Easy-to-use Wireless Sensor Network Simulator for Estimating Power Consumption and Communication Availability

Yuta Hosokawa, Minoru Tanaka, Kazuki Nakamura
Information and Communication Technology Division
Railway Technical Research Institute
Kokubunji, Tokyo, 185-8540 Japan
e-mail: {hosokawa.yuta.84, tanaka.minoru.96, nakamura.kazuki.26}@rtri.or.jp

***Abstract*—In order to enable comparison and determination of node placement and modulation methods when introducing wireless sensor networks in railway environments, we developed an easy-to-use simulator. The simulator models the fixed-cycle transmission of sensor data and estimates communication paths and battery consumption on the network. The simulator is designed to be easily accessed from a web browser and parameters can be easily configured. This paper introduces the simulation model and implementation, as well as several examples of simulation results.**

Keywords—wireless sensor network; simulator; routing; power consumption.

I. INTRODUCTION

In recent years, there are high demands from Japanese railway operators to introduce more efficient and labor-saving technologies for the maintenance of railway equipment. One solution is to apply Wireless Sensor Networks (WSNs) to monitor the condition of equipment scattered along railways remotely. By using WSNs to collect equipment condition monitoring data, it is possible to reduce the need for frequent on-site inspections. When applying this principle, the following elements must be considered: communication range, modulation method, power consumption, and implementation of battery power supply. Each element affects the others, and multiple options are available, making it challenging for railway operators to design optimal WSNs.

Several network simulators are widely used to design optimal WSNs. Network Simulator-2 (ns-2) [1], Network Simulator-3 (ns-3) [2], and OMNeT++ [3] offer powerful tools for network simulation. These simulators can include power consumption modeling through additional modules. For instance, Energy Framework [4] for ns-3 and INET Framework for OMNeT++ provides extensions for simulating power consumption. However, these simulators typically require advanced technical expertise for command-line operations or custom scripting, making them challenging for non-technical stakeholders like railway operators.

This paper presents a user-friendly simulator designed to estimate the communication quality and battery consumption of WSNs in railway environments. Our tool supports multi-hop transmissions and mesh networking for nodes extending over long distances along railways. Featuring a web-based Graphical User Interface (GUI), the simulator allows users to easily set parameters, compare node placements and communication methods, and view results instantly. Our simulator meets the specific needs of WSN deployment planning in railway maintenance operations without requiring specialized software or technical expertise.

The rest of this paper is as follows. Section II describes the design of the simulation model. Section III shows the implementation of the simulator and simulation results. Section IV argues about the benefits and future work of the simulator. Finally, Section V concludes the article.

II. DESIGN OF SIMULATION MODEL

A. Node Types and Placement

In this model, a “node” consists of a radio transceiver, a microcontroller, a battery, and sensors. An arbitrary number of nodes can be placed on the simulation field.

Each node is classified into the following three roles, based on the Wi-SUN Field Area Network (FAN) model [1] to support multi-hop transmissions.

- Border Router (BR):
  A node that acts as a boundary with the external network and manages the entire network. Sensor data acquired by each node is aggregated to the BR, which transmits the data to a central unit or other devices via the external network. In the simulation, exactly one BR is required to be placed.
- Router node:
  A node with sensing and relay functionality, capable of relaying packets from distant router and leaf nodes that cannot directly communicate with the BR.
- Leaf node:
  A terminal node whose main objective is to measure and collect sensor data for transmission. The leaf node does not have relay functionality.

In the developed simulator, the position of a node is represented in a fixed X-Y coordinate [m]. Antenna height [m] and gain [dBi] are also specified for each node. The transmission power [dBm] is set to a common value for all nodes. Also, the node can be set to either with an external power supply or battery-powered, in which case battery capacity [mAh] is also specified.

