Design Method of Wireless Sensor Networks in Railway Environments Considering Power Consumption

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***Abstract*—In recent years, various researches have been conducted for the purpose of applying Wireless Sensor Networks (WSNs) to monitoring the condition of railway facilities. In designing WSNs, it is important to effectively arrange the nodes that compose WSNs. In railway environments, it is necessary to design WSNs in consideration of the presence of obstacles and constraints on the placement. In this paper, we propose a method of calculating an optimal relay nodes placement and a routing method of WSNs in railway environments by combining the mathematical optimization method and Sequential Monte Carlo method.**

Keywords-Wireless sensor network; Optimization method; Power consumption; Sequential Monte Carlo method.

I. INTRODUCTION

Nowadays, with the development of the ICT, researches on the condition monitoring system by mean of a Wireless Sensor Network (WSN) are proceeding. In the railway field as well, various condition monitoring systems by means of WSNs are being researched in order to apply them to such cases as the monitoring of structures along tracks [1], the monitoring of trains [2], and so on [3]. Most of the WSNs consists of sensor nodes for acquiring data of monitored objects, gateways for aggregating data, and relay nodes for transferring data when the sensor nodes and the gateway cannot communicate directly. In designing a WSN, it is important to effectively arrange these nodes. In WSNs for condition monitoring, the locations where sensor nodes and gateways are installed are often predetermined in advance. For this reason, how to efficiently arrange relay nodes is important in designing WSNs, and various researches have been conducted on methods for determining effective placements of relay nodes [4]-[7].

The railway facilities spread long over urban areas and mountainous areas, and there are many obstacles that interrupt wireless communication. In addition, the placement of nodes may be restricted due to safety and physical conditions. Therefore, it is necessary to design WSNs considering these characteristics when introducing WSNs in railway environments.

In this study, we propose a method of calculating an optimal relay nodes placement and the routing of the WSN considering the presence of obstacles and impossible placement in railway environments by combining a mathematical optimization method and Sequential Monte Carlo method.

The rest of the paper is organized as follows. In Section II, we present the related work. Section III presents the envisioned WSN in railway environments. In Section IV, we present the proposed design method of WSN. Section V provides the numerical results of the proposed method. Finally, the paper is concluded in Section IV.

II. RELATED WORK

Research on the relay nodes placement in WSNs is widely conducted and various methods have been proposed such as methods of determining the relay nodes placement so as to maximize the communicable range [4], methods with a focus on fault tolerance [5], methods of determining the efficient relay nodes placement from the viewpoint of network lifetime [6] and methods of determining the placement considering communication cost [7]. However, these methods are targeted at environments without obstacles, and it is assumed that there is no restriction on the node placement. Therefore, these methods are not suitable for environments in which many obstacles exist like railway environments.

In [8], a method for determining the relay nodes placement in consideration of constraints on node placement locations has been proposed. However, even in this method, the presence of obstacles is not taken into consideration, and it is difficult to apply it to railway environments.

Also, in [9], a method of determining the relay nodes placement for the WSN on roads considering the influence of obstacles has been proposed. In this method, the node placement is calculated for the WSN on roads considering the influence of obstacles by using digital maps. Furthermore, in this method, whether or not the intermodal visibility is hindered by obstacles is determined by utilizing the fact that nodes are placed on the road. Therefore, it is difficult to apply this method when nodes are not placed on the road but placed in railway environments.

III. ENVISIONED WSN IN RAILWAY ENVIRONMENTS

In this study, we envision the situation where the WSN consisting of sensor nodes, relay nodes, and a gateway is installed in railway environments. Here, the gateway is a device that gathers data from each sensor node, and the sensor node measures data from monitored objects and transmits the data to the gateway wirelessly. The relay node is a device having

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a function of relaying sensor data and in cases where data cannot be transmitted from a sensor node directly to a gateway, data is transmitted by multi-hop wireless communication via relay nodes. Additionally, the sensor nodes and the relay nodes are assumed to be driven by batteries. For this reason, it is necessary to replace these batteries before they become empty in order to operate the WSN continuously.

