Operation-Time Prolonging Method for IoT-Based Outdoor Environment Monitoring System

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***Abstract*—It is important to analyze and comprehend outdoor environmental conditions to address air pollution problems. Accordingly, while remote sensing is suitable for analyzing global environment data, the Internet of Things (IoT) technique can help us analyze and comprehend local environment data. Moreover, considering how IoT-based outdoor environmental monitoring can operate for long periods in environments is necessary during difficulties in securing a power supply. Therefore, this study proposes an operation time-prolonging method for an IoT-based outdoor environment monitoring system by combining solar power, storage devices, and intermittent operation for stable operations in outdoor environments. With our proposed method, while solar panels provides power during the day, storage batteries provides power after sunset, with the sensor devices operating intermittently during this period. Furthermore, because the energy supplied depends on daylight hours, the proposed system has a sleep period that considers daylight hours when prolonging the system's operation time. Consequently, the operation time of the sensor node during the adaptive sleep period control becomes 6.0 times longer than that without sleep period control, showing the effectiveness of the developed system. Hence, our results establish the effectiveness of the proposed adaptive sleep period control for prolonging the operation time of IoT network-based systems, indicating this finding's usefulness for future research approaches.**

***Keywords*—wireless sensor network, internet of things (IoT), environment monitoring system, solar power, solar storage, sleep period control**

I. INTRODUCTION

Although clean air is a fundamental requirement for the health and survival of humans, plants, and animals, air pollution due to urbanization and industrialization threatens our health [1]. Therefore, it has become important to analyze and comprehend outdoor environmental conditions, such as carbon dioxide (CO_2) and particulate matter 2.5 (PM 2.5), to address air pollution problems. Accordingly, remote sensing that investigates global environmental information through satellite sensing data is becoming popular for comprehending environmental conditions [2, 3]. In a previous study [2], for example, the environmental CO2 concentration was estimated by remote sensing data. Another study [3], the author also estimated the PM2.5 level using remote sensing data, confirming that remote sensing techniques can help us comprehend and predict environmental information. Unfortunately, although the remote sensing technique is suitable for analyzing global environment data, it challengingly comprehends local environmental data.

Interestingly, however, the IoT has been acquiring much attention with the improvement, miniaturization, and price reduction of wireless devices [4−18], enabling communication between physical objects or spaces. The IoT technique also helps measure, collect, and comprehend local environment data. Thus, many systems using the 5G infrastructure and IoT techniques are being studied, such as Smart metering, smart cities, and smart environmental monitoring. For instance, the authors' research team previously developed an indoor environment data collection system to monitor indoor environmental information and estimate emotional information [19]. Nevertheless, technical challenges have also been identified with IoT techniques: communication performance, power quality and reliability [20], mobility [21], establishing platforms [22], and security [23]. Moreover, although wireless sensor/IoT networks should supply stable power to sensor devices, they experience power supply problems because they should operate outdoors, creating limitations during their use.

Studies have thus hypothesized that the emergence of battery-free wireless sensor/IoT networks can effectively solve the abovementioned power limitation problems [24−26]. For instance, some studies have equipped battery-free sensor nodes with energy harvesting devices that can obtain energy from the surrounding environment, such as wind energy [27], solar energy [28], and radio frequency signals [29], thereby eliminating the need for battery replacement for power supply. However, although the potential application areas of battery-less IoT networks are extensive, especially where it is challenging to replace sensor batteries, the amount of power supplied by energy harvesting depends on the surrounding environmental conditions. For example, power generation from solar energy depends on the hours of sunlight. Therefore, energy harvesting characteristics also pose challenges for wireless sensor/IoT networks in battery-free IoT networks.

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Based on the background presented above, this study proposes an operation time-prolonging method for an IoT network-based outdoor environment monitoring system, combining solar power, storage devices, and intermittent operation while considering sunlight hours for stable operations in outdoor environments. In our proposed system, solar panels provide power during the day, whereas storage batteries provide power after sunset, with the sensor devices operating intermittently during this period. Furthermore, because the energy supplied depend on daylight hours, the proposed system has a sleep period that considers daylight hours. Hence, we first develop a solar power and storage device to supply power to the sensor nodes, causing the sensor devices to obtain power through a power supply consisting of a solar panel, a charge controller, and a storage battery. Subsequently, this study implements a sleep mode considering the daylight hours to prolong the system's operation time. Our experimental results show the effectiveness of the developed system.

