Hindawi
Journal of Sensors
Volume 2021, Article ID 3789699, 13 pages
https://doi.org/10.1155/2021/3789699

Research Article

Passive Wireless Sensor Network-Based In-Transit Health Status Monitoring for Railway Transportation

Jianpeng Wei[1] and Yaduo Song[2]

[1]*Department of Railway Transportation, Hebei Vocational College of Rail Transportation, Shijiazhuang 050000, China*
[2]*Training Center Hebei Vocational College of Rail Transportation, Shijiazhuang 050000, China*

Correspondence should be addressed to Yaduo Song; 20143195@stu.nun.edu.cn

Received 29 September 2021; Accepted 13 October 2021; Published 31 October 2021

Academic Editor: Guolong Shi

In this paper, passive wireless sensor network technology is used to conduct in-depth research and analysis on the monitoring of the in-transit health status of railway transportation. Safety detection sensors, train communication networks, and other onboard devices organically constitute a train sensor network with comprehensive state sensing, information aggregation, and business collaboration. First, this paper analyzes the three-layer architecture of the sensing layer, network layer, and application layer of the train operation status safety detection sensor network. Based on analyzing the feasibility of Ethernet application in an onboard communication network, ring, multiring, and ladder-type sensor network structure schemes are designed. Next, the real-time performance and reliability of various sensor network structures are analyzed. First, the characteristics of bandwidth demand, priority, and importance of information transmission of each monitoring object are analyzed; then, the system utility function is established according to the bandwidth usage efficiency and communication demand of information transmission of each monitoring object; finally, the bandwidth allocation optimization model is solved by using a particle swarm optimization algorithm, and the remaining bandwidth resources are dynamically rationed on demand while ensuring the complete transmission of basic information of each monitoring object. Rail transit technology has profoundly affected and changed the travel and lifestyle of residents in the new era and will provide strong infrastructure support for the smooth advancement of new urbanization construction and development strategies. The remaining bandwidth resources are dynamically allocated on the premise of ensuring the complete transmission of basic information of each monitoring object. In summary, this paper presents a complete study on the optimal allocation of resources for wireless sensor networks dedicated to rail transit condition monitoring, starting from the perspectives of routing protocol optimization, data fusion rate optimization, and bandwidth dynamic allocation optimization to achieve the efficient use of limited resources. The achieved research results enrich the research content in the field of wireless monitoring of rail transit system conditions at home and abroad in a certain sense and will also provide theoretical and empirical support for practical practitioners, managers, and scholars of service condition monitoring of rail transit systems.

1. Introduction

The rail transit system has become one of the major transportation modes for intracity, intercity, and national traffic travel and cargo transportation in China and plays an irreplaceable global supporting role for the improvement of national living conditions, national economic development, and national comprehensive national power [1]. First, rail transit technology profoundly affects and changes the travel and lifestyle of residents in the new era and will provide strong infrastructure support for the smooth promotion of new urbanization construction and development strategies. Second, in the new international and domestic environment, the healthy and rapid development of the rail transit system will have a significant impact on defending national security and maintaining regional stability [2]. Thirdly, as the most resounding “national business card” in the new era, the development of rail transit technology will become the front-runner in the implementation of the national “Belt and Road” strategy and the export of enterprise technology and products. With the large-scale construction and rapid development of rail transit, its transport tasks and strategic significance are also more significant, which puts forward higher requirements on the stability, reliability, and safety of rail transit system operation. Practitioners and experts and scholars in the rail transit business at home and abroad use multisource sensing to obtain the operational status information of the rail transit system and conduct corresponding fault diagnosis and prediction and early warning research to provide technical and decision support for the safe operation of the rail transit system [3]. At present, the condition monitoring of the rail transit system mainly relies on the combination of manual inspection, comprehensive monitoring train inspection, and onboard testing equipment to conduct "regular" inspection of the operation status of the rail transit system, and off-line processing and analysis of the inspection data and the efficiency of the inspection are closely related to the frequency of the inspection.

