Field Measurement of an Implemented Solar Powered BS-based Wireless Mesh Network

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Abstract—Developing effective communications infrastructure, i.e., Base Station (BS) based communication system, in "off-grid" locations without electricity (such as rural areas without power grid, areas affected by disasters, and so forth) is a challenging research area in the information and communication technology (ICT) sector. Since the users of such areas usually exhibit demands for stable communication (e.g., mail service with constant delivery delay, voice call service with consistent quality, and so on), the BSs require to operate to utilize available resources under an energy-constricted environment. With the absence of power grid in rural regions and the occurrence of power outage in disaster-stricken areas, ambient energy sources such as solar and wind energy have become viable alternatives to power the BSs. These energy harvesting BSs, however, have to confront the variable behavior of the ambient energy sources that lead to variable amounts and rates of energy available over time. In this article, we present our considered Wireless Mesh Network (WMN) exploiting solar energy harvesting BSs, and conduct a study based on field experiments to estimate the factors which influence their energy harvesting capability. Particularly, the results of our conducted experiments demonstrate that the ON/OFF states of the radio links have a direct impact on the power consumption of the BSs. Also, the manner in which the amount of solar radiation during different weather conditions over different days affects the array voltage in an energy harvesting BS is investigated.

Index Terms—Renewable energy source, energy harvesting BS, wireless mesh network.

I. INTRODUCTION

During the last decade, there has been a remarkable shift in the communication networks market. The continuously growing demand for mobile phones has triggered the rapid expansion of the information and communication technology (ICT) industry, which comprises the largest network on earth with over five billion subscribers [1]. Unfortunately, many people still lack the access to this fundamental service. Approximately 95% of the global population live in rural areas without power grid [2], and therefore, they are unable to enjoy stable communication service. The primary reason for their inability to access the power grid (and consequently the communication service) is economic; power is the fundamental cost in any ICT infrastructure deployment, dominating both the capital and operating costs of rural networks. The International Telecommunications Union indicated that 50% of the operating expenditure cost for rural network is power [3]. In addition, the installation of wired backhaul interconnecting Base Stations (BSs) such as optical fiber is considerably expensive; thus, there is no incentive for operators to make the large infrastructure investments in poor and rural areas [4]. Moreover, the disruption of power supply and the damage of wired transmission lines due to natural disasters (e.g., earthquake, tsunami, hurricane, and so forth), leading to the disruption of telecommunication services (e.g., cellular networks, third generation (3G), long term evolution (LTE) services, and Internet infrastructures), have become a big challenge to be addressed in ICT [5]. Thus, providing communication services in rural areas with limited power infrastructure, and in areas affected by disasters is a challenging issue, which needs to be effectively addressed by researchers and engineers. In order to mitigate the high expenses in the deployment of wired backhaul in rural areas, or to construct disaster zone networks [5], researchers have to focus on exploiting alternate technology, namely the Wireless Mesh Networks (WMNs). The WMNs present an attractive choice for these purposes due to their multi-hop wireless connectivity, with a wireless backbone comprising BSs, which provide more bandwidth resources. Hence, the WMNs provide an alternative technology to extend network coverage in rural areas. Moreover, such networks can be exploited for fast deployment of an urgently required communication infrastructure to mitigate the collapse in communication due to disasters such as earthquake and hurricane. However, the BSs-based WMN technology in rural areas and disaster-stricken areas still suffer from a major challenge concerning the power supply due to the absence of power grid and the disruption of power supply cable in the rural and disaster-affected areas, respectively.