II. RELATED WORKS

There are several solutions for prolonged network lifetime, such as energy efficiency improvement by routing [30, 31], site sleep mode [32], and traffic estimations in the networks [33].

A. Energy Efficiency Improvement by Routing

Energy efficiency through routing has been proposed in WSNs, with the hierarchical routing algorithm widely considered as an effective way to save energy for wireless sensor networks. For example, in a previous study, the Quantum Genetic Energy-Efficient Iterative Clustering Routing Algorithm (QGEEIC) balanced energy consumption using a proposed energy-efficient iteration-based cluster selection method to select the optimal cluster heads [30]. Their simulation results showed superiority regarding network lifetime, number of surviving nodes, and total energy consumption. Similarly, another author proposed a new energy-efficient, high-performance routing protocol that extended AODV as a routing protocol in mobile adhoc networks (MANETs) [31]. This new routing protocol notably had two stages: route discovery and route maintenance. First, the routing procedure was modified so that energy-related information on nodes could be collected during this stage. Each node must provide two types of information: the total remaining energy and the estimated energy consumption rate. Then, after creating routing metrics to represent this information, a cost function was defined, using these metrics as an input for the given route. The cost function provides information on the total amount of energy consumed by all nodes on the route. It can also determine the number of hops (i.e., hop count) and the node with the least energy remaining. Consequently, the cost function selected an appropriate route for data transmission among the candidates as the one with high throughput, low energy consumption, and long life.

B. Site Sleep Mode

Urban base station sites in mobile networks can have overlapping coverage of adjacent sites, providing an opportunity to reduce energy consumption in mobile networks [32]. Moreover, by systematically selecting some sites and putting them in sleep mode, neighboring sites can compensate for the shortfall and maintain coverage/service levels. Sleep mode also reduces the amount of interference generated, saving energy, improving the remaining sites' performance, allowing more equipment to be powered down, and significantly reducing the energy consumption generated by load-independent components.

C. Traffic Estimations in Networks

Energy-efficient and sustainable network operations have been proposed through the load-adaptive operation of network elements such as routers, switches, and access multiplexers. However, since traffic is time-varying, robust traffic demand forecasting is required for load-adaptive network control. To this end, Wiener Filtering was identified as a robust solution for reliable traffic demand forecasting at relevant time scales [33], with investigations revealing that capacity dimensioning based on traffic forecasting and Wiener Filtering provides reliable results regarding predicted traffic, enabling sustainable and efficient network operations.

III. PROPOSED METHOD

Conversely, the proposed system collected and saved the environmental data. Sensor nodes first measured environmental data, such as temperature, CO2 concentration, and dust concentration. Then, the sensor nodes send the measured data to the coordinator node.

Since the one-board microcomputer controlled each sensor's operation, this study used Arduino as a one-board microcomputer, with each sensor measuring the environmental data periodically. Sensors of this system also measured the temperature, humidity, illuminance, atmospheric pressure, dust concentration, and CO_2 concentration, after which they sent their measured data through a wireless module. Notably, our system used XBee as the wireless module.

With XBee, each sensor first sent the measured data to the coordinator node. Then, the coordinator node transferred the received data to the cloud server. The logged files include measured data, sensor ID, and sensor data reception time. Subsequently, X-CTU configured the XBee module, setting the coordinator node to the API mode (one-to-many communication mode) in the developed system and sensor nodes to the AP mode (one-to-one communication mode). The authors provide details on the construction and configuration of the data measurement sensor networks in [19, 34].

Finally, this study combined solar power, storage devices, and intermittent operation for stable operations in outdoor environments, considering sunlight hours. In the proposed system, while solar panels provided power during the day, storage batteries provided power after sunset, with the sensor devices operating intermittently during this period. Moreover, because the energy supplied depended on daylight hours, the proposed system had a sleep period that considered daylight hours to prolong the system's operation time.

A. Power Supply

Figure 1. The developed power supply system.