Since the frequency of testing is generally based on the operational experience of field experts, there is a strong lag in the monitoring of unexpected faults. At the same time, the period of detection and the time of train operation must be strictly controlled in sections to avoid traffic accidents, which reduces the efficiency of rail transit system operation to a certain extent [4]. To improve the economy, in real time, reliability, and safety of rail transit system operation status monitoring, experts of rail transit system infrastructure monitoring built a wired based status information monitoring transmission system in the key monitoring section, using video, fiber optic grating, and stress-strain monitoring transmission technology, to achieve online monitoring of rail transit system infrastructure and real-time transmission of monitoring information. This puts forward higher requirements for the stability, reliability, and safety of the rail transit system. It has greatly improved the efficiency of rail transit infrastructure monitoring. However, the online monitoring system based on wired communication will encounter many difficulties in practical application, and it is difficult to achieve full coverage monitoring of rail transit infrastructure and its operating environment. The wireless sensor network is one of the current hot research directions, which consists of many miniature sensors arranged in the monitoring area and integrates sensor technology, network technology, wireless communication, and other technologies. Nodes with wireless communication function through highly integrated sensors to achieve real-time information monitoring of various environmental monitoring objects; the external information sensed by the wireless sensor network is transmitted to the user wirelessly from the detection area [5]. The wireless sensor network can help people to better achieve the objective world and human social communication. The emergence of wireless sensor networks has changed the interaction between humans and machines, humans, and nature to a certain extent, thus realizing the connection of the physical world, computing world, and human society, which greatly expands the human cognition of the world. Wireless sensor networks have become an important part of the next-generation Internet. Sensor technology, communication technology, and computer technology are the three bases of modern information technology, respectively, to complete the collection, transmission, and processing of information. The wireless sensor network combines the three technologies, to realize the true unification of information collection, transmission, and processing. The wireless sensor network is considered to be one of the most important technologies in this century, which will have a profound impact on the future way of life of human beings. In recent years, with the development of wireless communication technology, microprocessor, and integrated circuit technology, wireless sensor network technology has become increasingly mature, and its applications are becoming increasingly widespread.

In this paper, we will conduct an in-depth study on the application of wireless sensor networks in high-speed train operating environment monitoring from the theoretical and practical perspectives, propose the architecture of high-speed train operating environment monitoring system based on the wireless sensor network according to the current high-speed train operating environment monitoring business requirements, study the optimal deployment strategy and routing protocol of wireless sensor network nodes applicable to the strip area along high-speed railways, and study the vehicle-ground wireless sensor network transmission scheme for real high-speed train environment. Through the in-depth study of the above key technologies, the theoretical foundation is laid for the wide application of wireless sensor networks in high-speed railways; for the specific design of the wireless sensor network-based high-speed railway natural disaster and foreign object intrusion monitoring system, an important step for the implementation of the system on the ground; for large-scale deployment and long-term online monitoring in regional and remote areas; and for ground wireless sensor network and vehicle wireless sensor network through the vehicle-ground wireless sensor network, so that the monitoring information from the ground wireless sensor network is transmitted to the train in advance, providing the train with real-time data of the operating environment ahead, which ensures the safety of train operation.

2. Current Status of Research

To improve the real-time condition monitoring of the rail transit system, combined with the rapid development of sensor technology, data processing technology, and communication technology, experts and scholars at home and abroad use online monitoring to obtain the service status information of the rail transit system in real time, which greatly improves the efficiency of monitoring and enhances the safety of system operation [6]. Godala and Vaddella established a long-term monitoring point in Beijing-Shanghai high-speed railway to monitor the force and deformation of the track system of the elevated station in real time through the fiber optic grating and video sensing technology [7]. OMahony et al. proposed a noncontact longitudinal rail displacement online monitoring method based on the magnetostrictive principle [8]. Safe railway operation requires real-time monitoring of information along the railway line, which is transmitted to the onboard safety computer and monitoring center for analysis and judgment to take appropriate preventive measures [9]. How to communicate the information obtained by the sensor nodes instantly and reliably between the train and the vehicle to replace the existing intermittent information acquisition method has become an important issue to ensure the safety of traffic [10]. Research on monitoring train and ground environment information based on wireless sensor network technology has been supported by grants including the former Ministry of Railways and the Natural Science Foundation. In the rapid development and construction of railways, all countries in the world regard railway operation safety as the lifeline of railway enterprise development [11]. Many railway transportation-related colleges and enterprises have conducted research related to infrastructure monitoring along railway lines, and some systems have been improved in the actual railway safety management application. A classification has been made based on different network dynamics, communication functions, and data transmission models. This taxonomy helps to define the communication infrastructure in an appropriate way for different sensor network applications and helps wireless sensor network designers to select the network protocol structure that best fits the application goals [12]. By constructing a wire-based status information monitoring and transmission system in key monitoring sections, using video, fiber grating, and stress-strain monitoring and transmission technologies, online monitoring of rail transit system infrastructure and real-time transmission of monitoring information were achieved, greatly improving the efficiency of rail transit infrastructure monitoring. Optimal deployment schemes and routing algorithms are designed for wireless sensor networks used to monitor the status of railway tunnels, and a completely different approach to improving current railway operation detection using wireless sensor networks is proposed. A structural condition monitoring system is studied and designed using fiber optic grating sensors for monitoring the vibration of key components of tracks and trains and can convert these data into fatigue indices to provide a scientific basis for judging vehicle life.

