On Placement of End Devices in LPWAN Based WSN for Environmental Monitoring Applications

Ayumi Kaichi*, Shusuke Narieda†, Takeo Fujii‡, Kenta Umebayashi§ and Hiroshi Naruse¶
* Dept. Eng., Mie Univ., Japan.
†¶ Graduate School of Eng., Mie Univ., Mie, Japan.
‡ Advanced Wireless Communication Research Center, The Univ. Electro-Commun., Tokyo, Japan.
§ Dept. Electr. and Electron. Eng., Tokyo Univ. of Agric. and Technol., Tokyo, Japan.
E-mail: narieda@pa.info.mie-u.ac.jp†

***Abstract*—In order to understand the heat island phenomenon or air pollution caused by PM2.5, it is necessary to accurately measure physical quantities, which can be measured systems based on a wireless sensor network (WSN). For the purpose, it is necessary to consider the optimal placement of sensors considering cost for the installation. We develop 920 MHz band wireless sensor network for the measurement of some quantities including temperature, relative humidity, atmospheric pressure and dust. The developed system is based on LoRa networks. We measure these quantities in the actual environment (Kamihama campus at Mie University) and consider the tendency of the measured value for each observed quantities. In this paper, based on the measurement results, the spatially and temporally characteristics of each measured quantity for the optimal placement of EDs in LPWAN based WSN.**

I. Introduction

The Internet of Things (IoT) has become one of the major communication paradigms and can provide the possibility of centralized data accessibility and data fusion. Concretely, a lot of IoT devices will be deployed everywhere to correct information for physical quantities, i.e., it is possible to construct a wireless sensor network (WSN) of unprecedented scale. Low Power Wide Area networks (LPWANs), which is composed of one (or some) gateway (GW) and massive end devices (EDs), is one of the communication technologies to expect as communication infrastructures for such IoT systems [1]. Low Power Wide Area (LPWA) communication technologies can provide capabilities of long range communications and battery efficiencies, and these features are suitable for the construction of WSN. Among some LPWA technologies, e.g., SigFox [2], NB-IoT [3], and Long Range (LoRa) [4], it is presumed that such IoT systems can be easily developed based on LoRa networks because the LoRa networks can be used to build a private/local network in an unlicensed band. The LoRa employs chirp spread spectrum (CSS) modulation which is one of spectrum spreading techniques. Generally, six types of spreading factors which correspond to spreading code are used and allocated to LoRa EDs. Because of the orthogonality imperfectness of the spreading factors [5], [6], the LoRa communications can provide a rough interference avoidance capability by allocating an appropriate spreading factor to each ED [7], [8], etc.

On the other hand, some applications based WSN technologies have been evaluated and analyzed; for a smart city application [9], [10], a smart golf course [10], evaluations via experimental analysis in university campus [11], human centric health and wellness monitoring applications [12] and environmental monitoring [13], [14]. Among them, environmental monitoring is a broad area focusing on using scientific and engineering principles for the improvement of environmental condition. Furthermore, environmental informatics, which is an interdisciplinary field involving computer science, information science and environmental science, has a very rapidly developed, and it enables to provide a solution for specific environmental problems related to the computer science. The rapid development of environmental informatics has significantly improved environmental monitoring. Especially, the IoT is predicted to be able to facilitate the entire process of environmental monitoring. Therefore, it is important to construct and design of WSN for environmental monitoring. Traditionally, many researches have focused on a hardware for environmental monitoring [15], [16], [17] whereas the constructions of WSN for environmental monitoring, e.g., placement of the sensors (EDs), have never been focused.

In this paper, we discuss the placement of the EDs in WSN for environmental monitoring. A large scale environmental monitoring requires a requirement of the massive EDs and it causes to increased costs for the construction of WSN for environmental monitoring. By placing the required number of the EDs in the appropriate places for the gathering of environmental information, it can be expected to manage the construction cost of WSN properly while maintaining the observation accuracy. To achieve this, this paper provides some experimental results for the optimal placement of the EDs.

