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Application of remote monitoring and management of high-speed rail transportation based on ZigBee sensor network

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Abstract

Operational safety is the prerequisite for high-speed railway to carry out transportation work, and with the increasing mileage of high-speed railway in China, higher requirements are put forward for monitoring the operation environment of high-speed trains. From the point of view of the whole road, the wireless sensor network technology is fully applied to the monitoring of high-speed train operation environment. Based on the actual requirement of the high-speed train operating environment monitoring, the overall structure and logic frame of the high-speed train operating environment monitoring system based on wireless sensor network are put forward. By establishing the node structure model algorithm, and taking natural disaster and foreign object intrusion detection as an application example, the natural disaster and foreign object intrusion detection system based on wireless sensor network are designed.

Keywords: ZigBee sensor network, High-speed rail transport, Remote monitor and control

1 Introduction

Railway is the major artery of national economy, key infrastructure, and major livelihood projects, and is one of the backbones of the comprehensive transportation system and one of the main modes of transportation, which is of great importance and role in the economic and social development of our country (Xu D et al. 2016) [1]. Since the implementation of *Medium and long term railway network plan* in 2004, China's railway development has achieved remarkable results, which plays an important role in promoting economic and social development, ensuring and improving people's livelihood, supporting the implementation of the national major strategy, and strengthening our country's comprehensive strength and international influence (Zhu H., 2016) [2]. In recent 10 years, China's high-speed railway network has made remarkable achievements, and the scale of the road network has been expanding. By the end of 2015, the national railway business mileage reached 121,000 km, of which the speed railway was 19,000 km, accounting for more than 60% of the total mileage of the world high-speed railway (Gharghan S K et al. 2017) [3]. According to the newly revised *Medium and long term railway network plan*, by 2020, the scale of the railway network will reach 150,000 km, including 30,000 km of high-speed railway, and it will cover more than 80% of the large cities. By 2025, the scale of the railway network will reach 175,000 km, of which the high-speed railway is about 38,000 km, the network coverage is further expanded, and the road network structure is more optimized, the role of backbone is more significant, which can better play the role of railway in ensuring economic and social development (Mosleh M F et al. 2017) [4]. On the basis of the "four vertical and four horizontal" high-speed railway, the high-speed railway with passenger flow support, standard suitability, development requires should be increased, a high-speed railway network which takes the "eight vertical and eight horizontal" main channel as the skeleton, with connection of regional connection lines and intercity railway supplement is formed to realize the efficient and

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convenient connection between the provincial capital cities and the high-speed railways (Zhang Z et al. 2017) [5].

2 State of the art

Foreign scholars have been trying to apply wireless sensor networks in the railway field very early. While describing the application of wireless communication in railway, a railway monitoring system based on wireless sensor network is put forward by scholars (Alhmiedat T., 2017) [6]. In 2008, scholars put forward a railway monitoring system based on wireless sensor networks, which includes two aspects of train monitoring and line monitoring, and can be used to monitor the train running state in real time (Alhmiedat T et al. 2017) [7]. In orbit monitoring, Huo Hongwei and others put forward a railway track monitoring model based on multi gateway mobility, and when the specific node installed on the train is near the sensing node, the node covered currently is awakened, and nodes collect data to transmit the data collected to the gateway in a single hop or limited multi hop mode, when the mobile gateway leaves, the node enters a dormant state, which can store energy to achieve passing track and other carrying facilities monitoring information to the train, and it enables the train to understand the condition of the specific section in the course of running (Wu Q et al. 2018) [8]. To sum up, experts and scholars have carried out a preliminary study on wireless sensor networks for monitoring the operation environment of high-speed trains, including lines, trains, stations, natural environment along the way, transportation of dangerous goods, and so on, but most of studies remain in a specific area of research, various wireless sensor networks are self-contained and non-interference, resulting in a variety of complex problems in wireless sensor networks. The research on comprehensive monitoring of railway operation environment is in its infancy, and it is urgent to build a unified wireless sensor network to conduct overall monitoring of train operation environment.

