Paper:

Analysis of Radio Wave Propagation in an Urban Environment and its Application to Initial Disaster Response Support

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When disasters strike, it is important to quickly collect and analyze disaster-related information immediately after the event. We have suggested ZigBee and geographic information systems (GIS) technologies to resolve these problems and provide an effective communications system. In this paper, a method for the rapid setup of short-range wireless networks infrastructure, which estimates the radio wave propagation and optimizes the positions of transmitters is proposed. Our estimation method is experimentally verified, and it combines ray-tracing with preliminarily obtained statistical attenuation information, which allows us to consider different types of the land and its elevation. Thus, we can determine the effective ranges for radio communication for each potential location in the actual environment. This information is then used in our optimization procedure to reduce the number of transmitters needed to establish connections.

Keywords: emergency response, GIS, ZigBee, propagation, optimization

1. Introduction

One of the most important tasks as an initial response to large-scale disasters is the recording of the disaster damage. This can, however, be difficult to do if communication systems such as internet and mobile phones are not available in the disaster struck areas. This was, for example, the case after the Great Eastern Japan Earthquake in 2011 [1]. There, the disruption of communication systems caused the delays in decision-making about rescue effort and distribution of relief goods in the early stage of the disaster. Hence, alternative communication methods are desired, that are available immediately after large-scale disasters [1–4]. Some efficient technologies with regards to Wi-Fi communication network have been developed after the Great Eastern Japan Earthquake [5, 6]. These technologies have a possibility to establish temporary Wi-Fi network right after the disaster in disaster-damaged area. However, authors are thinking that information should be consolidated by control center in such critical situation. Otherwise, the important information will be buried in rumor.

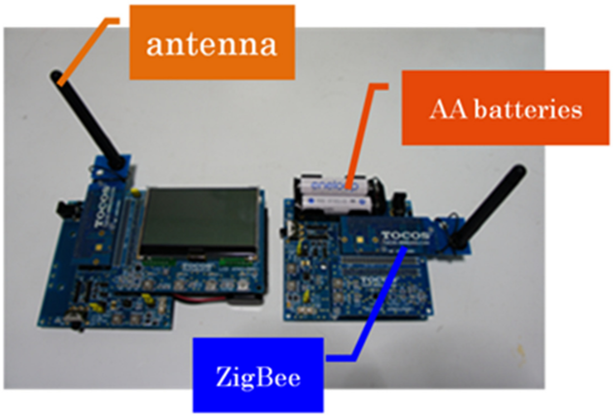

Fig. 1. ZigBee modules.

In this series of research, a disaster management system which collects and manages disaster information in an integrated fashion at control centers has been proposed [7]. These centers act as emergency response headquarters and they support rescue efforts, the distribution of relief goods, etc. through ad-hoc networks. Concretely, a wireless meshed network is expeditiously constructed with ZigBee terminals (**Fig. 1**) which are inexpensive and serve as nodes of the wide-area wireless radio. Although there are many methods of constructing wireless communication networks, wide area network systems that can be constructed rapidly are limited. In this research, the ZigBee protocol specification based on the IEEE 802.15.4 standard for wireless personal area networks was adopted for the communication method. There are several reasons for considering ZigBee. ZigBee is characterized by a large network capacity and a multi-hop function for transmitting data via repeaters when the sending terminal cannot directly transmit the data to the receiving terminal. In order to communicate with the terminals, the sending terminal transmits nearby to the receiving terminal, so the transmission power can be reduced. Moreover, if the network capacity is large, large number of terminals can be configured as one wireless network. By selecting two or more forwarding routes on the ZigBee network, data can be transmitted safely. In addition, because of this benefit, a mesh network can be constructed. Moreover, since ZigBee designs the networks with automatic operation, easy maintenance is possible. Thus, as a means of constructing a simple wide area network, ZigBee has many advantages. Consequently, we adopted ZigBee for our study.

Investigators collect disaster information through the network with mobile terminals. This system is useful not only for public-help on a governmental scale, but also for self-help on a local scale.

One problem that arises when the network is planned is that it needs to cover spots and large areas such as the control center, the evacuation centers and the disaster area. In addition, investigators place the ZigBee terminals to create wireless network on foot or by vehicle; thus, covering the objective area is difficult for them, so markings which show where to arrange the terminals are considered crucial [7]. The range of radio communication is significantly affected by land-use and geographic characteristics such as vegetation and buildings, and it is dificult for investigators to know where they can connect the network. Consequently, a visualization of the range of radio communication is also mandatory especially for maintenance purpose of network.

Figure 2 shows the flow of the proposed system in our previous paper [7]. Geographical information about the target area is collected before a disaster. Once the disaster happens, if possible, the geographical information is updated using satellite images, as changes of structures (e.g., collapsed buildings) may have occurred in the meantime. Then, the location of the ZigBee terminals is optimized to set up a wireless network between a disaster control center and an evacuation center. Additionally, the range of communication is also analyzed for visualization (mapping). The ZigBee terminals are installed by the investigators with half an eye on their own location (determined via GPS) and the optimal location map; thus, the whole system is created and the disaster information is managed to support any kind of aid. Although, the ZigBee nodes will be deployed to ballpark position flexibly in case of real operation, these ballpark positions could be calculated and determined by professionals before a disaster. Also, an optimized deployment will clearly show how many nodes will be required for particular cover area. This will be very important fundamental research to develop our entire proposed system.

