Design of Wireless Sensor Network in the Railway

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Abstract: In recent years, research and development on the condition monitoring systems using the wireless sensor network in the railway have been proceeded. However, there are few cases of the wireless sensor network design based on the features of the railway environment. In this paper, we propose the procedure to design the wireless sensor network in the railway. And we introduce the demonstration test and the result in the railway slope based on this procedure.

1 INTRODUCTION

The railway is the essential transportation mode in many countries. Especially, in Japan, passenger transport in FY2015 stood at 24.3 billion persons, and freight transportation stood at 43.21 million tons (Ministry of Land, Infrastructure, Transport and Tourism, 2016). However, many Japanese railway infrastructures were built before the 1970's, so the average age of many tunnels and bridges is over 60 years.

To maintain and manage these aged facilities properly is important for safe and stable operation in railways. Therefore, regular inspections are carried out on the structures once every two years, the soundness of the structures is evaluated according to the inspection results, and, if necessary, repair and replacement and so on are carried out (Railway Technical Research Institute, 2007).

In recently, condition monitoring by the WSN (Wireless Sensor Network) has attracted attention, and research on the condition monitoring system utilizing the WSN is under way in the railway as a matter of course. By monitoring the status all the time with the WSN, it is expected that we can take necessary measures based on right timing. However, there is concern that the railway environment may not be so created that, in there, we can collect data frequently not enough to monitor the structure states unless network design is properly made, since in the railway environment, areas with different radio environment such as urban areas and mountainous areas are mixed and there are many metal objects.

Therefore, we propose a procedure for designing a WSN in railway environment considering these problems. Furthermore, based on the proposed WSN design procedure, a WSN using the 920 MHz band wireless communication standard Wi-SUN (Wireless Smart Utility Network) was experimentally introduced to an actual railway slope and a demonstration test was conducted. In this paper, we report the outline and results of the verification test.

2 CONDITION MONITORING USING THE WSN IN THE RAILWAY

2.1 Condition Monitoring System

In the condition monitoring system using the WSN that we are working on in this research, data is collected by the WSN installed in the object to be monitored, and these data are transmitted to the M2M cloud via the Internet network and accumulated (Fig. 1). These data can be viewed or downloaded via the Internet network as necessary.

2.2 WSN

The WSN handled in this paper consists of a gateway, relays, and wireless sensors. The wireless sensor consists of a sensor for measurement and a wireless terminal, and is attached to the object to be

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monitored. The data measured by the wireless sensor is wirelessly transmitted to the gateway. If they cannot be directly transmitted from the wireless sensor to the gateway, they are transmitted to the gateway via relay by multi-hop transmission. And the collected data is sent to the cloud through a public or private network and accumulated. In this paper, the gateways, the relays and the wireless sensors are collectively called nodes.

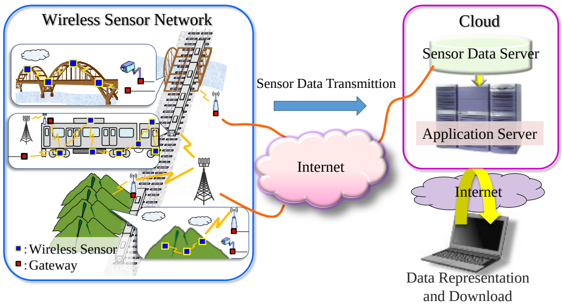

Figure 1: An example of the condition monitoring system using the WSN.

WSNs have static and dynamic networks (Bakaraniya and Mehta, 2012; Potdar et al., 2009). The static network is a network for making data transmission by a preset route. On the other hand, the dynamic network is a network that communicates between nodes and autonomously composes.

The static network has the advantage that the power load at each node can be calculated in advance because the route is designed beforehand. Thus, it is possible to formulate the battery design of each node and an efficient battery replacement plan. However, when a route change occurs due to the addition of a node, it is necessary to change the setting for the nodes on the route. Also, when a node failure occurs, sensor data from that node and sensor data passing through that node cannot be obtained until the node is exchanged.