A common aspect of the users inhabiting in the aforementioned localities (i.e., the rural and disaster-affected areas) is their demand for stable communication (e.g., mail service with constant delivery delay, voice call service with consistent quality, and so on). As a consequence, the BSs require to operate to utilize available resources under an energy-constricted environment. With the absence of power grid in rural areas and the occurrence of power outage in disaster-stricken areas, ambient energy sources like solar and wind energy have become promising alternatives to operate the BSs. The BSs exploiting renewable energy sources are referred to as the "green" or energy harvesting BSs. Although being promising, the energy harvesting BSs are not without shortcoming. In particular, their performance may be influenced by the variable behavior of the ambient energy sources. Among many examples, possibly the simplest one the readers might think of is solar energy harvesting, which can be heavily affected by unfavorable weather

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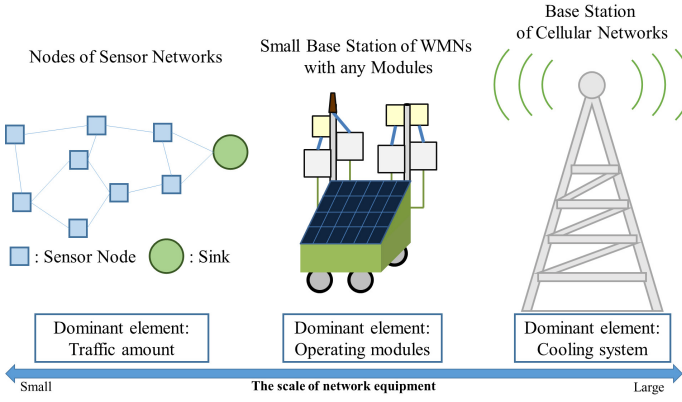
Fig. 1. Difference in the property of power consumption depending on the scale of network equipment.
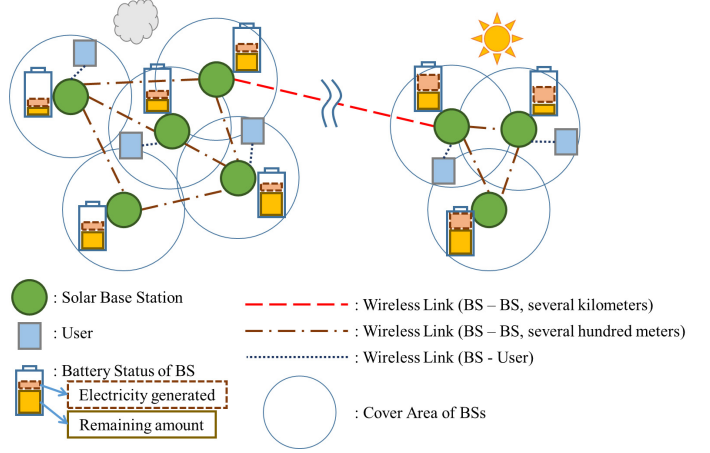

Fig. 2. Considered wireless mesh network exploiting solar energy harvesting BSs for providing stable communication service by expanding communication coverage in rural/disaster-affected areas.

conditions such as cloudy or rainy days. As a consequence, the energy harvesting BSs are subject to variable amounts and rates of energy available over time. In this article, we present our considered energy harvesting BSs, and conduct a study based on field experiments to estimate the factors which influence their energy harvesting capability. Particularly, the results of our conducted experiments demonstrate that the ON/OFF states of the radio links have a direct impact on the available power. Also, the manner in which the amount of solar radiation during different weather conditions over different days affects the array voltage in the considered energy harvesting BSs setup is found.

The remainder of this article is organized as follows. In Sec. II, the relevant research works on energy harvesting BSs are surveyed. Our assumptions and the architecture of our considered energy harvesting BSs-based WMN are presented in Sec. III. Our conducted field experiments and obtained results are provided in Sec. IV. Directions toward how to improve the energy harvesting BSs through BS-synchronization with changing ON/OFF state of the radio links are delineated in Sec. V. Finally, the article is concluded in Sec. VI.

II. RELATED RESEARCH WORK

According to Navigant Research [6], approximately 0.4 million off-grid mobile telecommunications BSs using renewable or alternative energy sources are expected to be deployed within 2012 to 2020. In this section, we overview the existing research works on energy harvesting wireless BSs. The alternative energy program [7] initiated by the Alcatel-Lucent aimed to assist service providers meet their need for reliable and sustainable power for remote areas. The objective of the program is to deploy hybrid or energy harvesting BSs to increase the number of users, reduce operating costs, and lower the carbon footprint in offgrid locations in Qatar. On the other hand, in Japan, the work in [8] focused on developing a disaster-resilient regional platform by implementing wireless mesh networks, which are referred to as the "NerveNet". The NerveNet is a regional wireless access platform comprising BSs powered by renewable energy sources. In the NerveNet, multiple service providers offer their respective services with the shared use of the network, thereby enabling a range of

context-aware services. It acts like a human nervous system, which enables a reliable and managed WMN.