As shown in Fig. 1, this study subsequently developed a solar power and solar storage device consisting of a monocrystalline solar panel (10W), a charge controller (5A), and a storage battery (12V/7Ah) to supply power to the sensor nodes. The charge controller, located between the solar panel and the storage battery, controlled the charge voltage to the battery, prevented overcharging, regulated load shutdown, and eliminated reverse current when the battery was under-voltage. We also used a storage battery to pool the electricity generated by the solar panel. Consequently, while the solar power and storage battery device charged nine Ah in about 20 h if located directly south in clear weather and with a conversion efficiency of 90%, the amount of electricity generated on cloudy days was 40%–60% on sunny days. This finding indicates that the solar power and storage device could supply sufficient power to the sensor nodes during the daytime when the weather was sunny and cloudy, the time from sunrise to sunset was seasonally dependent in many areas, and sufficient power could be supplied to sensor nodes during a mix of sunny and cloudy weather in summer. Nevertheless, it remained challenging to store enough operation power after sunset, even on sunny days in winter. Furthermore, since the power generation during cloudy weather was 40%–60% of that during sunny weather, it was impossible to supply sufficient power to sensor nodes during winter.

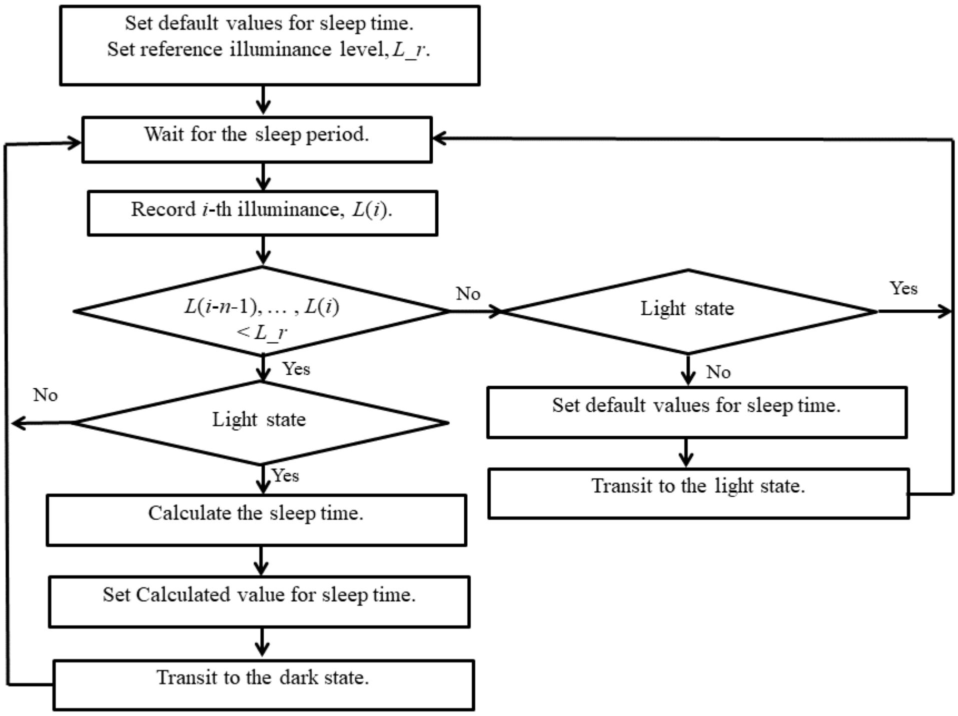


Figure 2. Flowchart showing the sleep-period control.

Hence, it was better to reduce the power consumption of sensor nodes by providing a sleep function. Meanwhile, the amount of power that could be generated and stored depended on the hours of sunlight, making it better to set the sleep period according to the hours of sunlight. Thus, this study proposed a power source that operated day and night regardless of weather and seasons, using solar panels and storage batteries that provide a sleep function and an appropriate sleep period according to the hours of sunlight.

B. Sleep Mode

Although the power supply devices in this study stored electricity while generating solar power, they might not store sufficient electricity if the sensor nodes were in constant operation. Therefore, this study suppressed power consumption by adding a sleep mode to the sensor node. In the developed sensor, Arduino periodically controlled the sensor node to sleep mode, using a watchdog timer to measure the sleep period.