Leaf and router nodes periodically transmit sensor data to the BR. In the simulation, the size of this data [bytes] and the transmission cycle [sec] may be specified for each node. When applying the WSN to real-world scenarios, the contents

 ISBN: 978-1-68558-207-4

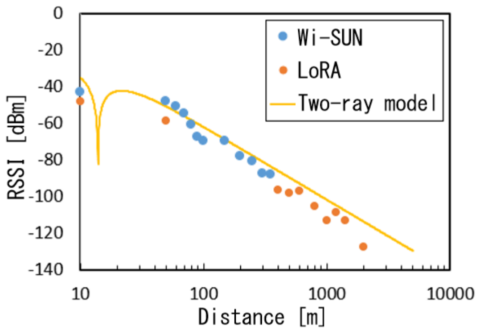

Figure 1. Relationship between the distance and RSSI

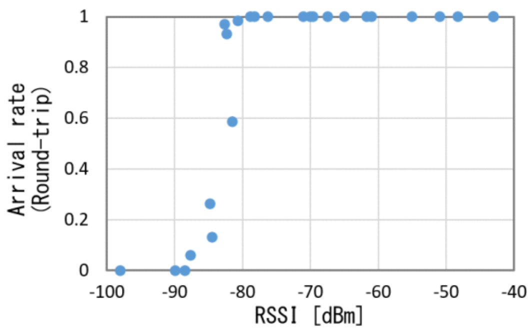

Figure 2. Relationship between RSSI and the arrival rate

of each sensor and data size may differ, so the data size and transmission cycle can be set to different values for each node.

B. Estimation of Communication Coverage

To build an estimation model of the communication coverage, we conducted an experiment to obtain basic data on radio communications. On a straight viaduct, we measured the Received Signal Strength Indicator (RSSI) and data arrival rate while varying the distance between two nodes. The relationship between the distance and RSSI for Wi-SUN and LoRa in the 920 MHz band is shown in Figure 1. We confirmed that the obtained RSSI generally matches the results estimated by the two-ray ground-reflection model [6] regardless of the modulation method. The relationship between RSSI and the data arrival rate for Wi-SUN is shown in Figure 2. While RSSI is above a certain value, the data arrival rate is close to 100%. In contrast, when RSSI is below that value, the arrival rate decreases significantly.

From these results, our simulator applies the two-ray ground-reflection model to estimate the RSSI value for each pair of nodes. Whenever an estimated RSSI value exceeds the pre-defined threshold, communication is deemed possible. The threshold value should be determined by actual measurements or expectations about environmental factors such as noise level.

C. Simulation of Routing

All router and leaf nodes have to determine a transmission path towards the BR to collect and/or distribute data. The simulator determines the transmission path from each node to the BR using the Routing Protocol for Low-Power and Lossy Networks (RPL). RPL is a routing protocol for selecting an appropriate route among multiple possible routes. It is used in

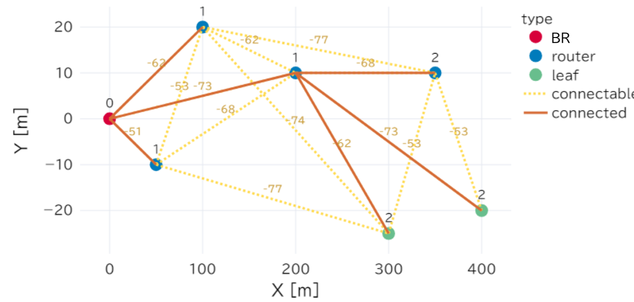

Figure 3. Example of routing

Wi-SUN and other networks capable of multi-hop transmission. In RPL, a Destination-Oriented Directed Acyclic Graph (DODAG) is constructed based on an objective function that defines the criteria for route selection. For example, the objective function of Wi-SUN FAN is calculated using the hop count and time series data of arrival rate [1]. Since our simulation model assumes a static communication environment, we use a simple algorithm that considers the hop counts and RSSI. The details are described below:

1) Assign Rank = 0 to the BR, where Rank is the number of edges that pass through to reach the BR.
2) Assign Rank = 1 to the nodes that can communicate directly with the BR (Rank = 0) and adopt a route that directly connects these nodes to the BR.
3) Assign Rank = 2 to the nodes that can communicate with a node with Rank = 1 but whose route has not yet been determined. If there are multiple candidates, the route with the highest RSSI value is adopted.
4) In the same way, the nodes that can communicate with the node with Rank = k but the route is not yet determined are set to Rank = k+1.