Against this background, in this article, we propose a radio propagation analysis method and an optimization method to establish stable and large coverage communication. The radio propagation analysis needs to be available for any actual environment such as forests, grassy places, buildings, etc., so that we can apply it to the radio range visualization of the ZigBee terminals, and so that

Fig. 2. The flow of the proposed system.

we can use it in the placement optimization. The proposed method combines the Ray-Launching method, which is a Ray-Tracing method, and estimation formulae obtained by field tests in an actual environment. Furthermore, this method considers elevation not only to improve accuracy of analysis, but also to deal with additional types of environment. As to the optimal location problem to create connections between two points, location spots for the ZigBee terminals are searched via a computationally effective bi-directional search. Experimentally, we validate the accuracy of the proposed radio propagation analysis in an actual environment.

2. Radio Propagation Analysis Method

2.1. Existing Radio Propagation Analysis Methods

There are mainly two types of radio propagation analysis methods: one is based on formulas statistically determined by field tests, and the other is based on numerical computations. **Table 1** shows an overview over existing radio propagation analysis methods. The Okumura-Hata model is one of the statistical methods. It models radio attenuation features on three modes to obtain approximation formulas of each mode; the modes are for urban, suburban, and open areas. The model was built based on data collected in the city of Tokyo, Japan. The method is only applicable to the radio propagation prediction within urban areas with many structures, when not too many blocking structures are present [8].

The Finite Difference Time Domain method (FDTD) and the Ray-Tracing method are radio propagation pre-

Table 1. Characteristics of existing radio propagation analysis methods.

Method	Advantage	Disadvantage
· Moment method · Boundary element method	· Effective analysis of antenna · Low computational time depending on shape of antenna	· Shape is limited only liner and flat shape which is perfect conductor · Requiring accurate model of targets
· Ray-Tracing method	· Simple principle · Analysis on city environment · Accurate simulation of reflection and diffraction	· Requiring accurate model of target area · Target is limited to city area · Computational time requirement for wide area
· FDTD method	· Simple principle · Unhomogeneous material and any shape can be analyzed · High accuracy in small target	· Requiring accurate model of target area · Computational time requirement for wide area
· Okumura-Hata method	· Wide range analysis is possible · Actual environment	· Target is base station on high building or ground

diction methods based on numerical computation. In the FDTD method, Maxwell equations are discretized to space and time, and the electric field intensity over time is calculated for the analysed region. On the one hand, the basic algorithms of the FDTD method are simple and the estimation is relatively accurate. On the other hand, they are computationally very expensive and therefore not suitable to our proposed disaster management system [8–10].

As for the Ray-Tracing method, a radio wave transmitted from a base station is regarded as a ray, and the electric field intensity at receiving point is calculated based on geometric optics [11]. **Fig. 3** shows the fundamental rule of the Ray-Launching method, which is a form of ray-tracing. There, a sufficient number of rays are launched from the transmission point Sx, and the launched rays are tracked. If the tracked ray reaches the neighbourhood of the receiving point Rx, the reached ray is regarded as a received ray; therefore, the precision depends on how the neighbourhood is defined.

Generally, the electric field intensity of the ray that reaches a receiving point from a transmitting point (with N_r times reflection and N_d times diffraction) is given by

$$E_i = E_0 \frac{R \cdot D}{d} \exp\left(jk \sum_{l=1}^{N_d+1} s_l \right) \quad . \; . \; . \; . \; . \; . \; . \quad (1)$$

$$\begin{cases} R = \prod_{m=1}^{N_r} R_m,\ D = \prod_{l=1}^{N_d} D_l \\ \dfrac{1}{d} = \dfrac{1}{s_1} \prod_{l=1}^{N_d} \sqrt{\dfrac{s_1 + \ldots + s_l}{(s_1 + \ldots + s_{l+1})\, s_{l+1}}} \end{cases}$$

where R_m represents the reflectivity coefficient of the m-th reflecting surface, and D_l represents diffraction coefficient of the l-th diffracting edge. S_k represents the approximate distance between the $k1$-th diffraction point and the k-th one. $N_d + 1$ is an approximate distance from the last diffracting point to receiving point. E_0 is the electric field intensity of transmitting point and k is the wave number.

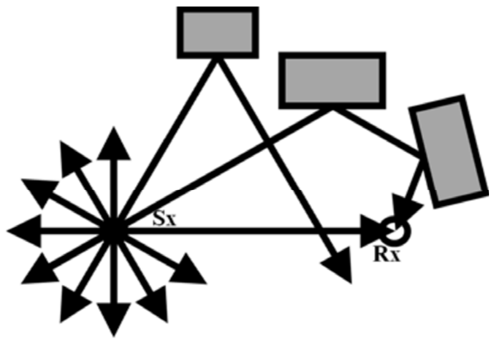

Fig. 3. Principle of Ray-Launching method.

For the estimation of the area that the radio waves cover, the electric field intensity needs to be calculated at a suffcient number of receiving points. This makes this method computationally expensive. It is necessary to obtain information about precise configurations of structures on the target areas; additionally, the computation time increases exponentially with the number of structures in the area. Due to the nature of the Ray-Launching method, it is not possible to apply it on non-urban areas such as forests, grassy places and so on [8, 11].