Several researches have been conducted on renewable energy powered BSs to mitigate the variability of energy resources over time, such as the obstruction of daylight, the day/night cycle, weather, and seasons [9]. Green communications in cellular networks via user cooperation was first introduced in the work in [10] which shows increased data rate. Despite its advantages, however, energy efficiency issues of user cooperation render this paradigm unappealing in wireless mobile networks because the increased rate of a user comes at the price of the energy consumed by another user acting as a relay. The limited battery life time of mobile users in a mobile network leads to selfish users who lack incentive to cooperate. Recently, Zhou *et al.* [11] proposed the idea of dynamic BSs switching by coordinating the ON/OFF toggle of the BSs. Their scheme takes into consideration the energy availability of each BS, and the trend of the users' traffic and demand under each BS at a given time, allowing in that respect the sites with low energy availability and low users demand to be switched off.

With the development of information and communications technology, communication networks rely on various scales of BSs. For example, smaller BSs (pico/micro BSs), installed on buildings and often directly connected to power source of the building, are prone to damage by disasters and usually non-existent in rural areas. The bigger BSs (macro BSs), on the other hand, are located in specific areas well aroused by sun or wind, and equipped with renewable energy modules (e.g., photovoltaic cells and small wind turbines). Thus, the bigger BSs are more resilient to disasters. Moreover, they are equipped with technology enabling wireless communication between macro BSs over a long distance through the wireless backhaul [12].

In addition, the power consumption model of the network equipment is an important factor for developing effective communication networks. Fig. 1 shows the difference in the property of power consumption depending on the scale of network equipment. At the large scale, for example in case

(a) The prototype used in our considered solar BS.