Furthermore, the characteristic of railway environments is that railway facilities spread long over urban areas and mountainous areas, and there are many obstacles that interrupt radio wave propagation. In addition, the placement of nodes may be restricted due to safety and physical conditions in railway environments. In this study, we propose a design method for the WSN to be constructed in railway environments where there are many obstacles and there are constraints on the location of nodes as described above.

IV. PROPOSED DESIGN METHOD OF WSN

In railway environments, it is necessary to monitor a long distance section along railway tracks depending on the objects monitored. Therefore, it is important to construct a WSN in railway environments in such a way that the data can be relayed from each sensor, in which case, as long as each sensor data reaches the gateway, the smaller the number of relay node is, the more economical the WSN is. Also, since the power consumption of each node in the WSN affects battery replacement frequency, the lower the power consumption is, the lower the cost of replacing the batteries.

In this study, we propose a method of calculating the optimal number of relay nodes, the relay node placement and the routing of the WSN considering the presence of obstacles and impossible placement in railway environments by combining a mathematical optimization method and Sequential Monte Carlo method.

The procedure of the method proposed in this paper is shown in Figure 1. In the proposed method, we first optimize the number of relay nodes of the WSN considering the presence of obstacles and places where node placement is impossible in the railway environments. Next, based on the result of the above optimization, we perform the operation simulation of the WSN using time series Monte Carlo method, and calculate the power consumption and data

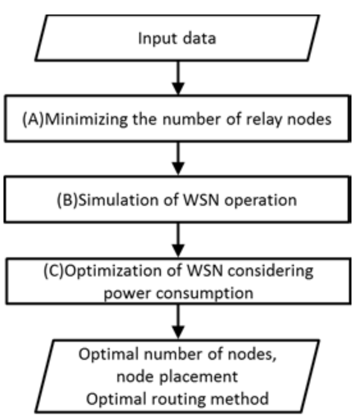

Figure 1. Proposed Design Method of WSN

arrival rate of the WSN. Then, we calculate a combination of the optimal relay node placement and the routing method by optimizing from the viewpoint of power consumption of relay nodes based on the power consumption and data arrival rate calculated. The detail of each item in Figure 1 are described below.

A. *Minimizing the number of relay nodes*

Regarding minimizing the number of relay nodes, the relay nodes placement in which it is minimized is calculated provided that communication can be established considering the presence of obstacles and places where node placement is impossible in the railway environments. More specifically, the relay nodes placement is calculated by the following optimization setting the minimization of the number of relay nodes as the objective function [10].

[Objective function]

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

[Constraints]

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

$$P_i(\mathrm{x,y}) \neq N_j(\mathrm{x,y}) \quad (3)$$

In the above equations, R_{num} is the number of relay nodes, and $r_{i,j}$ 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, $P_i(x,y)$ is the position (x coordinate, y coordinate) of the relay node *i*, and $N_j(x,y)$ is the position (x coordinate, y coordinate) where the relay node cannot be installed. Equation (2) represents the constraint relating to the arrival of data from each sensor node to the gateway, and $r_{i,gat}$ represents the reachability of data from the sensor node i to the gateway. Equation (3) represents the constraint relating to the position of the relay node.

Here, the position $N_j(x,y)$ where the relay node 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 according to the following procedure by giving as input such conditions as the position of the gateway, the number of sensor nodes, the position of each sensor node, the communication distance of each node, and the position of the obstacles.

STEP1 Generation of the adjacency matrix based on the communication distance.

STEP2 Updating the adjacency matrix based on the internodal visibility.

STEP3 Calculation of the reachability matrix based on the adjacency matrix.

Details of the above procedure are shown below.

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, on the premise that 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.

2) Updating the adjacency matrix based on visibility

Here, the adjacency matrix generated in STEP1 is updated based on the presence or absence of the internodal visibility. The presence or absence of the internodal visibility is determined based on the position of the obstracles given as input. As shown in Figure 2, the position of the obstacles is input as the coordinates of a line segment constituting the area where the obstacles exist like L_i (x_1, y_1, x_2, y_2). In this paper, the presence or absence of the internodal visibility is judged by the possibility of the intersection of a line segment constituting a certain area of the obstacles and a line segment connecting the nodes. Here, assuming that the two line segments are L_1 (x_1, y_1, x_2, y_2) and L_2 (x_3, y_3, x_4, y_4), the two line segments intersect when the following (4) is satisfied.

$$tc \times td < 0 \tag{4}$$

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

Here, the intersection determination is made based on (4), and if any two 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).