Figure 3 shows an example of routing simulation. Seven nodes are placed on a simulation field and the yellow dashed lines represent edges where communication is estimated to be possible. The numbers show the estimated RSSI and the orange lines represent the selected route. The number above each node is the Rank value. For example, there are two nodes with Rank = 1 that the upper right router node (Rank = 2) can connect to, but the node in the middle with the higher RSSI value (-68 > -77) is selected as the parent. The leaf node in the lower right can be connected to two router nodes, but the node with the smaller Rank value is selected as the parent to minimize the number of hops.

D. Estimation of Power Consumption

The simulator estimates battery consumption for each battery-powered node. The estimation is based on a model with a constant voltage output. To calculate the total battery consumption over time, we sum up the current [mA] drawn at each moment. This gives us the cumulative charge used, measured in [mAh].

The model of the current consumption is shown in Figure 4. Each node is assumed to consume c_{wait} [mA] during the time it is not transmitting data, and c_{tx} [mA] during data transmission. Since the current consumption may differ depending on the node type, these parameters can be changed for each node type. For example, a leaf node saves power by

 ISBN: 978-1-68558-207-4

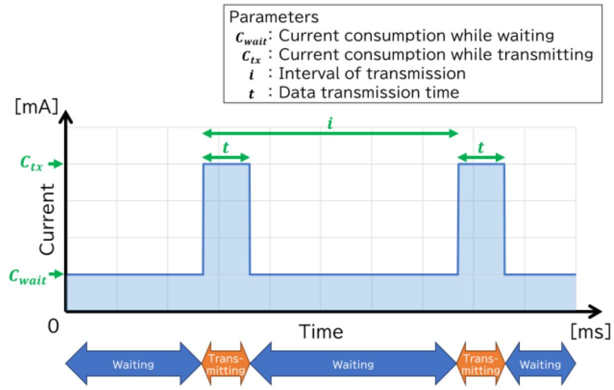

Figure 4. Current Consumption model

putting the transceiver to sleep when it is not transmitting, while a router node should always be on standby for reception.

To calculate the cumulative power consumption, it is necessary to determine the transmission time t [msec] per data. Generally, the transmission time increases linearly with the data size. Therefore, in our simulation model, it is expressed as t=ax+b, where x [bytes] is the data size to be transmitted. The parameters a and b are common values in the simulation based on actual measurements with wireless modules. This model assumes that each node transmits data once every i [sec], which is set for each node. In multi-hop transmissions, the router node is required to transmit both its own sensor data and the data received from its child nodes to the parent node, resulting in higher power consumption.

III. Implementation of the Simulator

A. Implementation of the Simulator

Based on the model described in Section II, we developed a simulator for WSNs that considers both data transmission and power consumption. The simulator was implemented in Python 3.11 using the Streamlit 0 library to enable GUI controls. Streamlit is an open-source Python library for creating web-based GUIs. The simulator was developed on a Linux server and made accessible through a specific URL, allowing users to interact with it via a web browser on any PC connected to the private network. The simulator consists of three components described below:

1) Parameter input interface

The simulator provides a web-based interface for users to input all necessary parameters. These include:

- Node placement and characteristics (Section II. A)
- Communication availability estimation (Section II. B)
- Power consumption estimation (Section II. D)

The interface features real-time updates, where changes in input values are instantly reflected in the corresponding graphs, facilitating rapid iteration of simulation parameters.

2) Network and Communication Path Visualization

The simulator generates a visual representation based on input parameters, illustrating:

- Node placement
- Inter-node communication availability
- Data transmission routes to BR

A dynamic timeline feature allows users to simulate battery consumption over time. This includes dynamic re-routing when nodes deplete their batteries.

3) Time-series analysis of battery capacity

The simulator provides a graph depicting the relationship between the elapsed time and the remaining battery capacity for each node. Key features include:

- Simulation continues until all battery capacity is depleted.
- Time resolution set to 1 day, optimized for planning battery replacement strategies for WSN deployments.
- Visualization of long-term network behavior without battery replacement.

