases and it can recharge its battery in sleep state. Therefore, both SPBSs must operate to communicate. Thus, because the links have to be established to conduct real time communication with the user of the purpose, all of the SPBSs must be in the active state. Therefore, we define that all SPBSs are synchronized in active time and sleep time. The active time slot is a certain time interval when the SPBS must be active state.

2) Energy harvesting:
The energy harvesting that comes from SPBSs equipped solar panel said to be the input energy. Each SPBS is in different location, thus, having different amount of energy generation time wise by the changing weather conditions. However, the input energy can be estimated preliminarily by combining the history of the weather condition and the weather forecast because the energy harvesting for each SPBS is determined by factors such as illumination, intensity and so on. The related work of energy provision and prediction can be found in [8] [9]. We assume that the weather profiles for energy harvesting are known.

3) Energy consumption:
We consider that the shelters are scattered spatially due to the crack in the ground and collapse of buildings in earthquake-stricken area. When wireless communication is performed in this area, there is attenuation by the distance between the shelters. We assume that the necessary transmission power is increased by the distance during SPBS.

B. Wireless Mesh Network Model

Fig. 3 shows an example of the considered model of WMN. In this model, we use an undirected graph $G = (N, L)$ to denote the network topology. We assume that N is the number of existing SPBSs in the disaster area, and let $N = \{n_1, n_2, \cdots, n_m\}$ be the set of these SPBSs, where $\mid N \mid = m$. Denote u as the number of air interfaces of SPBS. Let L represent the set of interconnection links between SPBSs, and $L_{n_i}(t)$ is the number of links of SPBS n_i in t. Additionally, $l_{(n_i,n_j)}(t) \in L$ is the link between n_i and n_j. Moreover, t is the length of timeslot in active state of SPBS, where $l_{(n_i,n_j)}(t)$ is a boolean variable and it satisfies:

$$l_{(n_i,n_j)}(t) = \begin{cases} 1, \text{if link between } n_i \text{ and } n_j \text{ is active during } t \\ 0, \text{otherwise} \end{cases} \tag{1}$$

When the link between n_i and n_j is inactive in t, ($l_{(n_i,n_j)}(t) = 0$), it is cut off and there is no energy consumption in t. Eq. 1 demonstrates that the link is available if the antennas both n_i and n_j are active. Thus, there can be energy consumption which is determined by the number of activated links.

C. Energy Harvesting Model

We define the amount of energy harvesting that comes from the solar panel of SPBS n_i in t as $H_{n_i}(t)$. We assume that the amount of energy harvesting $H_{n_i}(t)$ changes according to weather condition.

D. Energy Consumption Model

We consider the transmission power between SPBSs because it affects the essence of our assumed situation. Let $P_{n_i}(t)$ be the total energy consumed by SPBS n_i in t. Let $P_{l_{(n_i,n_j)}}(t)$ be the transmitting power consumption between n_i and n_j, where $P_{n_i}(t)$ can be calculated as follows:

$$P_{n_i}(t) = \sum_{k=1}^{N} P_{l_{(n_i,n_k)}}(t) \cdot l_{(n_i,n_k)}(t). \tag{2}$$

Additionally, let L_B be the propagation loss, G_T be the transmitting air interface gain and G_R be the Reception air interface gain. Then, L_B can be calculated as follows:

$$P_{l_{(n_i,n_k)}}(t) = 10^{(\frac{L_B - G_T - G_R}{10}) - 3}. \tag{3}$$

Moreover, let $D_{(n_i,n_j)}$ be the distance between n_i and n_j and λ be the wavelength of the radio wave output from an air interface. Then, L_B can be calculated as follows:

$$L_B = 10 \log(\frac{4\pi D_{(n_i,n_k)}}{\lambda})^2. \tag{4}$$

E. Energy Storage Model

In order to store the remaining harvested energy, each SPBS is equipped with a battery that has finite capacity. Let $B_{n_i}(t)$ describe the available energy of n_i's battery at the beginning of t, and $B'_{n_i}(t)$ denote the remaining energy of n_i's battery at the end of t. $B'_{n_i}(t)$ equals $B_{n_i}(t)$ plus the amount of energy harvesting in t and minus the consumed energy in t:

$$B'_{n_i}(t) = B_{n_i}(t) + H_{n_i}(t) - P_{n_i}(t). \tag{5}$$

The battery capacity of SPBSs is B_{max}, and B_{min} is the lower limit threshold value. Therefore $B_{n_i}(t)$ should satisfy the following constraint:

$$B_{min} \leq B_{n_i}(t) \leq B_{max}. \tag{6}$$

Algorithm 1 Proposed scheme

while True **do**
  Make the Minimum Spanning Tree (MST) from distance between n_i and n_j;
  Figure out the energy consumption $P_{n_i}(t)$ for each n_i according to equation (2);
  Calculate the remaining energy $B'_{n_i}(t)$ for each n_i according to equation (5);
  if $u \leq L_{n_i}(t) \mid\mid B'_{n_i}(t) \leq B_{min}$ **then**
    Cut off $l_{(n_i,n_j)}$ of $max(D_{(n_i,n_j)})$;
    Update $G(N, L)$;
  end if
end while
return $G(N, L)$, $B'_{n_i}(t)$
Connect the links so as not to fall below a threshold value B_{min} for each n_i

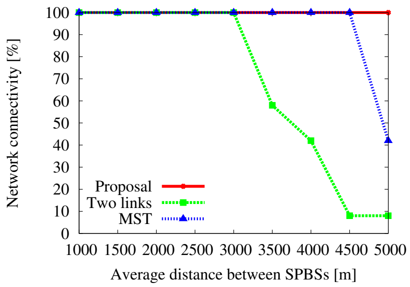
Fig. 3 shows the relation of the energy harvesting, the energy consumption, and the energy storage.

IV. Proposed Scheme

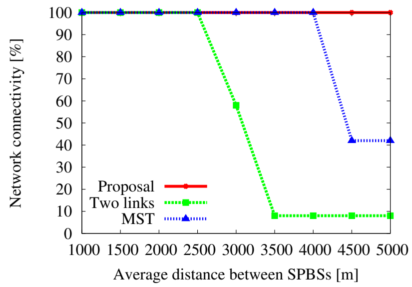
In this part, we introduce our proposed on-off scheme to decide the on-off cycle of links of each SPBS. Algorithm 1 shows a process of using SPBSs to construct the network topology. Thus, each SPBS uses this algorithm to construct the topology. This algorithm ensures communication path from each SPBS to other SPBSs by considering remaining energy of each SPBS and distance between SPBSs, and the SPBSs that have much remaining energy improve the network redundancy by increasing number of links. When we apply the cost of node, remaining energy that each SPBS has and the cost of edge, distance between SPBSs to graph theory, the optimization problem in consideration of both is NP-complete. Therefore, we aim to ensure network connectivity by using graph theory to make Minimum Spanning Tree (MST), and improve the redundancy of the network by increasing number of links. To achieve this goal, we propose a scheme that can ensure the network connectivity by controlling the on-off cycle of the air interfaces in active timeslot, and construct flexible network. Firstly, in our algorithm, each SPBS makes MST from the distance between SPBSs. This is solved by using the shortest path problem. Secondly, after the topology is constructed, each SPBS figures out its total energy consumption $P_{n_i}(t)$, and calculates its remaining energy $B'_{n_i}(t)$ at the end of active timeslot. If $B'_{n_i}(t)$ is not more than the threshold value or $L_{n_i}(t)$ is more than number of air interfaces, SPBS that does not satisfy the condition cuts off the link with the longest distance in connecting the links, and each SPBS reconstructs MST from the graph except for links that are cut. If according to the condition, each SPBS repeats construction of MST and cannot construct MST, each SPBS uses MST which is constructed last even if the MST do not satisfy the condition. After that, when SPBS has a remaining energy $B'_{n_i}(t)$ exceeds a threshold value, the SPBS connects the links so as not to fall below a threshold value and exceed number of air interfaces.