2.2. Flexible Acquisition of Geographical Information and Speeding up Radio Propagation Analysis

Our proposed system intends to construct ZigBee-based wireless networks immediately after a large-scale disaster. For this, the electric field intensity analysis on a variety of different areas is required to connect the network between a control center and the evacuation centers. First, the computational time must be reduced by a large degree compared with other existing methods. Second, the analysis needs to be possible for target domains involving forests, water areas, grassy places and so

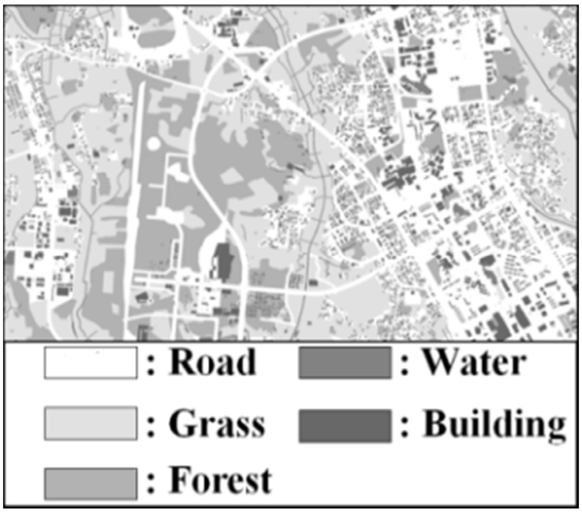

Fig. 4. Digital map with land-use information.

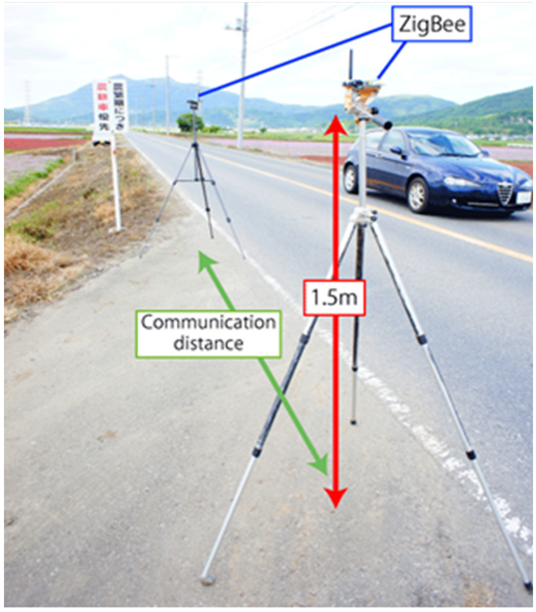

Fig. 5. Attenuation measurement experiment.

forth. Third, the method must be able to quickly consider changed landscapes due to a major disaster such as earthquakes (e.g., new and/or collapsed buildings). The proposed method must meet these three requirements which are (1) a low computational time, (2) the applicability to any environment, and (3) the possibility to address the collapse and change of buildings caused by a disaster.

In our proposed system, GIS (Geographic Information System) is used to obtain geographical information on the target areas to address any environment and the collapse and change of structures.

In our study, the information about vegetation, structures, land-use and other almost all geographical information is freely obtained from Ministry of the Environment of Japan and Geospatial Information Authority of Japan. Addressing the collapse and change of structures is possible by using GIS and satellite images taken right after disasters. For example, this information can be processed with ArcGIS, which is a commonly used GIS. In this article, we classify the areas based on the available information into the five classes building, grassy place, forest, water area, and road. With this classification, we pre-process a map exclusively for radio attenuation prediction, and each classification is given a particular pixel value on the map. An example around Tsukuba Center station, Tsukuba city, Japan is shown on **Fig. 4**. The darkest parts of **Fig. 4** indicate buildings (pixel value is 0) and the second darkest parts express water areas (pixel value is 36) as just described. Acquiring location information and classifications about the target area is possible by referencing to the processed map. Our actual problem of placing the ZigBee terminals in an optimal way then boils down to a combinatorial optimization problem.

2.3. Experiments for Attenuation of ZigBee Radio Field Intensity

The permitted frequency band used by ZigBee in Japan is 2.4 GHz. The radio band of 2.4 GHz tends to propagate straight ahead, compared with lower frequency bands of radio, and it diffracts less than lower frequency radio. The range of radio communication depends on geographical information on the target area by a large margin, which is why we divide the geographical information into five classes. In the following, we report on our experiment to investigate the radio attenuation characteristics of each classification.

Received Signal Strength Indication (RSSI) values were measured in the experiment; the unit is decibel milliwatt (dBm). RSSI shows the signal intensity of wireless communication devices such as Bluetooth and Wi-Fi. **Fig. 5** indicates the experimental setup for measuring the RSSI. The ZigBee terminal of transmission is located on a tripod which is 1.5 m high on each classification.

RSSI values are measured by the receiving ZigBee terminal every 100 m (or less) from the transmitting terminal unless RSSI value attenuates to −80 dBm because stable communication is not possible under −80 dBm [12]. With regard to the eventual approximation formula, the height of both transmitting and receiving (measuring) terminals are identical, so the only parameter is the distance between transmitting and receiving terminals. The approximation formula is given by

$$\mathrm{RSSI} = A - B\log_{10}\left(\frac{1}{r}\right) \quad \ldots\ldots\ldots\ldots \quad (2)$$

where, r represents the distance. A and B represent constants depending on the situations.