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.

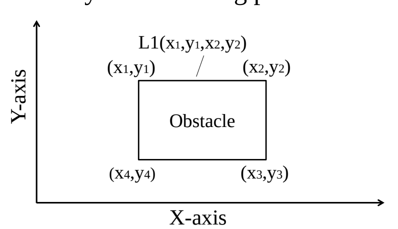

Figure 2. The coordinates of the line segment

STEP1 Add unit matrix I to adjacency matrix A
STEP2 Under the Boolean algebra operation, $A + I$ is repeatedly multiplied by itself r times until the state represented by the following (5) is obtained

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

$(A+I)^{r+1}$ 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.

B. Simulation of WSN operation

In simulation of WSN operation, power consumption and data arrival rate of the WSN are calculated based on the number of relay nodes and the arrangement of relay nodes obtained in Section IV-A. At this time, if there are multiple relay nodes placement candidates as a result of the calculation described in Section IV-A, simulation is performed for the plural placement candidates. In this study, we estimate the power consumption and data arrival rate of each node of the WSN in railway environments using sequential Monte Carlo method, which is a method of obtaining approximate solutions by repeatedly performing time series simulation using random numbers. In the proposed method, sequential Monte Carlo method was used to perform simulation considering the routing method, retransmission of data, and communication uncertainty. The configuration of the WSN operation simulation is shown in Figure 3.

The proposed method consists of a WSN evaluation program and routing simulation, and by combining the above two, the power consumption and data arrival rate of sensor nodes and relay nodes are predicted in consideration of the routing methods of the WSN. In the WSN evaluation program, the timing of routing is determined, and the operation of the WSN is simulated based on the result of the routing simulation, and the power consumption and data arrival rate of the WSN are calculated. In the routing simulation, the routing operation is simulated based on the routing method of the WSN to be evaluated, and the routing table is generated. Here, the routing table is a collection of information about routing to the destination contained in each node, and is used to deliver the data. As routing methods used in the WSN, there are a reactive type in which a route is determined immediately before data transmission, a proactive type in which a route is determined in advance before communication, a hybrid type in which both the types are combined, and the like. In railway environments, various monitoring targets exist, but in general, a suitable routing method differs according to the monitoring target. Therefore, when applying the WSN in railway environments, it is important that the design of the WSN includes the routing method. In the proposed method, we estimated the power consumption and data arrival rate of the WSN, including the routing, so that we can examine what kind of routing is desirable.

Next, the flow of the simulation of the WSN is shown in Figure 4. In Figure 4, "time" is the time frame which is being calculated, Δt is the time step width of the simulation. In the simulation of WSN operation, the communication environ-

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ment at each time frame, and the routing method of the WSN are provided, and the power consumption and the number of communications at each time frame and the data arrival rate of the WSN in railway environments are calculated. To do this, we probabilistically simulated the occurrence of packet loss by a pseudo random number. We ultimately calculated the power consumption and data arrival rate during a stipulated period by repeating the calculations while updating the time frame. Details of each item shown in Figure 4 are discussed below.

1) Input data

In the simulation of WSN operation, the following data are provided as inputs for calculating the power consumption and data arrival rate.

- Routing method of the WSN
- Transmission timing of sensor data
- Number of retransmissions of sensor data
- Position of each node
- Specifications of each node (power consumption, transmission time, etc.)
- Battery capacity
- Communication environment (communicable distance, packet loss rate, etc.) at each position
- Time step width and duration of the simulation

2) Settings of various conditions

In the settings of various conditions, we set the communication environment, and battery health at each time frame in order to calculate the power consumption and data arrival rate at each time frame.

3) Routing simulation

Here, the network is constructed based on the routing method used in the target WSN, and the routing table is generated. In the proposed method, the routing method is simulated by utilizing a network simulator or the like, the routing timing is judged by the WSN evaluation program, and routing simulation is performed when it is judged as the routing timing. The inputs and outputs in the routing simulation are shown below.