V. Performance Evaluation

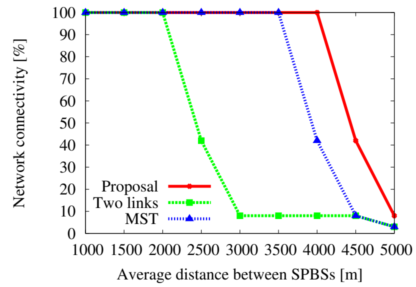
In this section, we evaluate the performance of our proposed scheme in terms of the network connectivity. In our



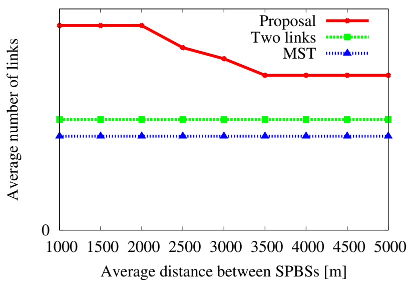
(a) The network connectivity ratio of sunny scenario.



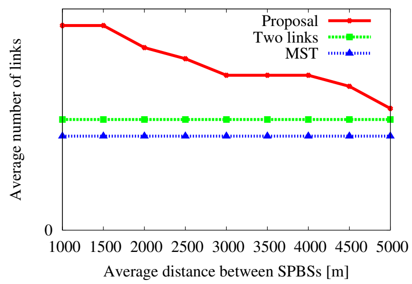
(b) The network connectivity ratio of cloudy scenario.



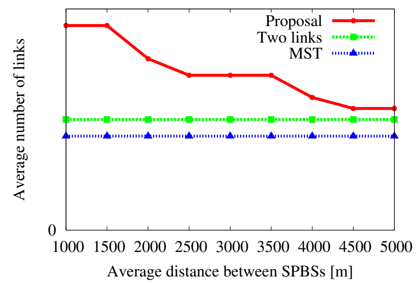
(c) The network connectivity ratio of rainy scenario.



(d) The average number of links of each SPBS of sunny scenario.



(e) The average number of links of each SPBS of cloudy scenario.



(f) The average number of links of each SPBS of rainy scenario.

Fig. 4: Performance evaluation results

proposed scheme, we show that the high network connectivity is maintained and the links are thick without dependence on the weather condition.

A. Evaluation Metric

In order to evaluate the performance of our proposed on-off scheme, we introduce an evaluation metric, namely, network connectivity ratio, which measures the network connectivity. Once the topology is constructed, each SPBS can communicate with SPBS that is connected. However, because the energy of each SPBS is limited, it is impossible for SPBS to work forever, thus resulting in disruption of network topology until the next topology construction. Each SPBS constructs a graph by using the distance information that is calculated from the geographical position relationship with the other SPBS. Network connectivity ratio demonstrates the network connectivity of this graph and is calculated as the percentage of the SPBS pairs that can communicate to the total number of SPBS pairs in the network. A SPBS pair (n_i, n_j) represent whether there exists a path from n_i to n_j or not. Denote C as the network connectivity ratio of a given network topology, and N is the set of SPBSs, C can be calculated as follows:

$$C = \frac{\sum_{n_i, n_j \in N} c_{(n_i, n_j)}}{|N|(|N|-1)}, \tag{7}$$

where

$$c_{(n_i,n_j)} = \begin{cases} 1, \text{if } n_i \neq n_j \text{ and } (n_i, n_j) \text{ is connected} \\ 0, \text{otherwise} \end{cases} \tag{8}$$

TABLE I: Performance Parameters

Parameter	Value
Number of SPBSs (N)	9
Battery capacity (B_0)	100kJ
Amount of energy harvesting (H)	30, 20, 10W
Transmitting and Reception air interface gain (G_T, G_R)	35dB
Wavelength (λ)	0.125mm
Number of air interfaces for each SPBS (u)	4
Threshold value of remaining energy (B_{min})	20kJ
Timeslot (t)	2hours