3 Methodology

3.1 Node structure and typical energy consumption model algorithm

The node of wireless sensor network is a kind of micro embedded system, which consists of four parts: sensor module, processor module, wireless communication module, and energy supply module. Usually, the power consumption of the processor and sensor module is relatively low, and most of the energy consumption occurs in the wireless communication module. In view of the volume of sensing nodes, it is often impossible to use large capacity batteries to supply them, and because of the characteristics of wireless sensor networks, it is often not possible to replace batteries for sensing nodes. Therefore, how to improve the efficiency of communication and reduce energy consumption is one of the key problems to be solved in wireless sensor networks. A typical energy consumption model for wireless sensor networks is adopted.

$$E_{\mathrm{Tx}}\begin{cases} k \times E_{\mathrm{elec}} + k \times \varepsilon_{\mathrm{ft}} \times d^2, d < d_0 \\ k \times E_{\mathrm{elec}} + k \times \varepsilon_{\mathrm{mp}} d^4, d_0 \end{cases} \quad (1)$$

$$E_{\mathrm{Rx}} = k \times E_{\mathrm{elec}}. \quad (2)$$

The formula (1) indicates the loss of energy when sending k bit data to a receiver with a distance of d, including two parts: emission circuit loss and power amplification loss. E_{elec} is the loss energy of a transmitting circuit, and power amplification loss uses different models according to the different distances between the sender and receiver: free space model and multi path fading model. When the transmission distance is within a certain threshold d_0 (d_0 is the constant), when $d < d_0$, free space model is adopted, the power of the transmission distance is proportional to the square of the distance, ε_{ft} is the energy required for power amplification in the free-space channel model; when $d \geq d_0$, multi path fading model is adopted, the power consumption is proportional to the four times of the distance, $\varepsilon_{\mathrm{mp}}$ the energy required for power amplification in the multi path fading channel model. The formula (2) indicates the energy consumed by the receiver when receiving k bit data.

3.2 Energy consumption model algorithm for linear wireless sensor networks

According to the structure of wireless sensor network along the railway, the location of sink nodes and sensing nodes in wireless sensor network is determined, which is deployed in accordance with the actual monitoring requirements and relevant regulations along the railway line. The deployment of relay nodes in wireless sensor networks is directly related to the lifetime of wireless sensor networks. In general, a uniform deployment strategy is adopted by relay nodes, that is to say, all relay nodes located in all perceptual nodes are deployed with the same spacing. Under this deployment strategy, the distance between all relay nodes is equal, and the amount of energy consumed by single forwarding unit data is equal, but the nodes with close distance from the sink node need more data forwarding than those with far distance, therefore, it is easy to form an energy hot zone, resulting in the “energy hole” problem, which makes the wireless sensor network premature early to die.

In view of the above problems, a strategy of non-uniform optimization deployment is proposed, and the policy is described as follows: there is a uniform deployment between two adjacent sensing nodes or the sink node and the sensing node, that is the distance between two adjacent relay nodes is equal between two adjacent sensing nodes or the sink node and the sensing node. The relay nodes closer to the sink node assume larger data forwarding capacity, and a smaller deployment interval should be adopted; however, the relay nodes with far distance from the sink node assume smaller data forwarding capacity, and larger deployment spacing should be adopted, as far as possible, each relay node consumes the same energy in single data forwarding. Therefore, for the two adjacent sensing nodes which are closer to the sink node or between the sink node and the sensing node, the relay nodes should be more densely deployed. When the number of relay nodes that can be deployed is the same as that of the average deployment strategy, the unevenly optimized deployment strategy can make the energy consumption of all relay nodes in the network balanced, which can prolong the network life cycle and improve the network efficiency. Therefore, a mathematical model based on this strategy can be established to solve the problem of the total number of relay nodes; the number of relay nodes should be deployed between the two adjacent sensing nodes or the sink node and the sensing node, so that the network efficiency can be maximized.

The researched wireless sensor network is a typical linear network, and in order to avoid the problem of "energy hole," the energy balance of all nodes must be consumed. Then, the energy consumption problem of nodes will be analyzed in detail. According to the hypothesis, it can be known that the amount of data collected by each sensor node in 1 cycle is $l$bit, the amount of data each node accepts in 1 cycle is $r$bit, the amount of data that each node sends in 1 cycle is $j$bit, obviously, the amount of data received and sent by $l \le j \le l + r$ for relay nodes in 1 cycle is $j$bit. Because the energy consumed by the sensing data is negligible, it is known that the relay node consumes more energy than the sensing node. Therefore, the bottleneck of the life cycle of wireless sensor networks lies in relay nodes. According to the model of energy consumption, the energy consumed by the i relay node before the sensing node s_n is shown in formula (3).