Figure 6 shows the results of experiment. Black dots (•) in the **Fig. 6** are the results of measurements and the results are approximated by estimated formula shown as curve lines in **Fig. 6**. As a result, the RSSI values on road and water area appear to gradually attenuate in an almost linear fashion. In contrast, the RSSI values appear to attenuate exponentially in forests and in areas with many

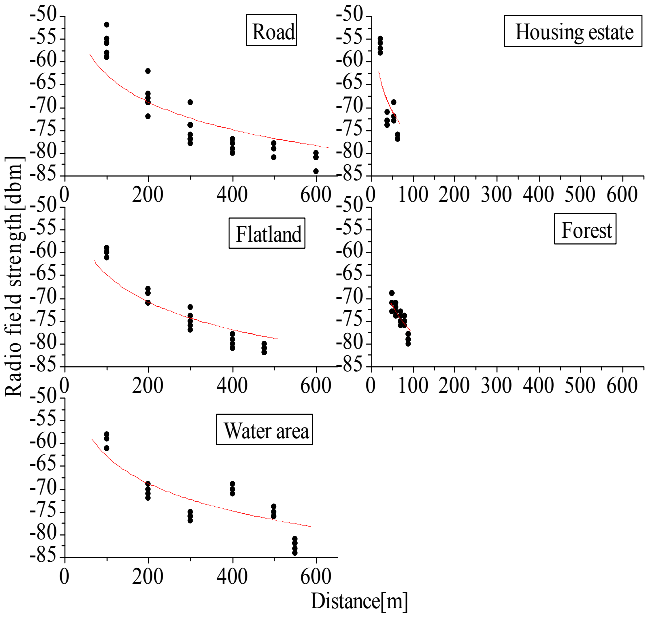

Fig. 6. Results of attenuation experiment.

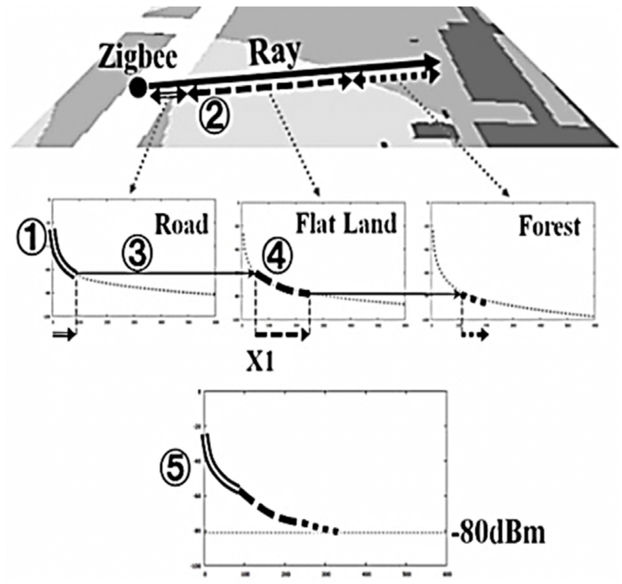

Fig. 7. Overview of the proposed method.

buildings. The distances which result in an attenuation down to −80 dBm on road was about 550 meters, on the grassy place it was about 400 meters, on water it was about 500 meters, around buildings it was about 70 meters, and in the forest it was about 90 meters, respectively.

2.4. Radio Wave Propagation Analysis Using GIS

Our proposed method combines the approximation formulae obtained by field tests in actual environments (**Fig. 6**) with the Ray-Launching method. However, in order to reduce the computation time, it does not consider reflection, diffraction, and permeation. Rays are launched from the transmitting terminal evenly as in the original Ray-Launching method. Instead of considering reflection, diffraction and permeation, the approximated formulae are applied to each ray depending on the five geographical classifications mentioned in the **Fig. 4**.

Figure 7 describes the way of applying approximation formulae to a ray. First of all, the ray in **Fig. 7** propagates along the road, so the electric field intensity (RSSI value) attenuates depending on the approximation formula obtained on the road (**Fig. 7**①). Second, the ray gets on a grassy place (**Fig. 7**②). From this point on, the ZigBee Radio field intensity attenuates depending on the approximation formula obtained on grassy places. At this point, the RSSI value reduces from the point which has the same RSSI value as the point of the approximation formula on road just before reaching the changing point (**Figs. 7**③ and **7**④). After that, this process continues until the RSSI value is calculated down to −80 dBm; hence, we have an attenuation estimation procedure that considers geographical information (**Fig. 7**⑤). We estimate the radio propagation by computing the rays in all directions evenly around the transmitting ZigBee terminal.

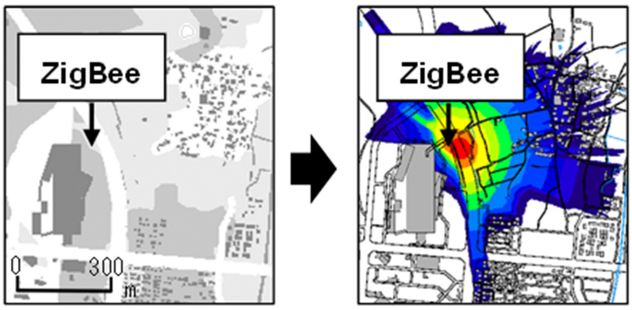

Fig. 8. Geographical location map (left) and analysis results (right).

2.5. Results of Radio Wave Propagation Analysis

Figure 8 (right) shows the result of radio propagation prediction by the proposed method. On the left, we show the geographical information divided into five classifications, and on the right we show the corresponding RSSI estimation. There is large building and a forest on the lower left of the located ZigBee terminal; therefore, heavy attenuation is predicted. Grassy place run on the upper right of the terminal, so radio wave is predicted to propagate further. The radio waves propagate farthest along the road: they reach the far upper left and far below.

2.6. Radio Wave Propagation Analysis Considering Elevation

In the previous section, we have presented our first model for the radio wave propagation analysis that considers different geological features. However, it does not yet consider the radio wave attenuation caused by difference of elevation. This is crucial, as elevation has a significant influence on radio wave propagation and attenuation over rough surfaces. In this section, we describe

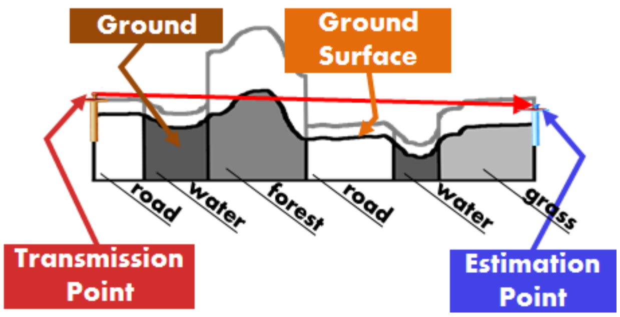

Fig. 9. Circumstances of estimation.