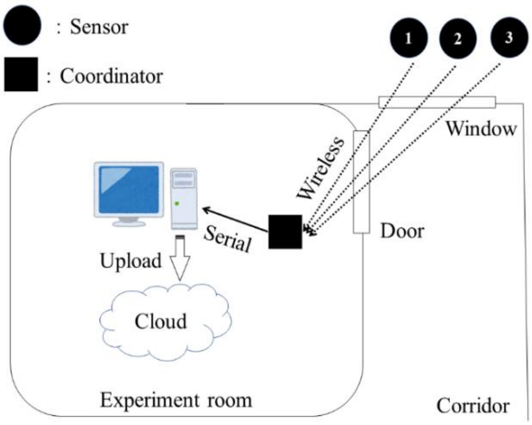
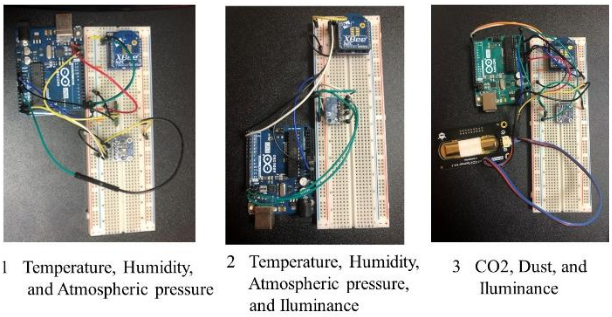


Figure 3. The sensor network's construction.


1 Temperature, Humidity, and Atmospheric pressure

2 Temperature, Humidity, Atmospheric pressure, and Iluminance

3 CO2, Dust, and Iluminance

Figure 4. The developed sensors.

C. Sleep Period Control

Since the amount of electricity generated by solar panels depends on the season and weather conditions, changing the sleep period according to the amount of electricity generated is desirable to ensure stable system operation independent of the season and weather. Accordingly, this study controlled the sleep period at sunset based on the value measured by the illuminance sensor. The sleep period after sunset, T_{night}, is thus calculated by the following equation:

$$T_{night} = T_{base}\frac{L_{base}}{L_{ave}}, \tag{1}$$

where T_{base}, L_{base}, and L_{ave} are the base sleep period (sleep period during the daytime), the base illuminance level, and the average measured illuminance level, respectively.

Afterward, the sensor node determined the light/darkness (day or night) around the sensor based on the observed illuminance level and switched its internal state. Here, the sensor node sets the base sleep period to the default value, followed by a measurement of the illuminance level every time the sleep period elapses. Fig. 2 shows a flowchart of the sleep period control. The sensor node transitioned to the dark state if the illuminance levels of the last 'n' times were less than the reference value. Otherwise, the sensor node transitioned to the light state. These findings indicate that if the illuminance level exceeded the reference value at least once out of the last 'n' times, the sensor node transitioned to the light state.

D. Measurement System Construction

The environment measurement devices used in this study include the developed sensors, one-board microcomputer, XBee router, and our proposed power supply system. Furthermore, we notably constructed a star topology sensor network: sensor nodes were placed outdoors near the experimental room, whereas the coordinator node was placed in the experiment room. Our model also comprised one coordinator node and three sensor nodes. Figs. 3 and 4 show the sensor network construction and the developed sensors, respectively. However, Table I shows each node's information on the equipped sensors.

TABLE I. XBEE MODULE'S CONFIGURATION

ID	Equipped Sensor	Sending Data
1	Temperature & Humidity and Atmospheric pressure	Temperature (Degree Celsius), Humidity (%), Atmospheric pressure (*hPa*)
2	Temperature & Humidity, Atmospheric pressure, and Illuminance	Temperature (Degree Celsius), Humidity (%), Atmospheric pressure (*hPa*), Illuminance (*lux*)
3	CO_2 and Dust concentrations, and Illuminace	CO2 concentration (*ppm*) Dust concentration ($\mu g/m^3$) Illuminance (*lux*)

IV. EXPERIMENT RESULTS

Our measurement experiment was conducted from January 24, 2022, to January 31, 2022. In this experiment, measurements were taken only on clear and cloudy days since the sensors, which had no precautions against rainy weather, measured outdoor environment data. However, sensor measurements stopped when it rained. Figs. 5–7 show the measured environmental data by the developed sensors, CO_2 concentration, and illuminance, respectively, and Table II shows the weather on the days during the experiment. It was evident from Figs. 5–7 that the observed data changed due to the time of day and weather conditions. Fig. 6 also shows that the daytime illuminance changed with the weather, meaning that the amount of electricity the solar panels produced depend on the weather. These results indicate the need for sleep control when considering the weather.