On the other hand, since each node autonomously makes a route in the dynamic network, it is not necessary to manually change the route due to the addition of a node. Unlike the static network, it does not always use the same route, so it is not possible to calculate the power load of each node in advance. So, for such a dynamic network, we developed a method of estimating the battery load by stochastically changing the route in time series by the Monte Carlo method (Kawamura et al., 2016). The details are omitted in this paper.

2.3 Problems in Designing WSN in Railway Environment

As the features of the railway environment, it can be cited that a wide area which urban areas and mountainous areas between which there may be a large difference in the radio wave environment extends linearly and long, and that there are plenty of metallic objects that are liable to hinder radio wave propagation. In addition, from the viewpoint of safety and physical conditions, restrictions may be placed on the installation location and installation height of nodes. For these reasons, the communicable distance varies depending on the installation location, and there is a concern that communication quality for collecting necessary data cannot be secured after their installation. Therefore, a method of designing a network in consideration of the environment of the installation site was examined.

3 PROCEDURE OF WSN DESIGN

There is research on the design of WSN, but there seems not to be found the network design considering the railway environment as mentioned above (Hodge et al., 2015; Tiwari et al., 2007; Xu et al., 2005; Youssef and El-Sheimy, 2007). So we propose a design procedure for introducing the WSN in railway environment. It is explained below.

STEP1 Determination of objects and items to be monitored
The railway operator decides the objects and the items to be monitored. And it sets the collection frequency and acceptable arrival rate of the data required according to the monitoring item. In the following procedure, the network is designed so as to satisfy the required specifications set here.

STEP2 Determining the location of the wireless sensors and gateway
It selects the location of the wireless sensor according to the monitoring items determined in STEP1. In addition, the location of the gateway is selected the area of public or private network, and a fixed power source is available, if possible.

STEP3 Survey of installation environment
In order to determine the location of the relay, it confirms the location where the relay cannot be installed and check the line of sight and obstruction between the wireless sensor and the gateway. In accordance with the installation environment, we

appropriately select the frequency band and the communication standard to be used. In addition, it conducts a radio wave environment survey and so on to derive communicable distance in the installation environment.

STEP4 Derivation of communicable distance in installation environment
From the result of the survey of the radio wave environment at the installation location implemented in STEP3, it derives the communicable distance in this environment. The term "communicable distance" means the distance at which the data arrival rate between the nodes which results in achieving the data arrival rate of STEP1 is secured.

STEP5 Determination of the installation location of relay
If data cannot be transmitted directly from the wireless sensor to the gateway, multi-hop transmission is performed. If the wireless sensor can be transmitted via another wireless sensor between the wireless sensor and the gateway, there is no need to take additional measures. However, if the number is insufficient, dedicated relays should be installed. By setting up this relay, we attain the achievement rate set in STEP1. The details of the method of determining the installation location of the relay apparatus will be described Chapter 4.

STEP6 Power supply design
Since wireless sensors and relays are not necessarily installed in locations where fixed power supply is available, and there is a possibility that many nodes may be installed for one monitoring location, basically, power supply by a battery or an energy harvesting is provided. Therefore, in accordance with the network operation period and so on, the design of battery capacity and energy harvesting generation capacity and so on are properly determined.

4 THE DETERMINATION METHOD OF RELAY LOCATION

We describe the method of determining the location of the relay in STEP5 of chapter 3. This method minimize the number of relays and satisfies constraints given such as the specifications of the nodes and the position of the obstacles. Also, since various shielding objects are present along the railway track, it is necessary to consider the influence on the wireless communication by the shielding object in determining the placement of the relays. It is difficult to consider the influence of the shielding objects in the conventional relay placement determination method. In this paper, we propose a method to decide the effective placement of the relays of WSN, taking into consideration the influence of shielding objects using mathematical optimization. The objective function of this method can be formulated as the minimization of the number of relays as shown in Equation (1).