(b) Inside of the solar BS.
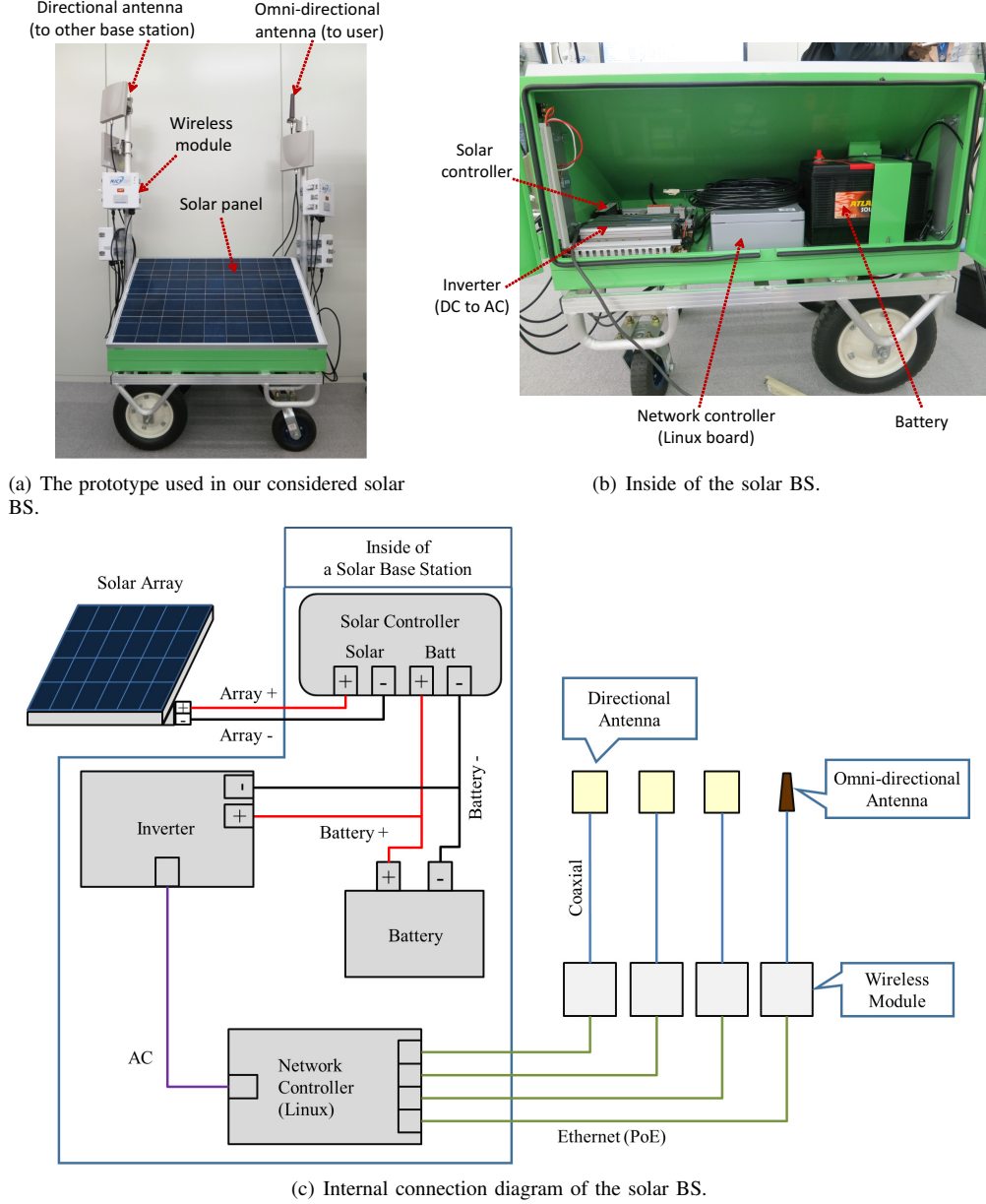

(c) Internal connection diagram of the solar BS.

Fig. 3. The configuration of the considered solar BS prototype.

of the macro BSs of cellular networks, the power consumption is significantly large and the dominant elements on the power consumption are static things, especially the cooling system [13]. On the other hand, at the small scale, e.g., in case of the wireless sensor network nodes, the power consumption dominantly depends on emitting radio waves for transmitting data [14], and other elements make a rather small impact on the power consumption. Because of its low-capacity battery, traffic are very critical for its life time. However, the medium scale network equipment (e.g., the small BSs of WMNs) exhibit a different dominating element of power consumption, i.e., the comprising modules. A small BS does not use power-hungry static units (e.g., big cooling systems in the large scale BS of the cellular network). Additionally, the power consumed by its traffic processing is negligibly smaller than the overall power consumption because of its scale. Therefore,

we expect that the modules of a networking equipment have an effect on its power consumption. Several researchers have already focused on this perspective, for example the bandwidth allocation of satellites [15], [16]; however, there is hardly any study which consider renewable energy powered WMNs. Thus, we focus on the medium-scale network equipment in this paper whereby the power consumption dominantly depends on the operating modules.

III. ARCHITECTURE OF CONSIDERED ENERGY HARVESTING BSS-BASED WMN

In this section, we describe the architecture of our considered energy harvesting BSs (also referred to as the solar BSs) -based WMN. Fig. 2 illustrates the considered WMN with a number of solar BSs for providing stable communication service. As depicted in the figure, every BS has its service area
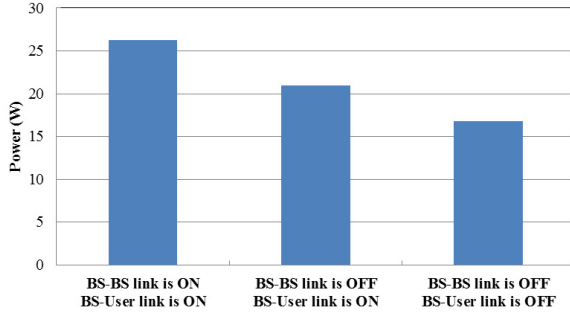
(a) Power consumption of an energy harvesting BS for various link states.
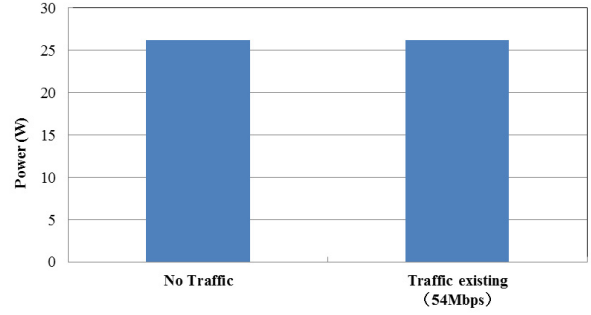
(b) Power consumption of an energy harvesting BS without and with traffic.