$$E_i \begin{cases} j_i \times E_{\mathrm{elec}} + j_i \times \varepsilon_{\mathrm{ft}} \times d_i^2 + j_i \times E_{\mathrm{elec}}, d_i < d_0 \\ j_i \times E_{\mathrm{elec}} + j_i \times \varepsilon_{\mathrm{mp}} \times d_i^4 + j_i \times E_{\mathrm{elec}}, d_i \ge d_0 \end{cases} \quad (3)$$

j_i represents the amount of data received and sent by the relay node. In order to improve network efficiency and reduce "energy hole" problem, ideally, the energy consumed E_i by each node is equal, and all relay nodes consume all the energy at the same time, which is almost impossible in reality. In view of this problem, the model E_i is assumed to be near a definite value, and the constraint conditions are shown in formula (4).

$$\frac{\tilde{E}}{q} \le E_i \le q \cdot \tilde{E}, q \ge 1. \quad (4)$$

In the formula, q is a constant greater than 1 and infinitely close to 1.The lifetime of the network ζ is defined as the time used by the network when the energy of any node in the network is exhausted, as shown in formula (5).

$$\zeta = \frac{E_0}{\tilde{E}} \cdot T_p. \quad (5)$$

E_0 indicates the initial energy of nodes in a network, T_p indicates the time consumed by data acquisition and transmission. In general, the life cycle of the network increases with the number of nodes deployed, but the rate of increase will decrease. This is because as the size of the network increases, the contribution of a single node decreases. Therefore, the new parameters are selected as the objective function of the model, and network efficiency is defined as the ratio of the network life cycle to the number of network nodes, as shown in the formula (6).

$$\eta = \frac{\zeta}{N_s + N_r}. \quad (6)$$

N_s represents the number of perceived nodes and N_r represents the number of relay nodes. Network use efficiency indicates the change rate of network life cycle with network scale, which makes balance between the network lifetime and node deployment costs.

4 Result analysis and discussion

The railway operation environment monitoring system deploys a sensing node every 1000 m along the railway line, and the sink node is located at one end of the system. The length of the monitoring area is selected in four cases: 1000 m, 2000 m, 3000 m, and 4000 m. Because of the use of data fusion strategy, the amount of data transmitted by the sensing node is 8 bytes, 10 bytes, 12 bytes, and 15 bytes respectively. In the same number of relay nodes, two different deployment strategies are compared. When using the same number of relay nodes, the two different deployment strategies are adopted. With equally spaced deployment strategies, it can be seen that 14 relay nodes need to be deployed between two sensing nodes. The optimal deployment strategy is adopted to maximize the efficiency of the network, and MATLAB software is used to solve the problem. Figure 1 shows the comparison of the life cycle of the two strategies, and Fig. 2 shows the comparison of the use efficiency of the two strategies. It can be concluded that the

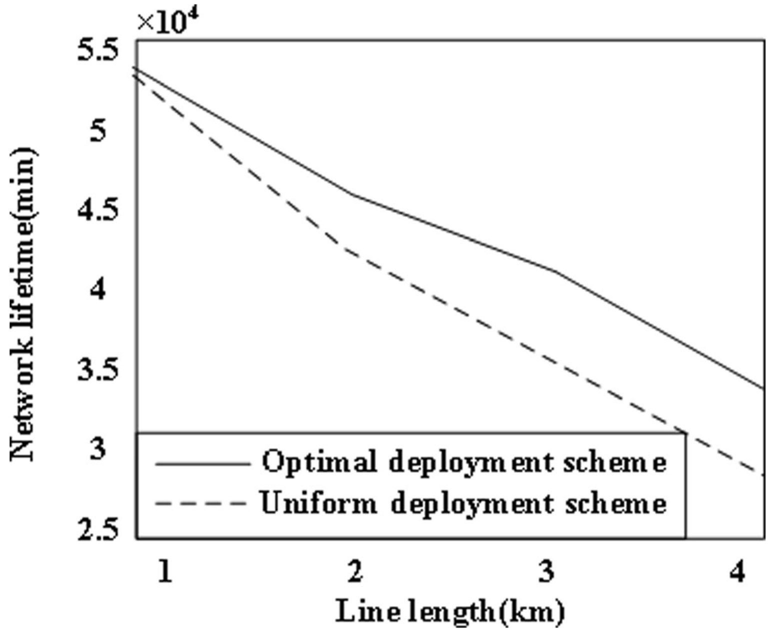

Fig. 1 Network use efficiency contrast diagram

network life cycle and use efficiency of the optimized deployment strategy are better than the equal distance deployment strategy. The life cycle of these two deployment strategies decreases with the increase of network length, but the reduction degree of network life cycle of the optimized deployment strategy is less. When the monitoring length is 4000 m, the network life cycle of the optimized deployment strategy is 20% higher than that of the equal distance deployment strategy. Therefore, the optimized deployment strategy proposed can effectively improve the life cycle and efficiency of the network.