B. Parameter Setting

We set the number of SPBSs, N SPBS , to 9, and arrange the SPBSs linked structure. We calculate the distance between SPBSs, and set them as $D_{(n_i,n_j)}$. The amount of energy harvested in each SPBS, $H_{n_i}(t)$, depends on three patterns of weather condition: sunny, cloudy and rainy, because the shelters are geographically scattered. The amount of power generated is changed among three values: 30W, 20W, and 10W. The maximum battery capacity, B_0, is 100kJ and each SPBS's available battery change within the range of 0 to B_0 and the initial value of B_0 assumes maximum value. We set the transmitting air interface gain, G_T, to 35dB, and set the reception air interface gain, G_R, to 35dB, and set the wavelength of the radio wave output from an air interface, λ, to 0.125mm (2.4GHz). Additionally, we set the timeslot, t, to 2hours (7200 seconds). We assume that the radio wave interference between each SPBS does not spring from air interfaces because each SPBS's equipped air interfaces are high directional antennas. In this work, we attempt our proposed scheme for each number of deployable SPBSs. To evaluate effectiveness of our proposed scheme in various network states, we change the average distance between SPBSs. A number of people within disaster area tend to use particular applications such as safety confirmation, and is restricted on the applications that they can use. However, we assume a constant data traffic since it does not affect the essence of our consideration. We assume that the WMN is constructed with a central focus on the evacuation center.

C. Numerical Results

Fig. 4(a) to Fig. 4(c) show the results of the network connectivity to three patterns of weather conditions: sunny, cloudy and rainy, to the average distance between SPBSs. According to their results, when the weather condition is good, when the average distance between SPBSs is long, they maintain the high network connectivity ratio. As the average distance between SPBSs is long, transmission power of each SPBS increase and the link is easy to cut off. However, because the energy harvesting amount generated from a solar panel is much, it is thought that the high network connectivity ratio is maintained. As the weather condition is bad, the expected results of the network connectivity ratio are achieved by our proposed scheme and the traditional scheme, and they are different. When the average distance is longer, although the network connectivity ratio tends to decrease together, we find out that our proposed scheme is the same or more than that of the traditional scheme. In addition, when the average distance between SPBSs is long, the high network connectivity ratio is maintained. Because the traditional scheme does not consider the amount of power that each SPBS has and the distance between SPBSs, when the average distance between SPBSs is longer, the power disappears and the link is easy to cut off. However, because our proposed scheme consider them, even if the average distance between SPBSs is longer, it is thought that the network connectivity ratio is maintained by controlling the link.

Fig. 4(d) to Fig. 4(f) show the results of the average number of links of each SPBS to three patterns of weather conditions: sunny, cloudy and rainy, to the average distance between SPBSs. According to these results, when the weather condition is good, each SPBS have multiple connected links, and they connect with respect to one another. When the average distance between SPBSs is long, the average number of links each SPBS of our proposed scheme is more than that of the traditional scheme. This is because there is much energy harvesting amount generated from a solar panel, it is thought that each SPBS provides many links. Additionally, even if the weather condition is bad, the average number of links each SPBS of our proposed scheme is more than that of the traditional scheme. This is because each SPBS can have the power margin by controlling the link, although there is little energy harvesting amount generated from a solar panel. Thus, it is said to use the available energy resources efficiently by using our proposed scheme. Finally, in this simulation, although the initial value of each SPBS's battery assumes maximum value, it is thought to expect a similar result even if the available energy of each SPBS is unevenness.

VI. Conclusion

In disaster areas, the network that can operate without existing infrastructures is necessary. In this paper, we focus on WMNs that consist of the SPBS. The assumed network can provide a number of people within disaster areas with means of communication in disaster situations. However, because the power supply from the solar electric generation is easily affected by weather condition, it is insufficient and unstable, thus resulting in communication blackout. In order to maintain the network connectivity, we aim to improve the network connectivity by controlling the on-off cycle of air interfaces, and have proposed an on-off scheme, which considers the power consumption affected by the distance between the SPBSs and the number of wireless links in each SPBS. We firstly analyzed the network connectivity issue in disaster area, formulated the problem, and proposed the on-off scheme of controlling the air interfaces by considering remaining energy of each SPBS and distance between SPBSs. Simulation results of our proposal showed that our proposed scheme can ensure the network connectivity and connect the links. We consider the topology construction method for the intermittent operation and real-time operation of SPBSs as future work.

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