Fig. 4. Comparison of power consumption of an energy harvesting BS for various link states.

in a rural and/or disaster-afflicted region. Note that the solar BSs are considered to be at a considerable distance from one another, and some of them are assumed to have overlapping areas. The users depicted in the figure can be either fixed or mobile. On the other hand, each of the solar BS prototypes that we consider for use are on a wheeled platform for easily moving and deploying in a rural or disaster-affected area (as shown in Fig. 3(a)). Also, as depicted in Fig. 3(a), each of the BSs is equipped with a solar array (typically referred to as a solar panel in common literature) comprising photovoltaic cells, a wireless module, a number of directional antennas to connect with other BSs, and an omni-directional antenna to provide service to the users in the target area. The inside of a solar BS can be seen in Fig. 3(b) that shows a solar controller, an inverter (i.e., for converting the direct current (DC) to alternating current (AC)), a network controller (which is basically a Linux board), and a battery storage. The detailed interconnection diagram of a solar BS is presented in Fig. 3(c). As shown in the figure, the solar array is connected to the battery through the solar controller. Solar energy is harvested using the solar array and stored in the battery by using the solar controller. The capacity of this battery is 5Ah, which can operate this BS for approximately 24 hours. It takes about a week to fully recharge this battery. If the remaining battery level is enough, this BS can operate at night. In order to operate the network controller (i.e., the router, hub, and Linux board) of the solar BS, AC electricity is needed, which is obtained from the storage battery through the inverter, which converts DC into AC. The network controller is connected to a number of wireless modules through Ethernet cables. One of the wireless modules is connected to the omni-directional antenna (i.e., for connecting the users with the BS) while the rest are connected to the directional antennas (for connecting the BS with the neighboring BSs). All the wireless modules are connected to their respective antennas by using coaxial cables. It is worth mentioning that the wireless modules and the antennas get powered by the Power over Ethernet (PoE) connections.

IV. FIELD EXPERIMENTS AND RESULTS

In this section, we first present our conducted field experiments and obtained results. In the first field experiment, two

solar energy harvesting BSs and two laptops were used to form a simple WMN topology whereby each BS served one user with a laptop in its respective coverage area. As mentioned earlier, the two BSs are connected by using directional antennas; while omni-directional antennas are employed to connect the laptops to the respective BSs. The distance between the BSs is about 2 meters. The link rate between the BSs, and that between a BS and its user is considered to be 54Mbps. No traffic is considered in this particular experiment. The power consumption of the BSs is recorded by varying the ON/OFF states of the radio links. The link is switched ON and OFF by plugging and unplugging the Ethernet cable on the wireless module, respectively. A clamp meter (with voltmeter) is used to measure the current and voltage use of the BS, and then its power consumption is calculated. The measurement is done in between the inverter and the network controller of a BS. The results are plotted in Fig. 4. First, Fig. 4(a) demonstrates the power consumption of the energy harvesting BS for three link states. In the first link state, both the BS-BS and BS-user links are considered to be ON. In the second considered link state, the BS-user link is kept ON while the BS-BS link is switched OFF. On the other hand, in the third link state, both the BS-BS and BS-user links are considered to be OFF. As demonstrated in Fig. 4(a), there is a dropping trend of power consumption (i.e., 26.25W, 21W, and 16.8W) for these three link states, respectively.