II. Overview

The purpose of this paper is to evaluate some statistics computed from measured physical quantities for the optimization of ED placement in the WSN based environmental monitoring. In the optimization of the ED placement, we will divide the measurement area into several small areas and attempt to optimize the density of the ED placement in each small area. Note that the small areas may be pre-divided or the resulting divided. To determine the density of the ED placement, we employ the cross correlation coefficient and

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the average relative error between each measured quantity. To compute the cross correlation coefficient and the average relative error, we set some reference points in the measurement area. The cross correlation coefficient and the average relative error are computed from the measurement quantities at the reference point and the point where the ED is placed. Note that the EDs are also placed at the reference points. We let $x(n)$, $x_{\text{REF}}(n)$, $\overline{x}$ and $\overline{x_{\text{REF}}}$ denote a measured quantity at n, a measured quantity at n on the reference point, an average of $x(n)$ and an average of $x_{\text{REF}}(n)$, respectively. Then, the cross correlation coefficient $\overline{C_{x,x_{\text{REF}}}}(\tau)$ is given by

$$\overline{C_{x,x_{\text{REF}}}}(\tau) = \frac{1}{N}\sum_{n=0}^{N-1}\frac{\{x(n)-\overline{x}\}\{x_{\text{REF}}(n+\tau)-\overline{x_{\text{REF}}}\}}{\sqrt{C_{x,x}(0)C_{x_{\text{REF}},x_{\text{REF}}}(0)}}, \quad (1)$$

where τ, N, $C_{x,x}(\tau)$ and $C_{x_{\text{REF}},x_{\text{REF}}}(\tau)$ are a time delay, the number of samples for $x(n)$ and $x_{\text{REF}}(n)$, an autocorrelation function of $x(n)$ and an autocorrelation function of $x_{\text{REF}}(n)$, respectively. Further, the average relative error $\overline{\epsilon}$ is given by

$$\overline{\epsilon} = \frac{1}{N}\sum_{n=0}^{N-1}\left|\frac{x(n)-x_{\text{REF}}(n)}{x_{\text{REF}}(n)}\right|. \quad (2)$$

Based on $\overline{C_{x,x_{\text{REF}}}}(\tau)$ and $\overline{\epsilon}$, we consider the optimal placement of the EDs in WSN for environmental monitoring. $\overline{C_{x,x_{\text{REF}}}}(\tau)$ close to 1 means that there is almost no difference in the behavior of changes in the two measured quantities. $\overline{\epsilon}$ close to 0 means that the two measured quantities are almost the same. If high $\overline{C_{x,x_{\text{REF}}}}(\tau)$ and low $\overline{\epsilon}$ are obtained in the divided small area, a low density of the ED placement is sufficient in the area. In this paper, we investigate the relationship of $\overline{C_{x,x_{\text{REF}}}}(\tau)$ and $\overline{\epsilon}$

III. Measurement Setup

A. LoRa Networks

In this subsection, we show the LoRa networks that build the infrastructure of WSN. In Japan, the unlicensed LPWA communications operate in the 920 MHz bands. The Japanese regulations [18] for the unlicensed LPWA communications can be divided into two categories in which the maximum transmission power are 20 mW and 1 mW. In the 20 mW case, an energy detection based listen before talk (LBT), i.e., carrier sense, is required whereas it is not required in the 1 mW case. The energy detection based LBT is important in unlicensed band because the unlicensed LPWA can construct the private/local networks and some communication areas may overlap with each other. Furthermore, in the 20 mW case, a duty cycle is not specified and the transmission time at one time is specified (4 sec). Therefore, we employ the case of maximum transmission power is 20 mW in this paper.

