Method for Creating Networks between Vehicles to Monitor Vehicle Condition

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Wireless sensor networks have been used over recent years to monitor the condition of railway facilities. This paper focuses on wireless sensor networks designed to monitor the condition of train vehicles. To collect measurement data from sensors installed on each vehicle, a network needs to be created between vehicles so that data in the sensors can be transmitted to the collection device via an appropriate route. However, coupling or decoupling raises the issue of how to modify networks when train composition is changed. As such, this paper proposes a two-tiered network composed of a single vehicle network and a multiple vehicle network, and describes the development of a method for creating multiple vehicle networks. This paper reports test results on a prototype system and results from a simulation using the proposed method.

Keywords: train condition monitoring, multiple vehicle network, wireless sensor network, prototype

1. Introduction

Maintenance of railway vehicles is generally based on a system of periodic inspections with intervals determined according to mileage or time in service, which is called time based maintenance. On the contrary, the condition based maintenance that detects symptoms and malfunctions of failure states by using condition monitoring system that monitors the operation state of train vehicles is garnering attention currently. This type of monitoring requires a system for collecting and displaying the operating condition of the vehicles. With the introduction of the condition monitoring system, it is possible to grasp the conditions of the bogie and the inverter for running vehicles and the operational conditions of the controlled apparatus for the vehicles before starting. Then, it is expected to achieve not only cost-effective maintenance but also to improve the safety by introducing the condition monitoring system.

The condition surveillance system has already been installed on some vehicles enabling the monitoring of inverters, brakes and doors are checked from the driving cab [1]. The transmission in these systems uses the train line between the vehicles, which makes it difficult to apply to vehicles such as freight cars, passenger cars and diesel cars without a train line. A wireless sensor network (WSN) was therefore developed to allow transmission of data about vehicle condition.

2. Problems of WSN for train vehicle monitoring system

Wireless sensor multilayer networks using two networks do exist [2]. In these systems, one layer of the network is composed of the sensor nodes on some vehicles and the relay collecting data from the sensor nodes, while the other is composed of the relays and the concentrator. Since it is assumed that these networks will be applied to fixed train compositions, the relay nodes are installed in only some vehicles and the transmission path between the relays and the concentrator is fixed. However, with frequent coupling or decoupling such as on a freight train, sensor nodes may be detached from the network. A fixed transmission path is therefore not suitable for train compositions that change.

To overcome this obstacle, ad hoc network technology exists which dynamically composes networks [3]. The risk however with this kind of ad hoc network technology is that a node forms a network with a node which is on a train on an adjacent line. This is avoided if the node IDs in a group on one train composition are registered in advance, facilitating the formation of networks for separate train compositions. The problem with this approach is though that coupling or decoupling can happen on route to a station. In the case of freight, train consists are changed frequently in freight stations. This means that the node IDs of the devices in a group have to be reset each time the composition is modified. This makes the process of registering node IDs in advance very complex because groups of node IDs have to be reconfigured with each change.

The new method proposed in this paper aims to solve this problem by designing the nodes to allow them to automatically compose a network in a single consist. This paper proposes a network that can adapt to coupling and decoupling of vehicles and forms a network automatically based on train composition.
3. Proposed WSN network for a train vehicle monitoring system [4]

The proposed WSN consists of sensor nodes which acquire data from the monitored targets, a concentrator which collects all sensor data and relays which relay the data to the concentrator. Also, the WSN comprises two networks; one is a “single vehicle network” that has sensor nodes sending data to the relay for a single vehicle, while the other is a “multiple vehicle network” that has relays to send data onto the concentrator (see Fig. 1). Using this multi-layer network formed by single vehicle networks and a multiple-vehicle network for the whole train, solves the problem associated with coupling or decoupling.

The concentrator in the multiple-vehicle network receives the information about the train composition from the data center. As relays are already associated to a vehicle number, the concentrator can identify relays in vehicles in the train composition. Transmission across the multiple vehicle network uses the 920 MHz band from the ISM (Industry Science Medical) band, because it has higher diffractive properties and enables communication that by-passes obstacles, and offers a wide range of channels.

Transmission inside the single vehicle network however, is either cable or wireless depending on the type of sensor used and the environment. If a wireless network is chosen, a frequency other than the 920 MHz band should be used to avoid radio interference [5]. For example, the 2.45 GHz band can be employed allowing direct communication between the sensor nodes and the relay due to its easy availability and low cost.

4. Composition of the multiple-vehicle network

The multiple-vehicle network consists of four stages; start of processing, creation of network, collection of data and end of processing (see Fig. 2). This section explains the functions of each device in the multiple-vehicle network and the data transmission procedure. Two methods for improving the communication matrix in the network composition are also presented.

4.1 Function of each device

As mentioned in the above, the multiple-vehicle network consists of relays and a concentrator. Hereinafter, the concentrator mounted in the lead vehicle is called the “host device.”

The functions of the host device are:

- Provide the trigger to start creation of the multiple-vehicle network.
- Obtain information train composition and time.