When the monitoring area is 4000 m long, the network deploys 4 sensing nodes, and the energy consumption of relay nodes in the network using the node optimal deployment strategy is more balanced, when the network fails,

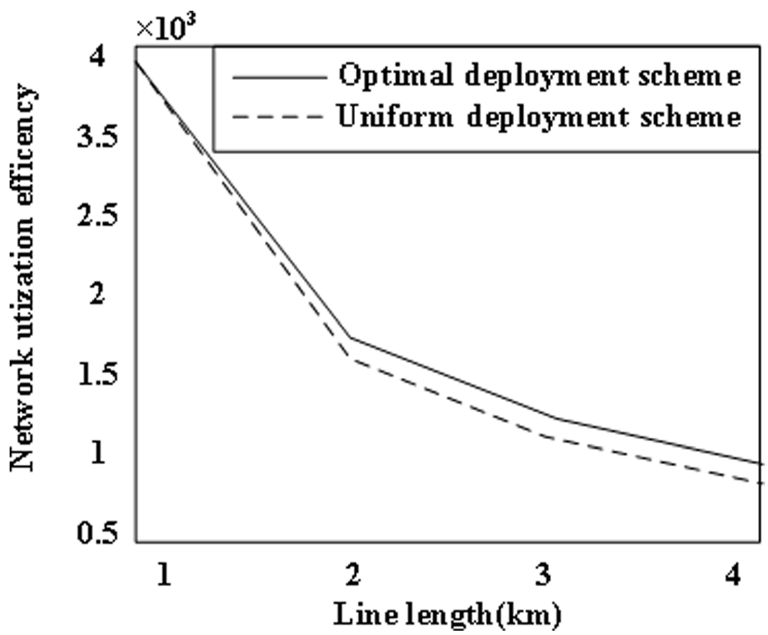

Fig. 2 Network use efficiency contrast diagram

the residual energy of nodes is 7.9% of the total energy of nodes. When the network with equal distance deployment strategy fails, the residual energy of nodes is 48.2% of the total energy of nodes. Therefore, the optimal deployment strategy designed can better save network energy and improve network efficiency. Without considering node failures, a network with only one row of relay nodes is simulated and analyzed. By simulating the linear wireless sensor networks with five relay nodes, the data packets with priority of 0, 1, 2, and 3 can be obtained in the network, and the number of data packets sent on average is shown in Fig. 3.

The routing protocol proposed is called mode I, which is compared with the following two data transmission modes. The mode II, which is a non-compulsory priority queuing system, is not adopted by the queueing form of full functional sensor node. The mode III, which is the priority of packet partition, is not considered, the intelligent forwarding mode is not adopted, and all data packets are transmitted by hopping step by step. Through simulation experiments, it can be seen that the total number of data packets transmitted by linear wireless sensor networks under these three data transmission modes is shown in Fig. 4. Among them, the total number of transmission data packets of modes I and II is the same, so the network life of these two ways is the same, and the total number of data packets transmitted by III is less, so the network life is slightly smaller in this way.

By the simulation of a network with five relay nodes, the average transmission delay of data packets with four priorities as 0, 1, 2, and 3 can be obtained under the two transmission modes of mode I and mode II. The delay comparison of the two transmission modes through simulation is shown in Fig. 5.

From the results of the graph, it can be seen that the method of non-mandatory priority queueing system is adopted, although the transmission delay of data packets with lower priority is increased, the transmission delay of the highest priority packet is effectively reduced, which improves the timeliness of packet transmission with higher priority. In this way, the queuing delay of the data packet is allocated to data packets with different priority levels, which makes $W_K < W_{K-1} < \dots < W_0$, while in general $\lambda_0 > > \lambda_K$, that is, the number of data packets with high priority is small. Therefore, on average, the transmission delay of data packets with high priority is reduced a lot, while on average the transmission delay of each data packet with low priority level is not much increased, which is a good way to reduce the delay. Therefore, the routing protocol can effectively reduce the transmission delay of high priority packets in the case of ensuring the network lifetime. On the basis of the existing hardware conditions, five communication technologies of the above eight modules are tested on the number of packets sent successfully through the instant uplink and downlink of the train at high speed.