In the second experiment, the power consumption of the BSs for varying traffic is measured. Also, in this case, the two BSs, each connected to a user (i.e., a laptop), are used. The link rate between the BS and its user, and that between the BSs are considered to be 54Mbps. The traffic was generated at a rate of 54Mbps by using the Iperf tool. The voltage measurement was done similar to that in the first experiment. The results are plotted in Fig. 4(b). As shown in the figure, the generated traffic did not influence the power consumption of the BS that remained in a consistent level of 26.25V.

Finally, in the third field experiment, the array voltage during ten days (since Jul. 14 to Jul. 23, 2014) is plotted in Fig. 5. Six distinct weather conditions, namely mostly sunny, sunny, slightly overcast, cloudy, misty rain, and rainy periods during the ten days were encountered. For example, during nights when there was no solar radiation to harvest energy
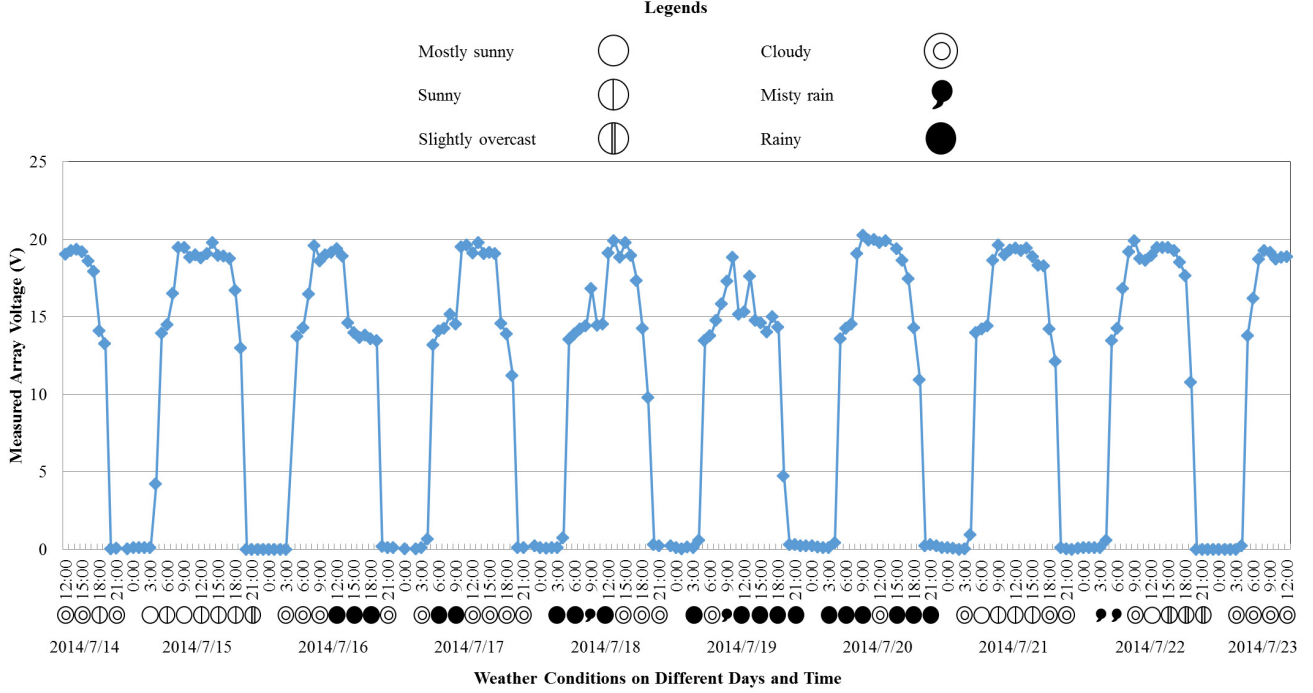
Fig. 5. Solar array voltage during different periods and weather conditions for over ten days.

from, the BS experienced zero array voltage. On the other hand, during the noons of sunny and even on cloudy days, the array voltage reached its peak (approximately 20V). Also, during the rainy days, the array voltage is three fourths of the peak. The point to note from this plot is that over any given day, there is continuous variation of the amount of energy available from the ambient source (i.e., solar energy in this case).