Sensor network technology has gradually received attention from relevant departments in China in recent years. At present, many scientific research institutions, universities, and enterprises have joined the research and development in the field of sensor network technology and have made large technical breakthroughs and achievements [13]. This system uses a trackside infrared probe to realize real-time detection of each bearing temperature of the train. The TFDS system uses trackside high-speed cameras to detect the safety-critical parts of the wagon such as the walking part and the brake beam; the TCDS system can prevent the train from the hot axle and fire accidents and effectively detect the walking part, brake part, and power supply failure [14].

A large amount of status information generated by onboard equipment during train operation needs to be transmitted on the train quickly and reliably, to realize functions such as information sharing of onboard equipment, train operation control, safety warning, passenger information service, and remote fault diagnosis. The current train component-level safety detection devices can only be responsible for real-time monitoring of each component separately, and each safety detection sensor cannot work together. The large volume of detection data cannot be processed in time due to the bandwidth limitation of the onboard network. Therefore, it is necessary to build a train-wide in-transit detection sensor network based on the train communication network and sensor network technology. The train operation status safety detection sensor network is an important means to ensure the safety of train operation. At present, the installed train safety detection sensors are developed by each manufacturer, and their communication modes and interface specifications are inconsistent, and the sensor nodes are independent of each other and belong to different subsystems, which cannot be detected collaboratively and thus cannot detect possible associated faults. The construction of the safety detection sensor network for train operation status realizes multisensor cooperative sensing and solves the problem of ineffective detection of associated train faults.

3. Design of Passive Wireless Sensor Network for In-Transit Health Condition Monitoring of Rail Transport

3.1. Passive Wireless Sensor Network Detection Network Design. The railway monitoring system based on a wireless sensor network includes three parts: wireless sensor network, railway monitoring center, and railway dedicated communication network. The sensor nodes monitor the relevant information along the railway line and transmit it to the data monitoring center and the onboard aggregation node in the form of a wireless relay through the aggregation node located at the cluster head. After receiving the data information along the railway line, the safety monitoring center uses data mining algorithms to analyze and process and evaluate the safety level along the railway line and display the position of trains before and after and provide corresponding disaster warnings and other information [15]. Wireless sensor networks have become an important part of the next generation of the Internet. Sensor technology, communication technology, and computer technology are the three foundations of modern information technology, which, respectively, complete the collection, transmission, and processing of information. The disaster information and warning level are released to the trains along the line, train dispatching center, public works department, and other related departments through the railway private communication network. The wireless sensor monitoring node communicates with the onboard convergence node, ground convergence node, and cluster member nodes through single-hop or multihop; it also has the function of routing and completing monitoring-related information and is responsible for collaborative monitoring of the monitoring area. The wireless sensor node determines whether the sensed data reaches the threshold value or not [16]. If the threshold value is reached, the node sends the data to the ground aggregation node in a single-hop or multihop manner. The train and the wireless sensor monitoring nodes along the railway line can communicate in both directions. For example, the wireless sensor monitoring node can report absolute position information and monitoring data to the onboard sink nodes within the wireless communication radius. The nodes should be protected from damage caused by natural disasters in the design of wireless sensor monitoring nodes to enhance the reliability of the nodes.

The monitoring subcenter receives and stores the information from the upper information transmission platform, uses data mining algorithms to analyze and process the received data, and evaluates and gives the security level to the information along the railway line within its authority. The information is shared among monitoring subcenters, and the early warning information sent by the monitoring center is transmitted to the mobile vehicle convergence nodes along the line through the upper layer information transmission platform of the wireless sensor network [17]. With the development of wireless communication technology, microprocessor, and integrated circuit technology, wireless sensor network technology has become more mature, and its applications have become wider and wider. The monitoring center stores information such as rainfall, water level, roadbed, bridge, tunnel, falling rocks, and other information and train location information of each sensor monitoring point along the railway line sent by the monitoring subcenter. The monitoring center server uses relevant algorithms for comprehensive analysis and then provides information on the evaluation of the transport safety level in each monitoring area along the railway line, the location and tracking distance of trains in a larger area along the railway line, and issues corresponding warning messages according to the actual situation. The monitoring subcenter server and the monitoring center server interconnect through the railway private communication network to share the monitoring data and train location information along the railway line. The onboard convergence node is connected to the onboard computer through the serial port. The onboard convergence node receives the information released by the monitoring subcenter and the information sent by the ground convergence node through the upper information transmission platform, which includes the location information of other trains in the vicinity, precipitation, bridges, track obstacles in front of the train, and the data information after analysis and processing by the monitoring subcenter, as shown in Figure 1. The train periodically sends its relevant information, such as train position, speed, forward direction, train number, stock identification, and train health status monitored by the train-level sensor network, to the upper information transmission platform of the wireless sensor subnetwork through the onboard convergence node, which is received by other onboard convergence nodes and monitoring subcenters. This process is vehicle-ground-vehicle wireless communication.