B. Measurement System

Fig. 1(a) shows the LoRa GW composed of the LoRa module and Raspberry PI 3 B+. The LoRa module is manufactured by EASEL Inc. [19] which includes Semtech SX1276 [20] made by Semtech Inc. The LoRa module can be controlled by an interactive format via Raspberry PI 3 B+ [21]. The

(a) (b) (c)

Fig. 1. (a) Configuration of GW, (b) configuration of ED and (c) overview of EDs.

measured quantities at each ED are sent from the deployed EDs and the measurement data can be obtained by using our developed systems programmed by Python [22] which is a programming language for general purposes. Fig. 1(b) shows the configuration of the ED. It consists of the LoRa module, receive antenna, Raspberry PI 3 B+, some physical sensors, prototyping board and battery. The LoRa module and some physical sensors are controlled by our developed system programmed by Python on Raspberry PI 3 B+. Some physical sensors, which are for the measurement of temperature, relative humidity, atmospheric pressure and dust, are connected to Raspberry PI 3 B+ via the prototyping board. These equipments are housed in one Styrofoam box except for some sensors which are for the measurement of temperature and dust. The overview of the box is shown in Fig. 1(c).

C. Measurement Scheme

Fig. 2 shows a measurement area for the experiments of the environmental monitoring system which is the part of the Kamihama campus of Mie University, Japan, having a land area of approximately $350\,\text{m} \times 280\,\text{m}$. We have confirmed that another LPWA technologies operating 920 MHz frequency bands are not activated in the area including neighboring. The GW is located at the center in Fig. 2 and is placed on the rooftop of a five-stories reinforced concrete building, approximately 19.4 m in height. The EDs is placed at white small circles with/without the alphabet in Fig. 2. The number of the circles is 35. The white small circles with the alphabet mean a reference point to compute the cross correlation coefficient and the average relative error.

IV. Experimental Analysis

A. Parameter Setup

Table I shows the parameters for the experiment. We employed LoRa signals of 922.0 MHz center frequency, 125 kHz signal bandwidth (200 kHz channel bandwidth), 10 spreading factor and 13 dBm (< 20 mW) transmission power. Each ED transmits each measured quantities to GW once a hour, and then, the sending timing at each ED is offset by 20 seconds to avoid packet collision among each ED. The measurement time in the experiment is 78 hours, and the measurement is executed in three times. Further, the number of EDs in the experiment is 35 EDs.

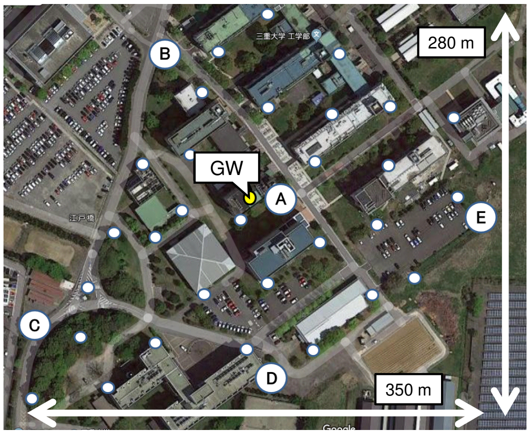

Fig. 2. Measurement area in experimental analysis.

TABLE I
PARAMETERS FOR EXPERIMENTS

Parameters	Value
Center frequency of LoRa	922.0 MHz
Transmission power	13 dBm
Signal bandwidth	125 kHz
Spreading factor	10
Measurement intervals at ED	1 hour
Offset sending time for each ED	20 seconds
Number of EDs	35
Measurement time	Total 78 hours

B. Measurement Results

First, Table. II shows the cross correlation coefficient between the reference points and each measurement points. Each value in Table. II is the average of the cross correlation coefficients between each reference point and each ED. As

TABLE II
AVERAGE CROSS CORRELATION COEFFICIENT ($\tau = 0$)

Ref.	temperature	atmospheric pressure	relative humidity	dust
A	0.814	0.839	0.847	0.338
B	0.875	0.867	0.866	0.280
C	0.860	0.886	0.878	0.232
D	0.853	0.844	0.867	0.180
E	0.788	0.842	0.841	0.160

shown in Table. II, it can be seen that high average cross correlation coefficient can be obtained for the quantities which include the temperature, the atmospheric pressure and the relative humidity. Besides, it can be seen that low average cross correlation coefficient can be obtained for the quantity which includes the dust. Further, Fig. 3 shows geographically plots of the cross correlation coefficient for the reference point A. It can be seen that the cross correlation coefficients are high at almost all EDs for the measurement of the temperature and the relative humidity. For the measurement of the atmospheric pressure, it can be seen that the number of EDs with a high cross correlation coefficient is slightly smaller than that of