4.2 Transmission matrix

This section describes terms used in the composition of the multiple-vehicle network. Information held by the host device which determines the availability of links between each device (host device and relay device, relay devices between themselves) is called “the transmission matrix.” Each relay device appears in the transmission matrix as part of a “routing table.” An example of the transmission matrix is shown in Table 1. In the “Host” row, relays 1, 2 and 3 are marked with a one while 4 and 5 are indicated with a zero, this shows that links between the host and relays 1, 2 and 3 are available but not with relays 4 and 5. In this paper it is assumed that the transmission matrix is symmetric, and it is described as an upper triangular matrix.

The information held by the relay devices which determine the availability of links between the relays and other devices is represented in “the routing table.” The route for upper devices is called “the upper routing table” and conversely devices in the lower half are in “the bottom routing table” with the relay device itself as the starting point. The
Table 1  Example of transmission matrix

|   | Relay1 | Relay2 | Relay3 | Relay4 | Relay5 |
|---|--------|--------|--------|--------|--------|
| Host | 1      | 1      | 1      | 0      | 0      |
| Relay1 | –      | 1      | 1      | 1      | 0      |
| Relay2 | –      | –      | 1      | 1      | 0      |
| Relay3 | –      | –      | –      | 1      | 1      |
| Relay4 | –      | –      | –      | –      | 1      |

Fig. 3  Routing table corresponding to transmission matrix in Table 1

4.3 Data transmission procedure

In cases where the host device and relays do not communicate directly because of distance, they communicate by constituting their network using several relay devices. If the sensor nodes and relay devices are battery fed, then the method used for forming the network needs to consume as little power as possible. An automatic method was therefore proposed to create the multiple-vehicle network using minimum transmission to reduce power consumption.

The host and relay devices transmit data based on the transmission matrix and the routing tables. Data transmission goes via the relay devices when it cannot be sent directly to final destination. Transmission via the relay devices also consumes electric power, therefore the fewer the number of intermediary relay devices, the lower the power consumption of whole system.

In this case, the relay device closest to the final destination is selected preferentially in the routing table. If the transmission to this device fails, the second closest relay device is selected. The data transmission procedure is shown in Fig. 4. Availability of the link is determined from the transmission matrix and the routing table, the answer is “Yes” if the element corresponding to the target device is one or “No” otherwise.
4.4 Updating of transmission matrix

In the second phase of the multiple-vehicle network set up in Fig. 2, two methods are proposed for updating the transmission matrix; one considering the radio wave environment, the other using the predetermined transmission matrix. The first is called “updating transmission matrix,” the second is called “holding the transmission matrix.”

4.4.1 Sequence for updating the transmission matrices

To update the transmission matrices, the host device updates the transmission matrix according to the communication conditions. Based on the results of a check carried out by the host device on the availability of links between the host and relays, the host device updates the row in the transmission matrix corresponding to the host device. Next, the host device requests the relay device to check the availability of links between relay devices, and the relay device transmits the result to the host device. The host device updates the transmission matrix based on the response from the relay device. The transmission between each device is performed according to the data transmission procedure described above.

A method for checking link availability could possibly be based on the success rate defined as the number of responses from relay devices to the host device in relation to the total number of requests made by the host device to check its links with relay devices. The method for checking the availability of the links between relay devices follows the same procedure. The relay device transmits the result after checking the availability of the links.

4.4.2 Sequence for holding the transmission matrices

In the case of holding the transmission matrices, the host device maintains the transmission matrix in which the availability of the links is noted in advance. This transmission matrix is generated based on the number of vehicles between which direct communication between the host device and the relay device and between the relay devices is possible, calculated from the wireless module specifications or the radio wave environment.

5. Confirmation and evaluation of the proposed method

The proposed method for creating a multiple-vehicle network was verified using a prototype. The proposed method was also verified and evaluated for situations where a network has a large number of relay devices by simulating the proposed method with a commercially available network simulator. In these two tests, the following items were evaluated.

• Time required to create the network
• Time required for collecting data

The time required to create the network, or “network creation time,” was calculated from when processing began up to commencement of data collection. The “data collection time” corresponds to the time need to collect all the data.

5.1 Evaluation with the prototype

A prototype was built capable of applying the network configuration method proposed. The prototype was given two host devices and six relay devices using the equipment shown in Table 2 (see Fig. 5). In the function verification test, a network consisting of one host device and six relay devices was evaluated. Tests were also performed to check the consequences of a flat battery or relay device failure, by turning off the power supply.

First, network creation time and data collection time for the two sequences were compared, for networks composed with one to six relay devices. For the case where the transmission matrix was held, the following matrix was used: the host device can transmit directly to the relay device on the second vehicle and the relay device can transmit directly to the relay device on the third vehicle. The function verification test was conducted five times.