[Objective function]

$$\min(R_{num}) \quad (1)$$

[Constraints]

$$r_{i,gat} = 1 \quad (2)$$

$$\mathrm{P}_i(x,y) \neq \mathrm{N}_j(x,y) \quad (3)$$

In the above equations, R_{num} is the number of relays, $r_{i,j}$ is the reachability matrix, $r_{i,j} = 1$ if there is a route by which data can reach node j from node i, and $r_{i,j} = 0$ if there is no reachable route. Also, $\mathrm{P}_i(x,y)$ is a position (x coordinate, y coordinate) of the relay device i, and $\mathrm{N}_j(x,y)$ is the position (x coordinate, y coordinate) where the relay cannot be installed. Equation (2) represents the constraint relating to the arrival of data from each wireless sensor at the gateway, and $r_{i,gat}$ represents the reachability of the gateway from the wireless sensor i by data. Equation (3) represents the constraint relating to the position of the relay.

Here, the position $\mathrm{N}_j(x,y)$ where the relay cannot be installed included in the constraint condition is given as input, and it shall be set according to the conditions of the environment where the WSN is installed. In addition, the reachability matrix $r_{i,j}$ is calculated by the following procedure by giving as input such conditions as the position of the gateway, the number of wireless sensors, the position of each wireless sensor, the communication distance of the wireless devices, and the position of the obstructions.

STEP1 Generation of the adjacency matrix based on the communication distance

STEP2 Updating the adjacency matrix based on internode of line of sight

STEP3 Calculation of the reachability matrix based on the adjacency matrix

Details of the above procedure are shown below.

4.1 Generation of the Adjacency Matrix based on the Communication Distance

In this paper, we consider the reachability matrix showing the reachability of one of the nodes from another by data using the adjacency matrix in the graph theory. The adjacency matrix expresses the presence or absence of the relationship between nodes in the graph, and the adjacency matrix of the graph consisting of n nodes is an n × n square matrix.

Here, if the adjacency matrix is $a_{i,j}$,
if there is an edge from node i to node j, $a_{i,j} = 1$.
if there is no edge from node i to node j, $a_{i,j} = 0$.

In this paper, the gateway, the wireless sensors, and the relays are assumed to be the nodes in the adjacency matrix, and the availability of communication between each node is expressed as an edge. That is, $a_{i,j} = 1$ when communication from node i to node j is possible, and $a_{i,j} = 0$ when communication from node i to node j is impossible.

Here, the determination of whether or not communication is possible between the nodes is made as follows using the communication distance of the wireless devices of the wireless sensor or relay given as the input condition.

if $D_{i,j} <= C_i$: Communication is possible ($a_{i,j} = 1$),
if $D_{i,j} > C_i$: Communication is impossible ($a_{i,j} = 0$)

Where, $D_{i,j}$ is the distance between nodes, C_i is the communication distance of each wireless device.

By performing the above judgment between any pair of all the nodes, the adjacency matrix is generated here.

4.2 Updating the Adjacency Matrix based on Internode of Line of Sight

Here, the adjacency matrix generated in (1) is updated based on the presence or absence of the internode of line of sight. The presence or absence of the internode of line of sight is determined based on the position of the obstructions given as input. As shown in Fig. 2, the position of the obstructions is input as the gateways of a line segment constituting the area where the obstructions exist like Li (x1, y1, x2, y2). In this paper, the presence or absence of the internode of line of sight is judged by the possibility of intersection of a line segment constituting a certain area of the obstructions and a line segment connecting the nodes. Here, assuming that the two line segments are L1 (x1, y1, x2, y2) and L2 (x3, y3, x4, y4), the two line segments intersect when the following equation (4) is satisfied.

$$tc \times td < 0 \quad (4)$$

Where,

$$tc = (x_1 - x_2)(y_3 - y_1)+(y_1 - y_2)(x_1 - x_3),$$
$$td = (x_1 - x_2)(y_4 - y_1)+(y_1 - y_2)(x_1 - x_4).$$

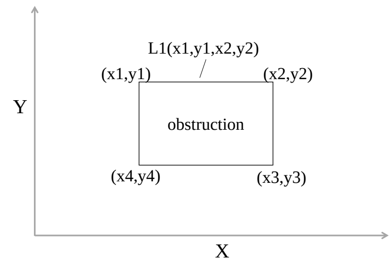

Figure 2: The coordinates of the line segment.