Furthermore, our investigations revealed that although the current consumption in the awake mode of Arduino was 16.26 (mA), and the current consumption in the sleep mode was 0.00657 (mA), the power consumption of the sensor node in the sleep mode was minimal compared with the sensor node in the awake mode. Hence, this study compared the operating time for a sensor node with controlled sleep periods during the night (adaptive sleep period control) and a sensor node operating with only a base sleep period (constant sleep period control). In this experiment, we set the base sleep period, T_{base}, to 17 min so that the sensor node operated during the day (12 h) in sunny and cloudy weather. Also, while we set the number of consecutive measurements in determining whether light or dark conditions as n = 5 (times), the base illuminance level was set to L_{base} = 1000 (Lux) in the experiment. Table III compares the operation time. We observed that the operation time of the sensor node with an adaptive sleep period control was 6.0 times longer than that without a sleep period control and 1.4 times longer than that with a constant sleep period control, showing the effectiveness of the adaptive sleep period control.

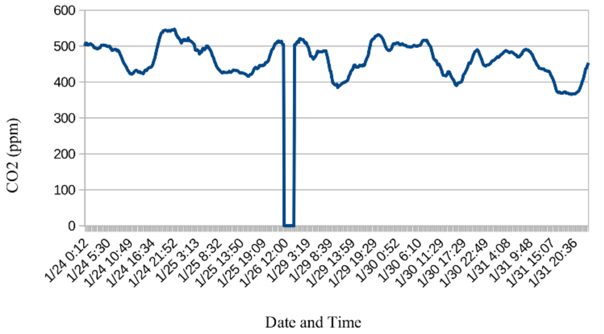


Figure 5. Measured CO_2 concentration obtained from our developed sensor.

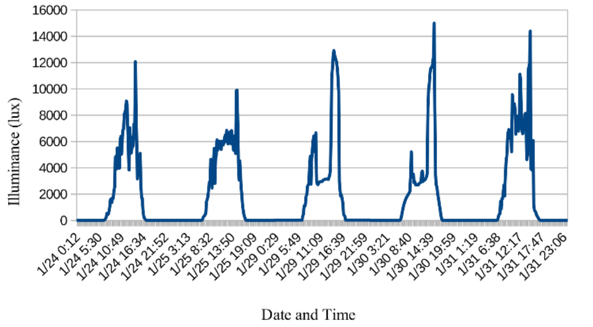


Figure 6. Measured illuminance obtained from our developed sensor.

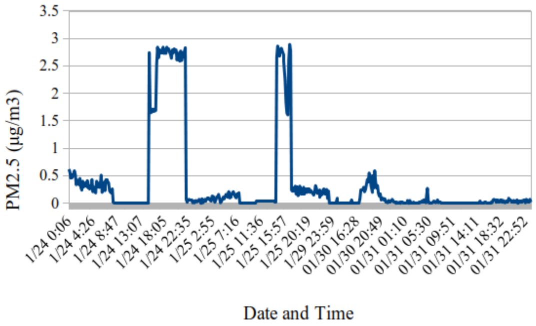


Figure 7. Measured PM 2.5 obtained from our developed sensor.

TABLE II. WEATHER CONDITION ON THE UNDERSTUDIED DAYS

1/24	1/25	1/26	1/27	1/28	1/29	1/30	1/31
Sunny	Cloudy	Rainy	Rainy	Rainy	Sunny	Sunny	Sunny

TABLE III. COMPARISON BETWEEN THE OPERATION TIMES

Method	**Operation time**
Without sleep-period control	12 hours
Constant sleep-period control	52 hours
Adaptive sleep-period control (Proposed)	74 hours

V. CONCLUSION

By combining solar power, storage devices, and intermittent operation, this study propose an operation time-prolonging method for an IoT network-based outdoor environment monitoring system, considering sunlight hours for stable operations in outdoor environments. In our proposed method, while solar panels provided power during the day, storage batteries provide power after sunset, with the sensor devices operating intermittently during this period. Furthermore, because the energy supplied depend on daylight hours, the proposed system has a sleep period that considered daylight hours to prolong the system's operation time. Consequently, our experimental results show that the operation time of the sensor node with the adaptive sleep period control is 6.0 times longer than that without sleep period control and 1.4 times longer than with constant sleep period control. Thus, our obtained results indicate that the proposed adaptive sleep period control effectively prolong the operation time of the IoT network-based system regardless of the season and the weather, which is a useful finding for future research approaches.

Nevertheless, future work should include continuous operation on days with short sunshine hours, continuous cloudy weather and rainy days, and environment time prediction.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

N.K. suggested the basic concept of this study and also suggested the algorithm demonstrated in this study. N.K. and S.M. designed and performed the experiments. They also analyzed the experiment data.

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