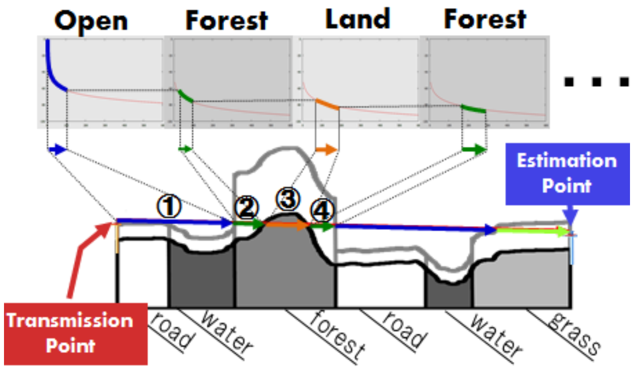

Fig. 10. Overview of estimation method.

how to consider elevation in the radio wave propagation analysis. **Figs. 9** to **11** show the outlines of the proposed method. **Fig. 9** indicates the locations of the sending ZigBee terminal, which is set up on the ground, and the receiving ZigBee terminal. Also, the geological condition which is obtained by ArcGIS is shown. The gray line in **Fig. 9** indicates the altitude affecting the radio wave propagation in particular geological conditions, such as road, forest, grassy area and water area. Actually, the altitude of those areas and the altitude affecting the propagation of radio waves are different. Concretely, the road area affects 2 m height from road surface, the water area affects 2 m height from water surface, the structure area affects 50 m height from structure surface, the forest area affects 30 m height from forest surface and the grassy area affects 3 m height from grassy surface, respectively. From **Fig. 9**, it can be observed that an emitted ray of a radio wave from the sending ZigBee terminal runs through above the road, above the water, forest affected area, along the ground, above the water, above the grassy area and along the grassy area to the receiving ZigBee terminal.

By considering the height which each geographical condition affects radio propagation and by slightly changing the classifications, we extend our previous method to rough place analysis. **Fig. 10** concretely represents how to estimate the radio wave propagation by the improved method on the same place mentioned in **Fig. 9**. **Fig. 11** indicates the attenuation estimating function obtained to each estimation points.

At the beginning, the ray propagates in open space, so

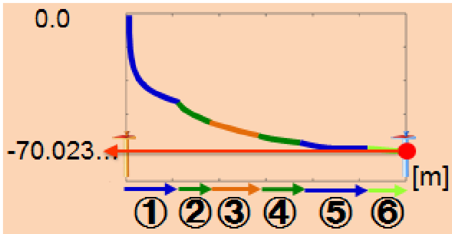

Fig. 11. Overview of estimation method.

the RSSI value reduces depending on the approximation formula obtained in open space (**Fig. 10**①). Then, it goes into forest affected space (**Fig. 10**②, **Fig. 11**②). In the same way as in the proposed method mentioned of Section 2.3, the RSSI value is reduced depending on each approximation formula until the ray reaches the estimation point, or until the RSSI value get down to −80 dBm. The same procedure is continued until the ray reaches the estimation point (③, ④, . . .) or the signal strength attenuates down to −80 dBm.

The RSSIs are calculated all over the target area around the located ZigBee terminals. With this information, we can then visualize the electric field strength of ZigBee terminals.

3. Accuracy Verification of Proposed Radio Wave Propagation Analysis Method with Field Test

Figure 12 shows the geographical information of the target area, which are the five classiffications on the left and the elevation on the right. 5 m mesh data were used for elevation model. **Fig. 13** shows a result of a radio wave propagation analysis described in Section 2.5.

The computational time needs to be as short as possible, as we aim to respond to disasters with our proposed disaster management system. Consequently, the number of estimation points needs to be considered carefully to achieve an acceptable trade-off between accurate estimations and computation time. However, in this paper, estimation points are located most thickly to verify the proposed method. They are located on all of 1 square meter patch of land around the ZigBee terminal. Then at all of the points, the electric field strength is analyzed based on the proposed method. In **Fig. 13**, RSSI attenuate less than −80 dBm along a river at left below of the ZigBee terminal due to the low elevation of the river.

An experiment is conducted to verify the accuracy of the proposed method. **Fig. 14** shows spots where the RSSI values are measured. The way how RSSIs are measured at 34 spots is identical to the way used in the experiment in the Section 2.3. The measured spots are decided randomly. The map of **Fig. 14** shows an area around Tennodai, Tsukuba city, Ibaraki, Japan.

In the following, we compare the results of our analysis with those of the field test. **Table 2** shows the results of the experiment, the estimated RSSI values by our pro-

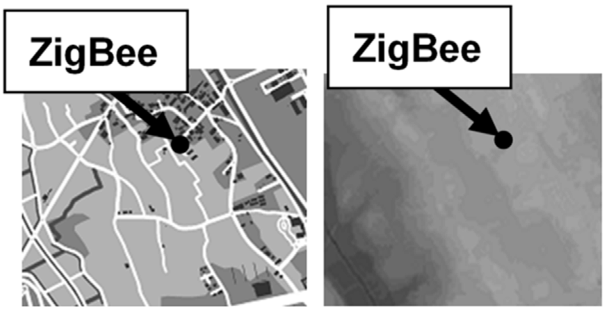

Fig. 12. Land-use and altitude information.