The network creation time is shown in Fig. 6 and data collection time is shown in Fig. 7 in accordance with the number of relay devices from one to six. The marker indicates the average time of the test. The maximum standard deviation was less than one second. Average test times are shown, not worst times. Figure 6 demonstrates that the network creation time increases as the number of relay devices increases for both sequences. The difference in network creation time between the two sequences grows as the number of relay devices increases since in the updating

| Table 2 Equipment specifications |
|----------------------------------|
| Device   | Equipment                  | Specification                        |
| Host device | 920 MHz band wireless module | Standard: ARIB STD-T108  |
|           |                            | Transmission Power: 1,10,20 mW  |
|           |                            | Outer I/F: UART1 port              |
| Control PC |                            | CPU: Intel Core i5              |
|           |                            | Memory: 8 GB                    |
| Relay device | 920 MHz band wireless module | Same as the host device       |
| Control PC |                            | CPU: ARM Cortex-A7              |
|           |                            | Memory: 1 GB                    |

Fig. 5 Prototype
transmission matrices sequence, the availability of links to the devices each need to be checked, whereas when holding the transmission matrices, predetermined transmission matrices are used.

In the test for updating transmission matrices, all relay devices can transmit to the host device. However, for the test on holding the transmission matrices, the given transmission matrix had a host device only able to transmit up to the relay device on the second vehicle, which led to an increase in the number of relay devices in the transmission sequence. Figure 7 shows that the data collection time when the transmission matrices are updated is shorter than when the transmission matrices are held.

In the next test the power supply to the relay device on the third vehicle was turned off in a network consisting of one host device and five relay devices. This situation is shown in Case2 of Table 3, and the result of turning on the power supply to each relay device, is shown in Case1 of Table 3. The two situations are compared. The network creation time and the data collection time are presented in Table 3. The numerical data in the table represents the averages from each test.

Regarding the network creation time in Table 3, the processing time in Case2 is 1.5 times longer than in Case1 for updating the transmission matrices, while it is 2.2 times longer than Case1 when holding the transmission matrices. The time needed to collect data however is shorter in Case2 than in Case1. The host device does not therefore request the turned off relay to send data since the row corresponding to the relay whose power supply is turned off in the transmission matrix is zero after updating the transmission matrix, and the number of relay devices transmitting the sensor data to the host device is reduced by one. When the transmission matrices are held, the host device requests the turned off relay to send data since the transmission matrix is not updated, thus increasing timing out frequency due to the number of retransmissions. This means that the processing time in Case2 is longer than in Case1.

5.2 Evaluation from the simulation

In the test using the prototype, the maximum number of relay devices was six because of the production limit. The maximum number in reality however in a train composition is 17 for a passenger train and 26 for a freight train. The simulation for creating a multiple-vehicle network, was therefore used to determine the network creation time and data collection time for a number of relay devices ranging from 1 to 26. OMNeT++ was used in the simulation. The simulation assumed no packet loss, and processing time comparisons were made in an ideal environment. The average time obtained in function confirmation tests using the prototype was adopted as the processing time for transmission in the simulation.

The number of relay devices

| Case   | Updating Creation | Updating Collection | Holding Creation | Holding Collection |
|--------|-------------------|---------------------|------------------|-------------------|
| Case1  | 73.6              | 6.4                 | 9.4              | 10.4              |
| Case2  | 110.8             | 5.0                 | 20.9             | 19.6              |

![Network creation time when transmission matrices are updated](image)

Fig. 8  Network creation time when transmission matrices are updated

y = 9.08x² - 1.21x

$R^2 = 0.99$
The network creation times obtained in simulation are shown in Fig. 8 and while those for data collection time are shown in Fig. 9, in accordance with the number of relay devices used each time. Figure 8 shows that the network creation time is proportional to the square of the number of relay devices when the transmission matrices are updated. The same result was obtained holding the transmission matrices. Figure 8 and 9 illustrate that the approximate quadratic curves fit well with the numerical data obtained from the simulation. They also show that applying this method in cases where the number of vehicles is 26 is not realistic, since the network creation time would be over 100 minutes if transmission matrices are updated. When the transmission matrices are held however, the process takes less than three minutes, which suggests it can be realistically applied.

The data collection times for the two sequences are shown together in Fig. 10, which shows that data collection time is proportional to the square of the number of relay devices in the two sequences. Also, the approximate quadratic curves fit well to the numerical data obtained from the simulation. The simulation results indicate that the data collection times when transmission matrices are updated are shorter than if the transmission matrices are held, which is the same result as in the prototype tests.

5.3 Test Summary

The results of the evaluation of the network creation time and the data collection time obtained from the prototype test and the simulation are as follows:

When updating transmission matrices, network creation takes more time, but the transmission matrix is very reliable, which cuts the data collection time.

Holding the transmission matrices offers the advantage of a shorter network creation time the drawback is that it takes longer to collect the data since the transmission matrices do represent the actual radio wave environment.

This paper therefore proposes a sequence where the host device updates the transmission matrix with link availability that is determined in advance like when holding transmission matrices, in order to reduce the network creation time. Link availability is then checked only for elements appearing in the matrix with a number one. The next simulation tests will consider cases where packet loss occurs.

6. Conclusion

This paper proposes a method for creating a network between vehicles to establish a vehicle monitoring system using a wireless sensor network. The proposed method was evaluated and verified in tests using a prototype and through simulation.

A new method will be submitted for the creation of this type of network which will reduce the network creation time and data collection time, and furthermore, with the aim of making it applicable to running trains.

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