B. Example of Running Simulation

1) Example simulation for Wi-SUN

We simulated a WSN including multi-hop transmissions under the assumption of Wi-SUN. Node placement is as shown in Figure 3. The BR is connected to an external power source and the other nodes are connected to 10000-mAh batteries. Each router and leaf node has an antenna height of 1.5 m and is set to transmit 16 bytes of data at 5-sec intervals. The transmission power of each node is 13 dBm. The parameters of data transmission time and current consumption values were based on the pre-measurement using ROHM's Wi-SUN evaluation module BP35C5-T01.

The simulation results are shown in Figure 5. At the beginning of the simulation (Day 0, as in Figure 3), nodes 4 to 6 used node 3 as the relay node, leading to rapid battery depletion in node 3 (Day 65). Afterward, they switched to node 2, which also ran out of battery by Day 78.

From these results, it can be said that nodes that relay information from distant nodes consume a particularly large amount of power and are likely to run out of battery power. Furthermore, under the same conditions, we conducted a simulation assuming that only node 3 could connect to an external power source, resulting in which all nodes could connect to the BR until Day 79.

2) Example simulation for LoRa

We conducted a trial simulation assuming a Long Range Wide Area Network (LoRaWAN) [8]. It is possible to simulate a network that is limited to a star topology like LoRaWAN by considering a gateway as BR and other end nodes as leaf nodes. One BR and six leaf nodes are placed and each leaf node has an antenna height of 1.5 m and a battery capacity of 10000 mAh. The transmission data size is set to a common value of 16 bytes for each node, and data transmission intervals are set to 5 sec for nodes 1 to 3 and 10 sec for nodes 4 to 6. The transmission power is 13 dBm. The parameters of transmission time and current consumption values were based on the datasheet of a LoRa wireless module.

The simulation results are shown in Figure 6. Initially (Day 0), all the leaf nodes are connected to the BR. Nodes 1 to 3, with shorter transmission intervals, ran out of battery earlier (Day 108), followed by all nodes running out of battery on Day 215. The LoRa module sleeps the transceiver during standby, resulting in very low power consumption. On the other hand, due to the long time it takes to transmit data, nodes that transmit data frequently run out of battery quickly.