Here, the intersection determination is made based on the above equation (4), and if any of the line segments intersect each other as a result of the judgment, it is determined that there is non-line of sight and the adjacency matrix is updated as $a_{i,j} = 0$ (communication is impossible).

4.3 Calculation of the Reachability Matrix based on the Adjacency Matrix

Here, the reachability matrix is calculated based on the adjacency matrix calculated above. The reachability matrix can be calculated by the following procedure.

STEP1 Add unit matrix I to adjacency matrix A

STEP2 Under the Boolean algebra operation, $A + I$ is repeatedly multiplied by r times until the state represented by the following expression (5) is obtained

$$(A+I)^{r-1} \neq (A+I)^{r} = (A+I)^{r+1} \quad (5)$$

$(A+I)^{r+1}$ obtained by the above calculation is a reachability matrix. In this way, in the method proposed, the reachability matrix is calculated based on the communication distance of the wireless devices and the line of sight between the nodes.

5 THE DEMONSTRATION TEST ON RAILWAY SLOPE

We conducted a demonstration test on the railway

			N	N	N	N	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
S			N	N	N	N	N	N	N	N	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	N	N	N									N	N
N	N	N	N	N					N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
	C										N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N												
									O	O																							O	O	O	O	O	O			S
									O	O																							O	O	O	O	O	O			

1cell = 10m × 10m, N: the relays installation impossible, O: the obstructions,
S: the wireless sensors' location

Figure 3: The result of survey of the installation environment.

	R		N	N	N	N	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
S			N	N	N	N	N	N	N	N	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	N	N	N	R								N	N
N	N	N	N	N					N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
	C										N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N												
									O	O																							O	O	O	O	O	O			S
									O	O						R																	O	O	O	O	O	O			

1cell = 10m × 10m, N: the relays installation impossible, O: the obstructions,
S: the wireless sensors' location, R: the relays' location

Figure 4: The result of the method to determine the location of relays.

slope, in accordance with the procedure proposed in chapter 3.

5.1 Wi-SUN

In Japan, the 920 MHz band is allocated as the ISM band in July 2012, and the application of the band to the WSN is progressing. Along with that, the development of the 920 MHz band LPWA (Low Power Wide Area) wireless module is progressing. The LPWA includes the LoraWAN, SIGFOX, Wi-SUN, and the like. Compared to other LPWAs in the same 920 MHz band, the Wi-SUN has the advantage that, although the communication distance is inferior, the transmission speed is 200 kbps and multi-hop transmission is possible (Harada et al., 2017). Therefore, it can be said that it is suitable for a WSN which requires high scalability due to such changes as the addition of wireless sensors, or one to be introduced sequentially. So we decided to design the WSN for monitoring the railway slopes by using Wi-SUN.

5.2 WSN Design on Railway Slope

First, we decided the location of the wireless sensors on the assumption of detecting the sign of land slide and land collapse by measuring the inclination and the soil moisture on the slope. And we decided to install the gateway in the location that can supply fixed power.

Next, we conducted survey of the installation environment, and confirmed the location where the relay can be installed and the shielding object and so on from topographic conditions based on topographic map (Fig.3). Then, we applied the proposed method in Chapter 4 to determine the setting location of relays for the wireless sensors far from the gateway in Fig. 3. Fig. 4 shows the location of the relays by the proposed method. Incidentally, the wireless sensors and relays were powered by solar panels in this demonstration test.

5.3 The Result of the Test

We installed 5 inclination wireless sensors, 2 soil moisture wireless sensor and 3 relays. Fig.5 shows the state of installation the nodes on the slope.

We accumulated the sensor data by the designed network for about 3 months. As a result, except for some sensors, the sensor data arrival rate was more than 99%. But some of those sensors have lost data from one day. We know that rain and snowfall don't have a big influence on radio wave propagation in the 920 MHz (ITU-R, 1998; Iwasawa et al., 2016). One of the reasons for this may be that the plants grew higher than the antenna of the wireless sensors and the relays. In fact, we saw the images from the camera on the site and confirmed that the wireless sensors and the relays were buried with plants. Also, we confirmed that radio waves attenuate when there are plants between the nodes. In the future, we think that it is necessary to design the WSN considering such attenuation.