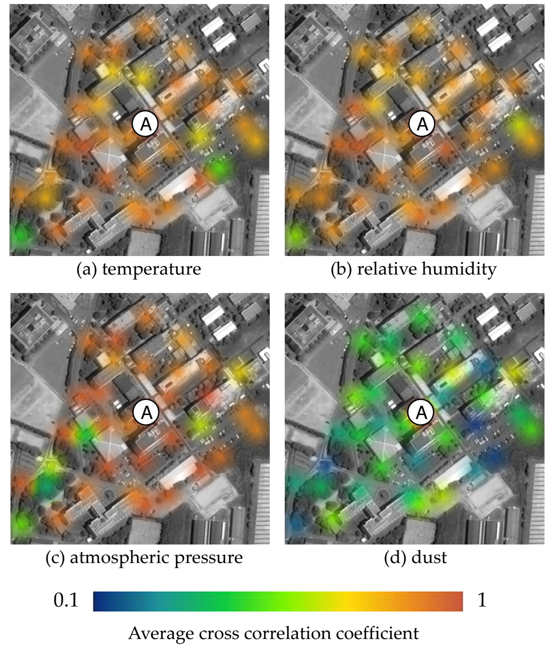

Fig. 3. Cross correlation coefficient plotted on the measurement area for each measured quantity at the reference point A.

the previous results. For the measurement of the dust, it can be seen that the cross correlation coefficient is low at almost all EDs. Finally, we show the relationship between the cross correlation coefficient and the relative error. Fig. 4 shows the relationship for all the measured quantities at all the reference points. As shown in Fig. 4, the low relative error can be obtained when the high cross correlation coefficient for the measurement of the temperature, the relative humidity and the atmospheric pressure. Especially, it can be seen that the relative error is extremely small for the measurement of the atmospheric pressure. For the measurement of the dust, it can be seen that the relative errors are almost the same regardless of the cross correlation coefficient.

C. Future Works

As shown in these results, it can be seen that the relationship between the cross correlation coefficient and the relative error and the obtained value of themselves differ depending on the measurement quantity. Based on these results, the density of the ED placement should be determined so that the accuracy required for each measurement quantity can be obtained. This should be a future work.

V. CONCLUSION

This paper provided the spatial and temporal characteristics of environmental information for the measurement using LPWAN based WSN. We developed 920 MHz band wireless sensor network for the measurement of some quantities including temperature, relative humidity, atmospheric pressure and dust. The developed system is based on LoRa networks. We

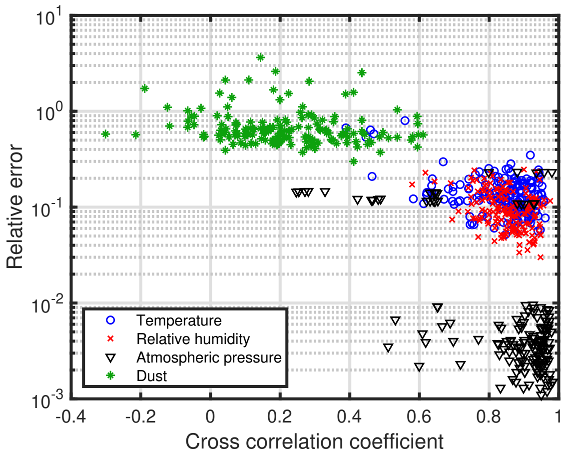

Fig. 4. Relationship between cross correlation coefficient and relative error for all reference point.

measured these quantities in the actual environment (Kamihama campus at Mie University) and consider the tendency of the measured value for each observed quantity. Based on these results, the density of the ED placement should be determined so that the accuracy required for each measurement quantity can be obtained. This should be a future work.

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