[Inputs]

- Position of each node
- Number of retransmissions of data
- Communication environment

[Outputs]

- Number of transmissions and receptions of each node

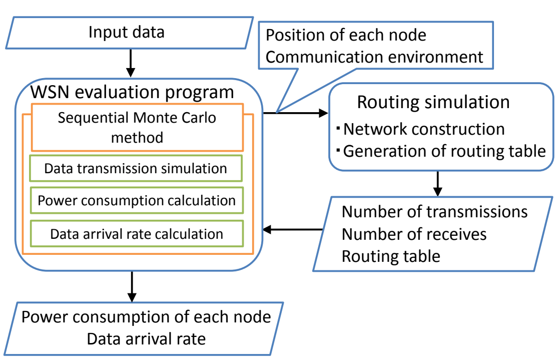

Figure 3. Configuration of WSN operation simulation

- Routing table

4) Simulation of data transmission

Here, we calculate the number of communications of each node and the data arrival rate when data are transmitted from the sensor nodes to the gateway. The calculations are performed on the basis of the conditions set according to various situations. To do this, we probabilistically simulate the occurrence of packet loss by a pseudo random number. Additionally, when packet loss occurs, each node retransmits data until the number of retransmissions reaches the predetermined number of times given as input and calculate the data arrival rate at the gateway and the number of communications (the number of data transmissions and the number of data receptions) of each node in each time frame.

5) Calculation of power consumption in each time frame

Here, we calculate the power consumption of each node in each time frame on the basis of the number of communications calculated in 4). Additionally, the remaining capacity of each sensor node battery is updated on the basis of the calculated power consumption.

In this study, we calculate the power consumption in each time frame using (6) in consideration of the number of transmissions and the number of receptions of each node in each time frame.

$$W_i(t)=P_t \cdot T_t \cdot Nt_i(t)+P_r \cdot T_r \cdot Nr_i(t)+P_w \cdot T_{wi}(t) \qquad (6)$$

Here, $W_i(t)$ is the power consumption of sensor node i in time frame t, $Nt_i(t)$ is the number of transmissions of the sensor node i in time frame t, $Nr_i(t)$ is the number of receptions of the sensor node i in time frame t, and $T_{wi}(t)$ is the standby time of the sensor node i in time frame t.

6) Calculation of power consumption and data arrival rate

Here, we calculate the power consumption and data arrival rate during the stipulated period on the basis of the results obtained by repeating the calculations shown in 2) to 5) while updating the time frame. Specifically, we calculate the power consumption of each sensor node up to the stipulated period as the sum value of the power consumption in each time frame. Likewise, we calculate the data arrival rate during the stipulated period of each sensor node on the basis of the sum of the data arrival rates in each time frame.

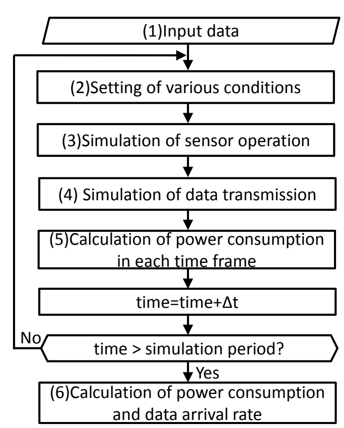

Figure 4. Flowchart of WSN operation simulation

C. Optimization of WSN considering power consumption

In the optimization of WSN considering power consumption, optimization is performed from the viewpoint of the power consumption of the relay node based on the optimum number of relay nodes calculated according to the description in Section IV-A and the node placement candidate, the power consumption of the WSN calculated according to the description in Section IV-B, and the data arrival rate.

The power consumption of the relay node will affect the capacity of the relay node's battery and the network lifetime when operating the WSN. Assuming that the battery capacities of all the relay nodes are the same, the battery of the relay node having the largest power consumption is exhausted first. Therefore, the lifetime of the network depends on the maximum value of the power consumption amount of the relay node. In this study, the WSN was optimized from the viewpoint of the maximization of network lifetime. The objective function can be defined as (7) as the minimization of the maximum value of the power consumption of the sensor node.

[Objective function]

$$\min(\max(W_1,..,W_i)) \quad (7)$$

In the optimization of WSN considering power consumption, it can be formulated as an optimization problem intended for the minimization of the objective function of (7) while satisfying (8) and (9).