When the train is running within the speed range of 300–350 km/h, the single output of the four modules' downlink and uplink packets are tested respectively. When the ground sends data packets to the train, the number of data packets successfully received by the vehicle test platform is instantaneous after the train passes the ground test platform. According to the test results, the number of data packets sent successfully decreases as the speed of the train increases, and the number of

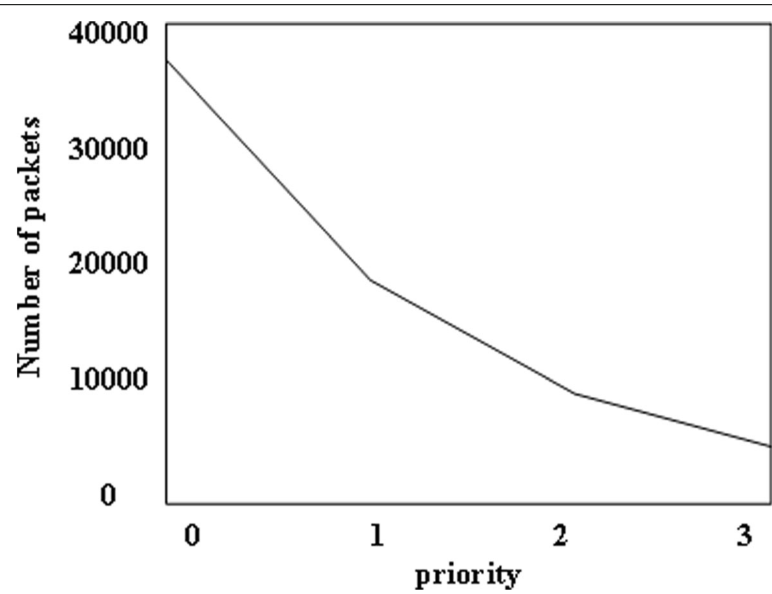

Fig. 3 Number of packets with different priorities on average

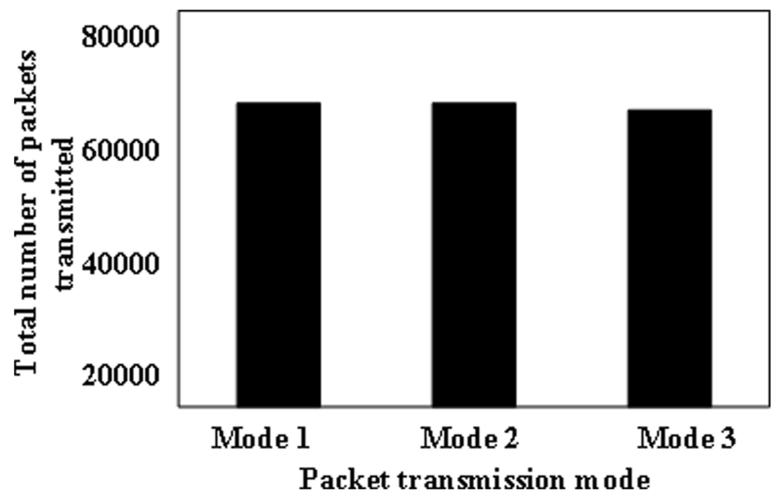

Fig. 4 Data packet transmission quantity contrast diagram

data packets sent successfully by the communication module based on ZigBee technology is the largest. When the train sends data packets to the ground, the number of data packets successfully received by the ground test platform is instantaneous after the train passes the ground test platform. According to the test results, the number of data packets sent by the communication module based on ZigBee technology is also the largest. Through several tests, the average packet loss rate of uplink and downlink of each communication module is calculated. According to the test results, when the communication module based on RFID technology is set to 250 kbps at the air speed and the baud rate is 9600, the rate of packet loss in both uplink and downlink is the lowest. The packet loss rate of communication module based on ZigBee technology is relatively high. By adding the delay of the uplink and the delay of the downlink, the problem of two laptops' time asynchrony can be eliminated and the more accurate round-trip delay of the packet transmission can be obtained.