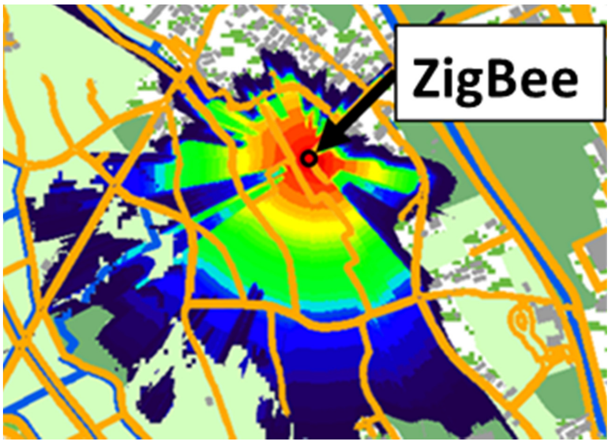

Fig. 13. Results of analysis.

Fig. 14. Sampling points.

posed method, and the error. The numbers of the sampling points in **Fig. 14** and **Table 2** correspond.

The measured RSSIs are higher than −80 dBm at 26 spots out of the 34 spots. At 16 spots, the absolute errors are less than 3 dBm, and the errors are less than 5 dBm for 20 out of the 26 spots.

At the spots where the errors are higher than 5 dBm and the values are positive (means: measured values are higher than estimated values) (see **Fig. 14** and **Table 2** of No.17, No.18, No.28, No.31), the landscape between them mainly consists of grassy places and roads, with nothing blocking. These errors are thought to be caused

Table 2. Results of experiment.

No.	Measured Value	Predicted Value	Error	No.	Measured Value	Predicted Value	Error
1	−52.30	−52.50	0.20	18	−64.06	−71.50	7.44
2	−62.17	−59.50	−2.67	19	−78.14	−77.00	−1.14
3	−65.32	−65.00	−0.32	20	−71.83	−72.00	0.17
4	−78.54	−76.50	−2.04	21	−80.02	−78.00	−2.02
5	−82.54	−80.00	−2.54	22	−76.67	−76.50	−0.17
6	−81.70	−79.50	−2.20	23	−77.09	−71.00	−6.09
7	x	x	x	24	−74.35	−76.50	2.15
8	x	x	x	25	−77.53	−76.50	−1.03
9	x	x	x	26	−67.09	−71.00	3.91
10	x	x	x	27	−68.98	−65.00	−3.98
11	x	x	x	28	−56.29	−68.00	11.71
12	−65.53	−69.00	3.47	29	−70.78	−70.00	−0.78
13	x	x	x	30	−69.11	−68.50	−0.61
14	x	−79.00	x	31	−68.68	−74.50	5.82
15	−76.03	−72.50	−3.53	32	−73.09	−74.00	0.91
16	−71.42	−71.50	0.08	33	−79.30	−74.00	−5.30
17	−65.11	−72.00	6.89	34	x	−73.50	x

by the inaccuracy of the approximation formulae in the Section 2. Indeed, in the **Fig. 6**, it is confirmed that the measured values from approximately 0 m to 250 m are higher than approximation formulae of grassy place and road. At the measured spots which they are higher than 5 dBm and the values are negative, which means that the measured values are lower than the estimated values (**Fig. 14** and **Table 2** of No.23, No.33), the landscape mainly consist of a few buildings. The elevation is a little different between the transmitting spot and measured spot; additionally, they are completely invisible from each other. The errors are thought to be due to the elevation difference and due to the few buildings. The 2.4 GHz band radio wave used in the ZigBee terminal is largely affected and attenuated by the situation.

The measured RSSIs are lower than −80 dBm at eight spots out of the 34 spots. At six spots out of the eight spots, the estimated values are lower than −80 dBm, so this means that the analysis was correct. However, at others 2 spots, the estimated RSSIs are −79.0 dBm and −73.5 dBm (**Fig. 14** and **Table 2** of No.13, No.34). At the spot No.13, geographical information between transmitting spot and measured spot involve two condominium buildings; moreover, the transmitting ZigBee terminal is near the buildings, so this situation is thought to have caused the large error. At the spot of No.34, geographical information between transmitting spot and measured spot contains three two-story buildings, trees, a concrete wall, and so on, and these are thought to have attenuated the radio propagation; consequently, the error occurred.

The proposed disaster-management system aims to provide investigators the range of radio communication to inform them where they are able to connect the network. Therefore, negative error values must be avoided, as they falsely indicate suitable spots where the connection cannot be established.

In conclusion, we confirm that the proposed radio propagation analysis method is applicable to mixed environments that consist mainly of roads, grassy places, water areas and small single buildings.

Large errors could be reduced by modifying the approximation formulae; as a result, the proposed method would provide even higher quality prediction for a wider range of environments.

4. Optimized Arrangement of Zigbee Terminals

4.1. General Idea of Optimal Arrangement

The manual location of wireless communication device terminals is difficult because the radio propagation largely depends on geographical information [13]. Consequently, if communication stability is very important and the placement is done without GIS-support, the unoptimized number of the terminals would often be unnecessarily high.

As mentioned before, ZigBee communication devices use 2.4 GHz radio frequency, so over-the-horizon communication cannot be expected. The proposed disaster-management system aspires to be constructed not only by rescue teams, such as self-help force, but also by sufferers themselves. Hence, it is not intuitive for them to locate the ZigBee terminals based on signal attenuation, as the sufferers are most likely not familiar with this technical detail. A straightforward way to place the terminals is to locate them every 550 m along a wide road, because the radio signals reach furthest there (**Fig. 6**). Another intuitive placement strategy is to place them along the shortest path between two terminals.