6 CONCLUSIONS

In this paper, we introduced the procedure for designing the WSN in the railway environment. And we reported the demonstration test to the railway slope based on the procedure. As a result, we found that the WSN design considering the change of the

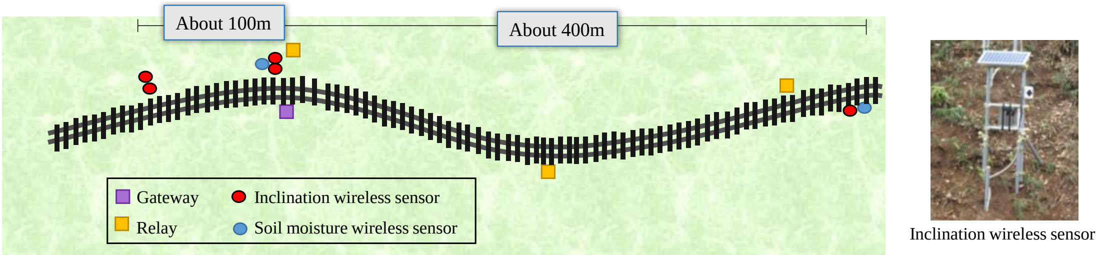

Figure 5: The state of installation the nodes on the slope.

surrounding environment is necessary. So we will improve the procedure by organizing the idea of margin due to environment change in the future. And we will plan to improve the proposed method so that we can consider the dynamic environment such as train movement.

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REFERENCES

Bakaraniya, P., Mehta, S., 2012. Features of WSN and Various Routing Techniques for WSN: A Survey, In *International Journal of Research in Engineering and Technology*.

Harada, H., Mizutani, K., Fujiwara, J., Mochizuki, K., Obata, K., Okumura, R., 2017. IEEE 802.15.4g Based Wi-SUN Communication Systems. *Transactions on Communications*. IEICE.

Hodge, V. J., O'Keefe, S., Weeks, M., Moulds, A., 2015. Wireless Sensor Networks for Condition Monitoring in the Railway Industry: A Survey, In *Transactions on Intelligent Transportation Systems*. IEEE.

Iwasawa, N., Ryuo, S., Kawamura, T., Kawasaki, K., Nozue, M., 2016. Transmission Performance evaluation of Wi-SUN Wireless Sensor Network During Snowing, In *23rd J-RAIL'16. IEEJ*.

Kawamura, T., Ryuo, S., Iwasawa, N., 2016. Power Consumption Prediction Method for Train-Health Monitoring Wireless Sensor Networks, In *23rd J-RAIL'16. IEEJ*.

Ministry of Land, Infrastructure, Transport and Tourism, 2016. *Annual report on railway transportation, MLIT*, Tokyo.

Potdar, V., Sharif, A., Chang, E., 2009. Wireless Sensor Networks: A Survey. In *AINA'09, 23rd International Conference on Advanced Information Networking and Applications Workshops. IEEE computer society*.

Railway Technical Research Institute, 2007. *Railway structures maintenance standard and commentary [earth structure] (embankment and excavation)*, Maruzen, Tokyo.

ITU-R, 1998. Specific Attenuation Model for Rain for Use in Prediction Methods, In *ITU-R Recommendations*, ITU, Geneva.

Tiwari, A., Ballal, P., Lewis, L. F., 2007. Energy-Efficient Wireless Sensor Network Design and Implementation for Condition-Based Maintenance, In *Transactions on Sensor Networks. ACM*.

Xu, K., Wang, Q., Hassanein, H., Takahara, G., 2005. Optimal Wireless Sensor Networks (WSNs) Deployment: Minimum Cost with Lifetime Constraint. In *WiMob'05, Wireless and Mobile Computing, Networking and Communications. IEEE*.

Youssef, M., El-Sheimy, N., 2007. Wireless Sensor Network: Research vs. Reality Design and Deployment Issues. In *CNSR'07, 5th Annual Conference on Communication Networks and Services Research. IEEE computer society*.