The onboard computer calculates the distance between the front and rear trains based on the received information of the front and rear train positions and the position of the car and displays the train position and the received warning information on the onboard computer. The use of a wireless sensor network can mainly complete the car and car and car and ground communication between each other, so that in the operation of the train, there can be real-time understanding of the latest position of the front and rear vehicles and information related to the railway line endangering transport safety; it can be predicted that the system can provide decision support for traffic scheduling and reduce railway accidents playing an active role and evaluate the relevant information along the railway within the authority and give the safety level. This information is shared between the monitoring subcenters, and the early warning information sent by the monitoring center is transmitted to the mobile vehicle convergent nodes along the line through the upper layer information transmission platform of the wireless sensor network.

To meet the requirements of scalability and real-time and easy management of wireless sensor networks, a certain number of convergence nodes are deployed along the railway line in equal parts according to certain rules; these convergence nodes form the upper information transmission platform of the railway monitoring wireless sensor network, which is a chain network topology structure. The nodes within the cluster transmit the information to the ground aggregation nodes by multihop and then forward it to the train computers and monitoring centers through the upper layer information transmission platform. From the geometry, the ribbon area coverage problem is much like the circle coverage problem. The wireless sensor nodes on the long ribbon area use a circular coverage model to achieve coverage of the long ribbon area by some evenly spaced strings of nodes. The maximum area of the rectangle that can be covered by a string of nodes is related to the distance of the string nodes, and the width of the rectangular area that can be covered becomes smaller if the node distance increases; however, the number of nodes in the area decreases with constant band length. If the node distance decreases, then the width of the rectangular area that can be covered increases, and the number of nodes needed increases with constant band length. If an appropriate value of neighboring node distances is chosen, an optimal match can be obtained between the width of the rectangle covered by the nodes and the number of nodes, thus ensuring full coverage of the band area using a smaller number of nodes.

In wireless sensor networks, wireless sensor nodes not only perform data acquisition but also use wireless communication to transmit the collected data to the data user side in a multihop manner. The communication range of a node is directly related to the transmitting power of the node. The greater the communication range of the node, the greater the transmit power, and the node is prone to failure, which affects the life cycle of the network. Communication coverage is the area covered by the sensor communication capability; two adjacent or nonadjacent wireless sensor nodes needing to achieve information exchange must meet the connectivity coverage; by the previous analysis of the vehicle and ground, two types of convergence nodes can be seen; it has an important position in the network, through the convergence nodes constituting the upper information