V. BSs Synchronization and Changing Links States Mechanism for Stabilized Operation of WMN Powered by Renewable Energy

From the result illustrated in Fig. 5, we found that the electricity generated by the BSs varies with time, which makes it impossible to keep the considered WMN powered by renewable energy stably operating all day long. The electricity generated by the BSs also varies with physical location, which occurs the location variability of the operation time of the BSs, causing locational instability in the considered WMN. Thus, some kinds of special regulations which control power consumption are needed for maintaining the network.

The often-used method is BSs' ON/OFF switching [17], [18]. However, from the result of the field experiment illustrated in Fig 4(a), we found another approach, i.e., changing the ON/OFF states of the radio links. In order to demonstrate the effectiveness of this idea, we introduced time slot-based BSs synchronization with changing link states as an early concept. Fig. 6(a) illustrates the summary of this method. Fig. 6(a) shows the weather of each BS, the battery status of each BS, the time variation of the BSs' ON/OFF switching in this concept, and the topology of the WMN consisting of the BSs. We assume there are more than 4 BSs in the WMN.

The upper part of Fig. 6(a) shows the case in which only the time slot-based BSs synchronization, i.e., synchronizing the BSs' OFF-switching and deciding the timing of ON-switching independently by remaining battery levels and generated electricity, is applied to the WMN. On the other hand, the lower part of Fig. 6(a) shows the case in which the method of changing the ON/OFF states of the radio links in addition to the above synchronization, i.e., controlling the the timing of one BS's ON-switching by changing the ON/OFF states of the radio links with which the BS is connected depending on their respective remaining battery levels and generated electricity, is applied. The synchronization-only method results in a temporally stable operation for the WMN. However, with the method of changing the ON/OFF states of the radio links, it is possible to mitigate the effects of location variability of the electricity generated by the BSs.

In order to show the efficiency of this method, we performed a simple analysis, which situation looks alike Fig. 6(a). In this analysis, we used only four BSs, each of which has four wireless modules. The BSs are denoted as BS1, BS2, BS3, and BS4, respectively. Any given BS is connected to all the other BSs. One of the wireless modules of each BS is used to provide service to the users, and the others are used to connect with the neighboring BSs. The considered parameters of the BSs are as follows. P_{static} represents the power consumption of the wireless module providing service to the users and the non-wireless module of the BS. The values of P_{static} in BS1, BS2, BS3, and BS4 are all considered to be 21W. P_{module} denotes the power consumption of the wireless modules connecting with the other BSs. For each of the four BSs, P_{module} is 5.25W. E_{batt} indicates the remaining battery level of each BS. The E_{batt} values of BS1, BS2, BS3,