[Constraints]

$$A_i \geq A_{\min} \quad (8)$$

$$R_{\text{num}} = R_{num\_min} \quad (9)$$

Where, W_i is the power consumption of node i, A_i is the data arrival rate of node i, $A_{\min}$ is the lower limit value of the data arrival rate, and R_{num_min} is the number of relay nodes obtained by minimizing the number of relay nodes considering railway environments described in Section IV-A. Equation (8) is a constraint on the data arrival rate, and (9) is a constraint on the number of relay nodes and consider limiting the solution to the same number of relay nodes as that obtained in Section IV-A.

Here, $A_{\min}$ included in the constraint condition shall be given as input. For W_i and A_i, the node placement, the routing method, and the number of data retransmissions are given as input, and values are calculated by the simulation of power consumption and data arrival rate described in Section IV-B. In this optimization, the combination of the relay nodes placement, the routing method, and the number of data retransmissions in which, provided that the constraints are satisfied, the objective function is minimized is calculated. This makes it possible to design optimum relay node placement, routing method and the number of date retransmissions from the viewpoint of power consumption.

V. NUMERICAL EXPERIMENT

In this section, we performed numerical experiments to verify the usefulness of the proposed method in regard to a WSN installed along a railway line.

A. Calculation condition

We have built a WSN for monitoring a slope condition along a railway line and have carried out demonstration tests [11]. In this study, numerical experiments were carried out for the WSN along the above mentioned railway line. The conditions of the numerical experiments are as follows.

- Figure 5 shows the WSN for monitoring a slope condition in the railway line environment targeted for the numerical experiments. In the targeted WSN, it is assumed that the data is aggregated from two sensors. The monitoring positions of the slope is fixed. In Figure 5, the positions of the sensor nodes are indicated as S, the position of a gateway is indicated as G. Further the positions of places where the nodes cannot be installed are denoted as N, and the positions of the obstacles along the railway line based on the terrain data is denoted by O, and the positions of the. In the numerical experiments, it was studied to select effective relay nodes placement and routing method to make sensor data reach from the sensor nodes to the gateway in the Figure 5. We conducted the numerical experiments under the condition of the communication distance of wireless devices of the sensor nodes and the relay nodes as 170 m with which stable communication can be made in the environment without obstacles according to the measurement result of the wireless device.
- The routing method of WSN is performed by checking the nodes that can communicate by flooding and generating the shortest route. In addition, we examined two patterns of candidates for routing: reconstructing the route every time data is transmitted (reactive type) and reconstructing the route at 0 o'clock every day (proactive type). In addition, the range of 0 to 3 times of data retransmissions was assumed as the candidate.
- The power consumption of the sensor nodes and the relay nodes was assumed to be 69.3 mW when transmitting, 52.8 mW when receieving, and 0.002 mW when standing by, based on the specifications of a commercially available wireless device.
- The transmission cycle of sensor data was set to once per 10 min, and the time step width of the simulation was set to 10 min. Also, it is assumed that power consumption and data arrival rate are calculated as values when WSN is operated for one year.
- The lower limit value of data arrival rate used for the calculation of Section IV-C was set to 95%.

B. Calculation result

Figure 6 shows an example of the result of calculating the relay nodes placement by the proposed method based on the above experiment conditions. As shown in Figure 6, as a result of minimizing the number of relay nodes considering the railway environment, the minimum number of relay nodes was three. In addition, the position indicated by Ri in Figure 6 was obtained as one of the relay node positions which can make all sensor data reach the gateway taking into consideration the obstacles and the positions where the nodes cannot be installed.

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O	O	O	O	O	O	O							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	O
										S1			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
S4						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
S5			N	N	N	N	N		O		G										N	N	N	N	N	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	O	O	O	O		S3	S2
N	N	O	O	O	O	O	O	O	O										O	O																							O	O	O	O	O	O			

Figure 5. WSN for the numerical experiment (top view of monitoring area)

O	O	O	O	O	O	O					R1		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	O
										S1			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	R3								N	N
S4						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
S5			N	N	N	N	N		O	O	G										N	N	N	N	N	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	O	O	O	O	O		S3	S2
N	N	O	O	O	O	O	O	O	O										O	O						R2																	O	O	O	O	O	O			

Figure 6. Calculation result of relay nodes placement by the proposed method (top view of monitoring area)