Figure 6 shows the relationship between the data packet transmission delay of four modules and the speed of the vehicle, and Fig. 6–9 shows the average delay of packet transmission of four modules. According to the test results, there is no obvious linear relationship between data packet transmission delay and vehicle speed. Among them, the third set of module based on RFID technology, because of its baud rate is 38,400, which is larger than other modules' baud rate of 9600, so the data packet transmission delay of it is the smallest, which concentrating between 149 ms and 195 ms, and the average transmission delay is 167.75 ms. Transmission delay

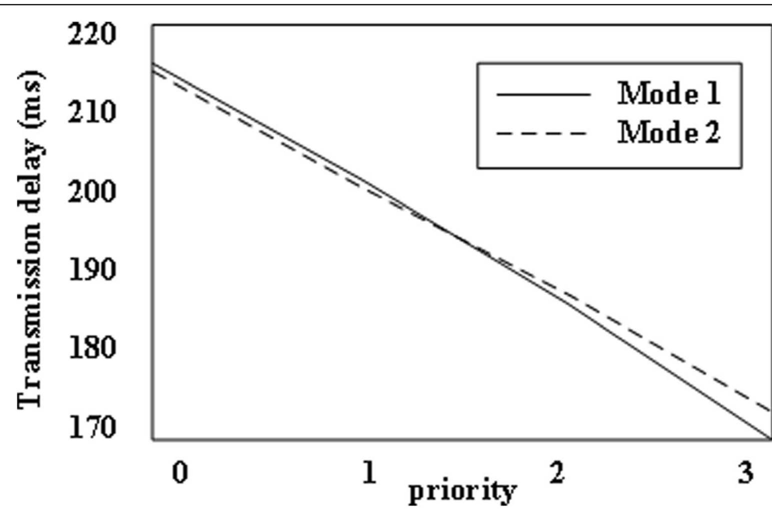

Fig. 5 Data packet transmission delay contrast diagram

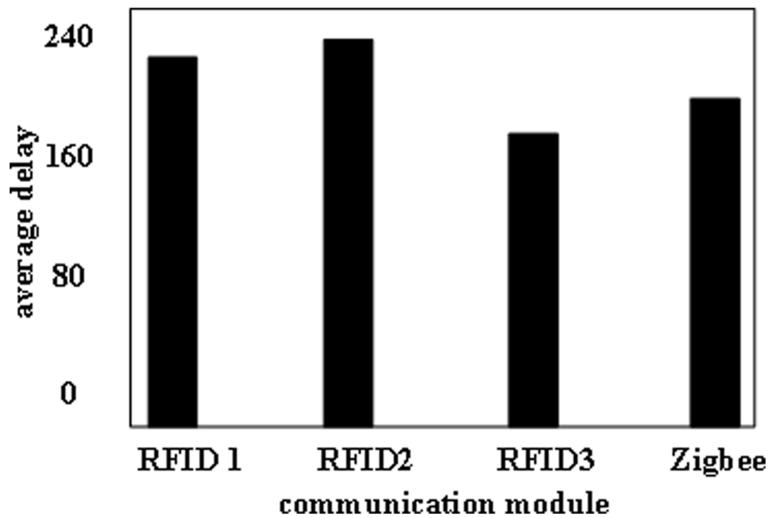

Fig. 6 Packet transmission average delay

time of module based on ZigBee technology is the second, which concentrating between 170 ms and 193 ms, and the average transmission delay is 186.89 ms. By the analysis of the above test results, the communication models based on ZigBee technology, the single transmission volume of uplink and downlink data packets is the largest, and the transmission delay is moderate to be recommended for building wireless sensor networks.

5 Conclusion

Based on the actual situation of high-speed train operation environment monitoring, the current situation and business requirements of the existing high-speed train running environment monitoring are fully investigated and analyzed, the advantages of wireless sensor networks is exerted, and the new idea of applying wireless sensor network technology in the field of high-speed train operation environment monitoring is put forward; the overall framework and logical framework of high-speed train operation environment monitoring system based on WSN are proposed; a topology structure for ground wireless sensor networks is designed; the node deployment strategy and routing protocol for linear wireless sensor networks are studied; the performance of ground to ground communication for various wireless communication technologies is tested in real high-speed rail environment, a transmission scheme of vehicle ground wireless sensor network based on relay transmission is designed, and it has been verified in field test; a natural disaster monitoring system based on wireless sensor network is designed. The overall framework of high-speed train operation environment monitoring system based on SOA and wireless sensor network is proposed. The framework runs through railway computer networks and wireless sensor networks, which can integrate all the sensor resources distributed in the bureaux, stations, and routes of all roads to form a unified sensor network. The comprehensive application of wireless sensor network in railway-related professional fields is realized to form an innovative application mode with internal and external penetration, and the integration of service and production.

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Authors' contributions
JZ has done a lot of research and analysis on ZigBee sensor network and contributed to the summary of the paper. The author read and approved the final manuscript.

Competing interests
The author declares that she has no competing interests.

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