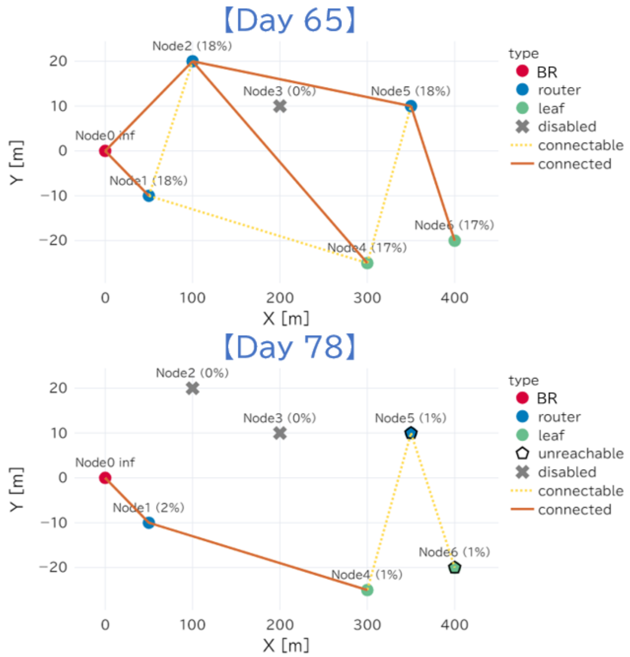

Figure 5. Results of example simulation for Wi-SUN

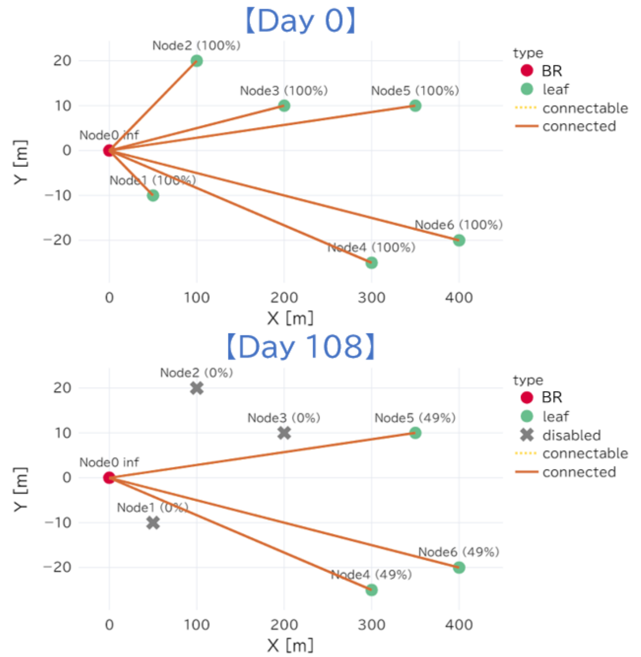

Figure 6. Results of example simulation for LoRa

IV. Discussion

The simulator we developed allows for easy estimation of data transmission paths and battery operating days in WSNs by simply inputting the sensor locations and battery capacities. In comparison to existing simulators such as ns-2, ns-3, and OMNeT++, our tool offers advantages in ease of use and real-time visualization. Users can configure parameters and view simulation results instantly without extensive technical knowledge through a web browser-based interface. This feature particularly benefits railway operators who need to design and evaluate networks quickly and effectively.

Our simulator's real-time feedback on power consumption and communication path visualization enables quick identification of nodes requiring external power or are at risk of battery depletion. This interactive functionality distinguishes our approach from the more static, script-based methods of traditional simulators.

However, there are several areas where we can enhance the accuracy and functionality. Future improvements aim to address:

- Incorporating terrain and railway equipment
- Simulating retransmission operation based on arrival rate estimation
- Supporting more advanced routing algorithms
- Modeling modules with multiple state transitions, such as sleep, receive standby, and data transmission

V. Conclusion

To enable comparison and determination of node placement and modulation methods for the introduction of WSNs in railway environments, we developed an easy-to-use simulator. This simulator estimates communication paths and battery consumption on the network. It models the fixed-cycle transmission of sensor data using the locations of wireless sensors, antenna performance, and battery capacity as input parameters. The simulator can simulate not only star networks but also mesh networks, such as Wi-SUN. Designed for ease of access, the simulator can be operated from a web browser, and parameters can be easily configured.

In the future, we plan to build a WSN using actual wireless modules to verify the accuracy and effectiveness of the simulator's estimates. Additionally, we aim to improve the model to accommodate more modulation methods and enhance estimation accuracy.

References

[1] The Network Simulator - ns-2, https://www.isi.edu/websites/nsnam/ns/ [retrieved: October, 2024]

[2] ns-3 | a discrete-event network simulator for internet systems, https://www.nsnam.org/ [retrieved: October, 2024]

[3] V. András and R. Hornig. "An overview of the OMNeT++ simulation environment," 1st International ICST Conference on Simulation Tools and Techniques for Communications, Networks and Systems, 2010.

[4] H. Wu, S. Nabar, and R. Poovendran, "An Energy Framework for the Network Simulator 3 (ns-3)," 4th International ICST Conference on Simulation Tools and Techniques, 2012.

[5] R. Hirakawa, K. Mizutani, and H. Harada, "Specification and Performance Analysis of Wi-SUN FAN," IEEE Open Journal of Vehicular Technology, vol. 4, pp. 849-866, 2023.

[6] Edited and supervised by Y. Hosoya, "Radiowave Propagation Handbook (in Japanese)," Realize Inc. Tokyo, pp. 125–126, 1999.

[7] Streamlit | A faster way to build and share data apps, https://streamlit.io/ [retrieved: October, 2024]

[8] About LoRaWAN | LoRa Alliance, https://lora-alliance.org/about-lorawan/ [retrieved: October, 2024]