O	O	O	O	O	O	O							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	O
										S1			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
S4						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
S5			N	N	N	N	N		O	O	G										N	N	N	N	N	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				R1													R2						O	O	O	O	O	O		S3	S2
N	N	O	O	O	O	O	O	O	O										O	O																							O	O	O	O	O	O			

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

Figure 6. Calculation result of relay nodes placement by the conventional method (top view of monitoring area)

Next, we optimized the WSN from the viewpoint of power consumption and data arrival rate based on the result of minimizing the number of relay nodes. As a result, it was found out that the optimal solution is setting the routing method to the proactive type and retransmission number to 1 time. Also, the power consumption and data arrival rate of the WSN of the optimal solution are shown in Table I.

Furthermore, for comparison, Table II shows the results in the case where the routing method is different from the conditions in Table I, and Table III shows the results in the case where the number of retransmissions is different from the conditions in Table I. Here, Ret in Table III indicates the number of retransmissions. It can be seen that although the data arrival rate of the two routing methods are not different from each other, the reactive type has higher power consumption from Table II. This is probably because the frequency of the reactive type routing is larger than that of the proactive type under the set condition, and the power consumption by routing is increased.

TABLE I. SIMULATION RESULT OF OPTIMUL WSN

	S1	S2	S3	S4	S5	R1	R2	R3
Power consumption (Wh)	1.13	1.12	1.12	1.13	1.13	5.56	3.77	3.77
Data arrival rate (%)	99.7	97.8	97.7	99.8	99.3	-	-	-

TABLE II. SIMULATION RESULT OF REACTIVE ROUTING

	S1	S2	S3	S4	S5	R1	R2	R3
Power consumption (Wh)	10.2	9.16	9.16	10.2	10.2	24.7	22.9	19.8
Data arrival rate (%)	99.7	97.8	97.7	99.8	99.3	-	-	-

Next, regarding the number of retransmissions, it can be seen from Table III that increasing the number of retransmissions increases the data arrival rate and also increases the power consumption. Since the data arrival rate is set to 95% as the condition of the optimization this time, it is considered that one time, the minimum number of retransmissions was selected within the range that satisfies this condition.

Finally, we compare the conventional method for determining the relay nodes placement that does not consider the influence of obstacles with the proposed method. Here, we calculated the relay nodes placement by a method not considering the influence of obstacles by calculating the determination of the relay nodes placement that minimizes the number of relay nodes in Section IV-A without considering the influence of obstacles. Figure 6 shows the result of determining the relay nodes placement by a method not considering the influence of obstacles. In Figure 6, the number of relay nodes is two, and it is smaller than the result by the proposed method. However, with the placement of the relay nodes in Figure 6, data from S2, S3, S5 cannot reach the gateway due to the influence of the obstacles.

TABLE III. SIMULATION RESULT OF DIFFERENT RETRANSMISSIONS

		S1	S2	S3	S4	S5	R1	R2	R3
Ret=0	Power consumption (Wh)	1.08	1.07	1.07	1.08	1.08	4.89	3.35	3.50
	Data arrival rate (%)	95.0	81.5	81.5	95.0	90.3	-	-	-
Ret=2	Power consumption (Wh)	1.13	1.13	1.13	1.13	1.13	5.64	3.80	3.79
	Data arrival rate (%)	99.9	99.8	99.8	99.9	99.9	-	-	-
Ret=3	Power consumption (Wh)	1.13	1.13	1.13	1.13	1.13	5.64	3.81	3.79
	Data arrival rate (%)	99.9	99.9	99.9	99.9	99.9	-	-	-

It is considered that in this way, the number of relay nodes, the nodes placement, and the routing method can be designed considering the influence of the obstacles in railway environments on the radio communication by using the proposed method.

VI. CONCLUSION

In this paper, we proposed a method to calculate the optimal relay nodes placement and routing of the WSN considering the presence of the obstacles and the positions impossible for installment in railway environments by combining a mathematical optimization method and Sequential Monte Carlo method. Additionally, we demonstrated the usefulness of the proposed method by performing numerical experiments using the proposed method for WSN installed along a railway line.

In the future, we plan to proceed with the verification of the proposed method, and consider effective nodes placement and routing method of WSN in railway environments under various conditions using the proposed method.

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