In this section, we propose an optimization method to solve the state problems. This method aims at minimizing the number of the needed ZigBee terminals.

4.2. Optimized Arrangement of ZigBee for Creating Wireless Network Between Two Nodes

To solve the mentioned problems, we propose an optimal location method using bidirectional search. The used information for this method is the geographical information used for radio propagation analysis. As stable communication is not possible below −80 dBm, we will use this as the minimum RSSI threshold.

The proposed method works as follows:

1. Firstly, the two to-be-connected points are decided: “Start” and “End” (**Fig. 15**, STEP1).

2. The radio propagation is analyzed (using rays) around the terminal of “Start” to a maximum of −80 dBm.

3. The total distance, with respect to the geographical information between a point ray reaches and the End terminal, is calculated (**Fig. 15**, STEP2). We will call this distance the attenuation-distance.

4. Three points of all points that the rays reach are maintained which the attenuation distances are from the shortest to third shortest with respect to the Start terminal (**Fig. 15**, STEP3). These three points are candidate points which would be connected to the Start point.

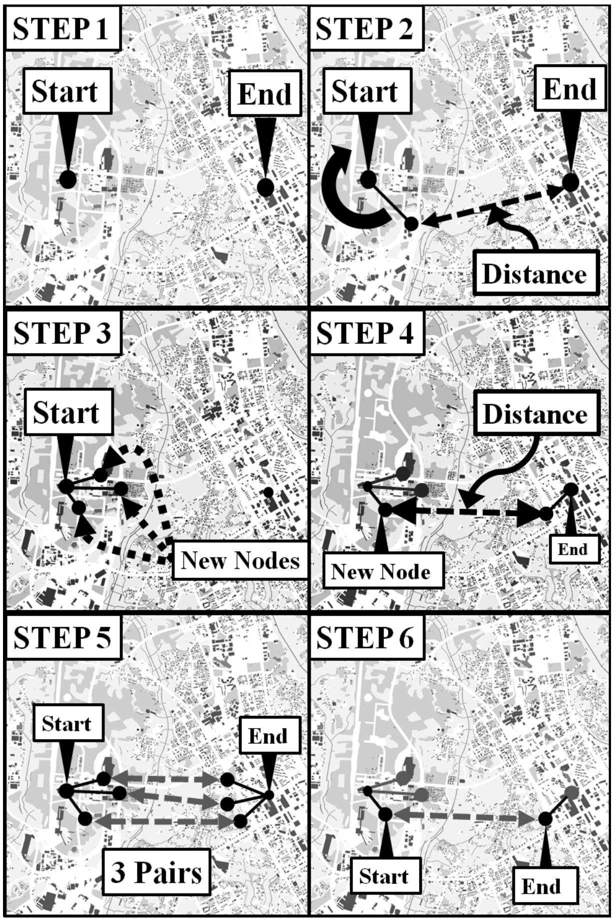

Fig. 15. Arrangement method of the ZigBee modules.

5. One point of the three candidate points is chosen.

6. Radio propagation is analyzed around the terminal of “End” to −80 dBm. The attenuation-distances from the “End” point to the three candidate points are calculated respectively (**Fig. 15**, STEP4).

7. The point that the attenuation-distance is the shortest of three candidate points is selected as a new “End” point.

8. Two remaining candidate points that are not chosen in procedure 5 are chosen. Likewise, the procedure 6 and 7 are applied to the two points.

9. Three peers are maintained (**Fig. 15**, STEP5). These peers are regarded as new “Start” and “End” points (**Fig. 15**, STEP6) and the same procedure from 1 to 9 is applied to these new peers of “Start” and “End” points.

10. If Start point and End point are able to connected, the all calculation is over.

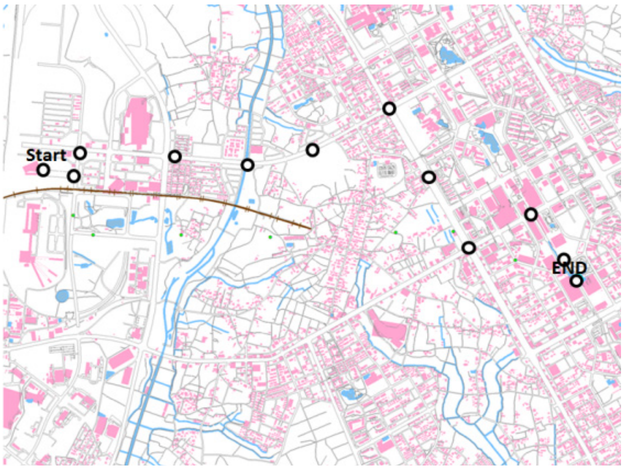

Fig. 16. Example of arrangement along wide road.

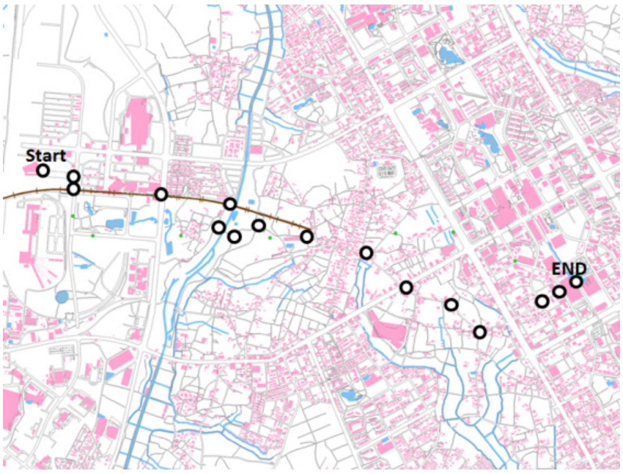

Fig. 17. Example of arrangement along the shortest path.