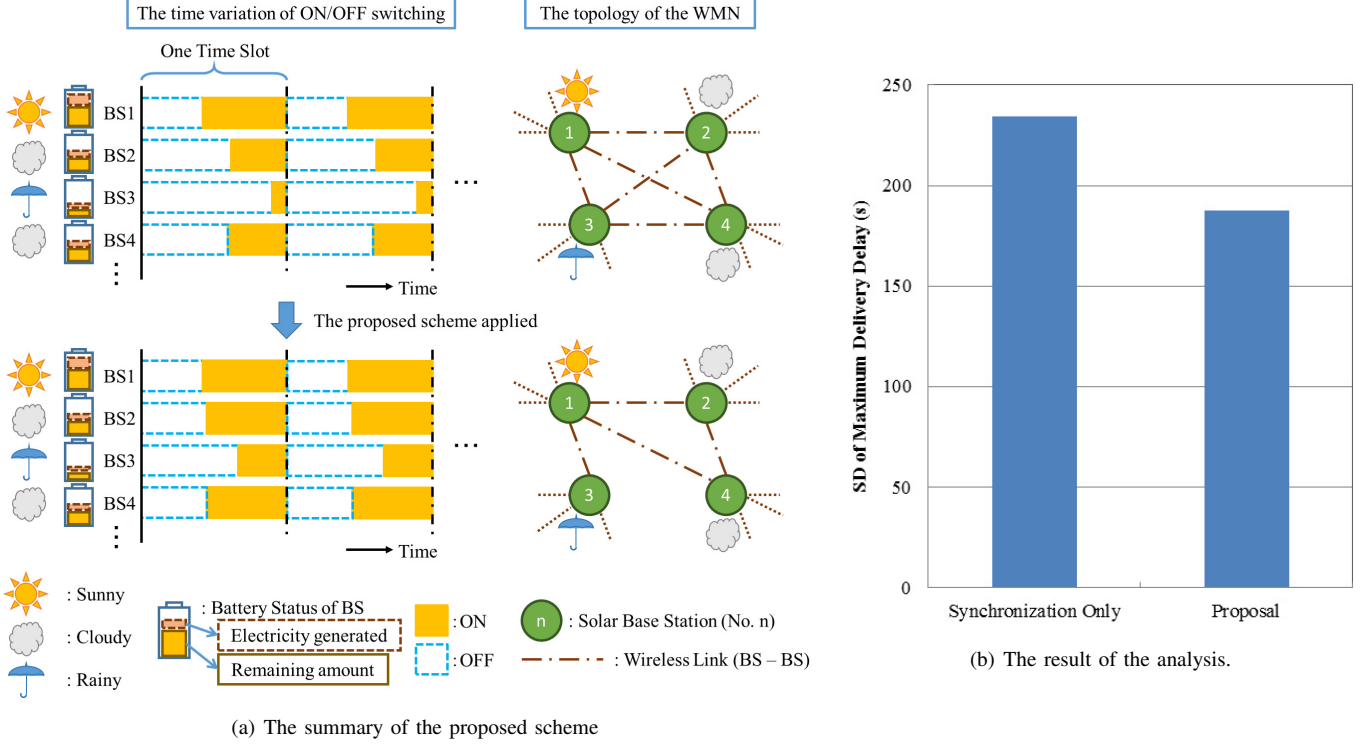(a) The summary of the proposed scheme

(b) The result of the analysis.

Fig. 6. The summary of the concept and the obtained result.

and BS4 are considered to be 30kJ, 25kJ, 10kJ, and 20kJ, respectively. E_{gen} refers to the power generated by each BS. The E_{gen} values of BS1 and BS4 are set to be 15kJ, and those of BS2 and BS3 are set to be 10kJ. We used the SD (standard deviation) of the maximum delivery delay from any given BS to any other BS for evaluation. Delivery delay is the time interval from the point when a user attempts to send packets to the point when a corresponding user receives the packets in a multihop communication. It is affected by the BSs' ON/OFF switching and radio links' ON/OFF states, i.e., packets are buffered in a BS when the next hop BS is OFF or the radio link to the next hop BS is in the OFF state. Also, when the BS with which a sending user is connected is OFF, the outgoing packets are buffered in the user terminal. The delivery delay for a user sending packets is the maximum when the BS connected to the user just becomes OFF. We used the maximum value of this delivery delay when computing the SD. Also, we assumed that each BS consumed all of it battery power and generated power. In the analysis, we compare the synchronization-only method with the proposed method, i.e. the time slot-based BSs synchronization with changing links states. The result is demonstrated in Fig. 6(b). At the result, the link between BS2 and BS3 and the link between BS3 and BS4 are deactivated. From the result, it can be said that the BSs-synchronization with changing links states mitigates the effects of location variability of electricity generated among the BSs on location variability of delivery delay, and ensures fairness regarding delivery delay.

Also, this is an early consideration and there are many other open issues that need to be addressed; for example, how does BS prevent from draining the battery power for stability operation, whether the synchronization and changing module state should be implemented in a centralized or a decentralized manner, how is the algorithm of the synchronization and the changing module state, and so forth. We aim to address these issues in future work.

VI. CONCLUSION

In this article, we focused on providing communication network services in "off-grid" locations (such as rural areas without power grid, disaster-affected areas with damaged power supply and wired communication lines) by using WMNs constructed by energy harvesting BSs. One of the key challenges in the WMN comprising such energy harvesting modules is to provide a reliable communication network supporting stable communication applications because the available energy resources are variable over time. In particular, we considered solar energy harvesting BSs-based WMN and conducted several field experiments to investigate the factors affecting its performance. Based on our finding, some hints toward possible performance improvement of the WMN via BSs-synchronization with changing links states were also provided.

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