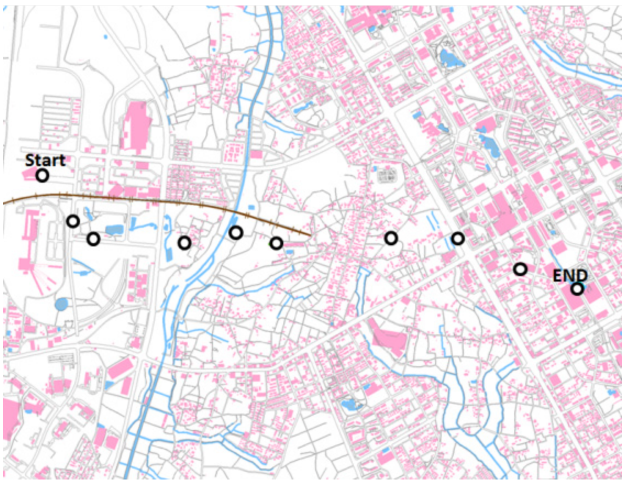

Fig. 18. Result of optimized arrangement.

4.3. Result of Optimal Arrangement and Visualization of Range of Radio Communication

This section describes how our optimized location method works in a real disaster damaged area. A GIS database was developed for Tsukuba City using ArcGIS

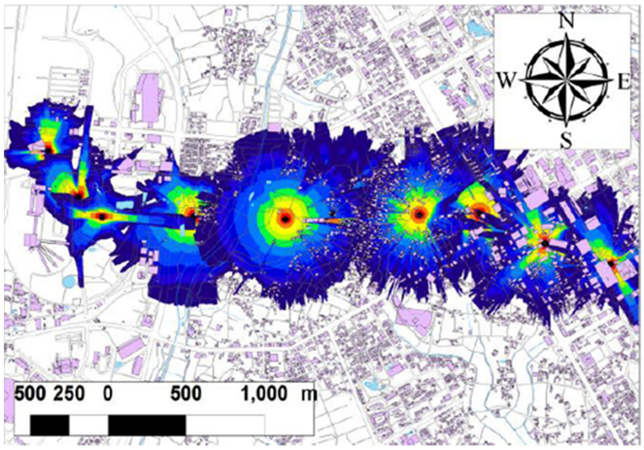

Fig. 19. Coverage map of wireless communication.

to provide a foundation for mapping the communications network coverage area and to be able to view and evaluate the parameters affecting the network establishment and operation. Basic thematic maps can then be downloaded from various online resources and then used immediately in the emergency operations on the ground. The radio wave attenuation coefficients related to the environmental factors are used to determine the optimal arrangement of the ZigBee nodes in the disaster-damaged area. The requirement is to construct a wireless network that covers the control center and the evacuation center with the minimum number of nodes. In this case, the Tsukuba City Office was set as the control center and Tsukuba Center station was set as the evacuation center, respectively. Let us first consider two naive approaches to place the ZigBee terminals. First, **Fig. 16** shows the example arrangement based on proposed method "along wide road," where ○ are the locations of the terminals.

Similarly, **Fig. 17** shows the result of the arrangement along the shortest path between two terminals. They require 12-modules and 16-modules respectively to connect the control center and the evacuation center with a ZigBee network system. The result of the optimized arrangement from a standpoint of minimizing the number of modules to create wireless network between the control center and the evacuation center is shown in the **Fig. 18**. This result demonstrates that the 10 modules can cover almost 6 km^2 in such situations. The distance between them is 3.8 km and the geographical information involves buildings, roads, grassy places, and forests. Also, **Fig. 19** shows the coverage of ZigBee wireless communication in case of **Fig. 18** arrangement. With this map, investigators can then build wireless network after a disaster. In the proposed overall disaster-management system, the investigators' own locations would be displayed in the map as points, so they can create the network efficiently. Although, the ZigBee nodes will be deployed to ballpark position flexibly in case of real operation, these ballpark positions could be calculated and determined by professionals before a disaster. Also, an optimized deployment will clearly show how many nodes will be required for particular cover area. This will be very important fundamental research to develop our entire proposed system. Note that optimizing the arrangement took only 2 minutes 34 seconds on a PC with an Intel Core i5 using 2 GB of RAM. This computational time is fast enough to build alternative wireless network after a disaster.

5. Conclusion

This research investigated a wireless network system that can solve some of the problems caused when public wireless network systems are damaged and communications are rendered inoperable due to large disasters. The study also included the applicability validation of the radio wave propagation analysis and of the visualization method. The goal of this research is to construct a system that can be deployed rapidly after a disaster to ensure that an adequate communication system is in place within the disaster-struck region, with the overall goal being the support of emergency and recovery operations.

The accuracy of our radio wave propagation analysis proved to be high on places that mainly consists of roads, grassy places, water areas, and small single buildings. Our method could be further improved by additional analysis of the problematic landscapes and through additional field tests.

Exemplarily, we used the proposed terminal placement optimization to create a network after an assumed disaster in a real city. The calculation results show that the proposed method works efficiently, and it outperformed two naïve approaches. The optimal ZigBee nodes arrangement can be automatically visualized on the thematic map, which investigators can effortlessly use to build wireless network efficiently after a disaster. Although, the ZigBee nodes will be deployed to ballpark position flexibly in case of real operation, these ballpark positions could be calculated and determined by professionals before a disaster.

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