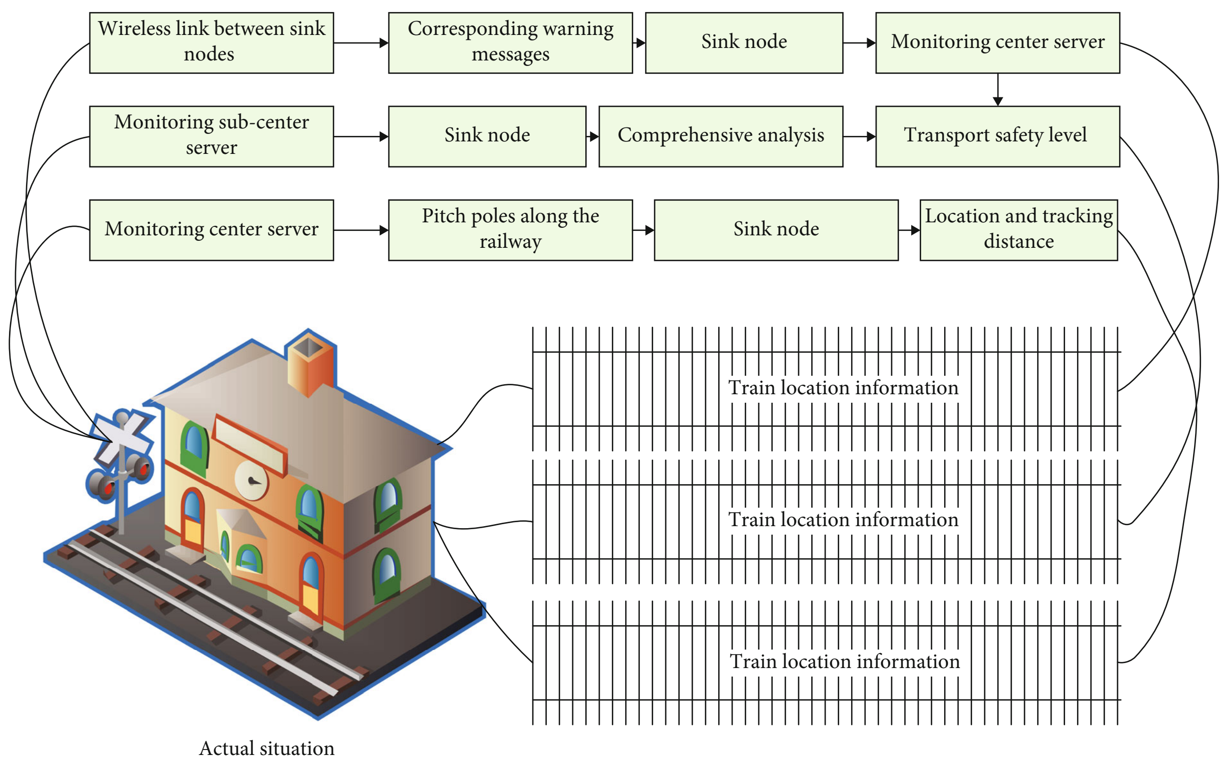

Figure 1: Schematic of the transmission platform of the wireless sensor network for railway monitoring.

transmission platform which can effectively reduce the number of information forwarding and transmission delay. It is clear from the analysis of the aggregation node that it has an important position in the network. The vehicle-mounted convergent node receives the information issued by the monitoring subcenter and the information sent by the ground convergent node through the upper-level information transmission platform. The nodes are designed with processors that have a large amount of memory, strong processing power, and high-performance wireless RF chips and are designed with a dual-processor system to enhance the reliability of the nodes in the transmission platform of the wireless sensor network for railway monitoring [18]. When one of the processors fails, for example, when the core processor ARM9 in the convergence node fails, the CC2431 on-chip system chip can still transmit monitoring information and train positioning information. Its communication range can be enhanced by adding RF amplification circuits when necessary; the power supply consists of a battery and an energy harvesting unit, as shown in Figure 2.

A sensing node is usually a miniature embedded system with relatively weak data processing, data storage, and wireless communication capabilities due to its limited energy. The sensing node usually only exchanges data with neighboring nodes within its communication range, and each sensing node combines the dual functions of a terminal and a router of a traditional network node. The aggregation node is relatively strong in data processing, data storage, and wireless communication and is a bridge between the wireless sensor network and the remote monitoring end, which issues monitoring tasks to the wireless sensor network and sends the collected monitoring information to the remote monitoring end. The aggregation node can be an enhanced sensing node with an uninterrupted power supply and sufficient storage resources and logical computing capability, or it can be a special gateway device without sensing function but only with wireless interface function.

3.2. Rail Transport In-Transit Health Condition Monitoring Analysis. A high-speed train operating environment monitoring wireless sensor network is a large heterogeneous wireless sensor network covering the whole road; the network cannot exist independently of the Internet; this paper introduces the idea of service-oriented architecture into the wireless sensor network and proposes a general architecture across the railway computer network domain and the wireless sensor network domain. The architecture spans the railway computer network and wireless sensor network with service as the mainline [19]. Communication coverage is the area covered by the sensor's communication capabilities. If two adjacent or nonadjacent wireless sensor nodes need to exchange information, they must meet the connectivity coverage. The previous analysis of the vehicle-mounted and ground-based convergence nodes affects the life cycle of the network. The sensing nodes within the wireless sensor network, as the original provider of services, register the services they provide to the aggregation nodes, and the aggregation nodes process the services provided by the sensing nodes within their jurisdiction and then provide them in the form of services to the service platform of the road bureau center and then provide them to the systems, which is the key idea of the overall network architecture design,

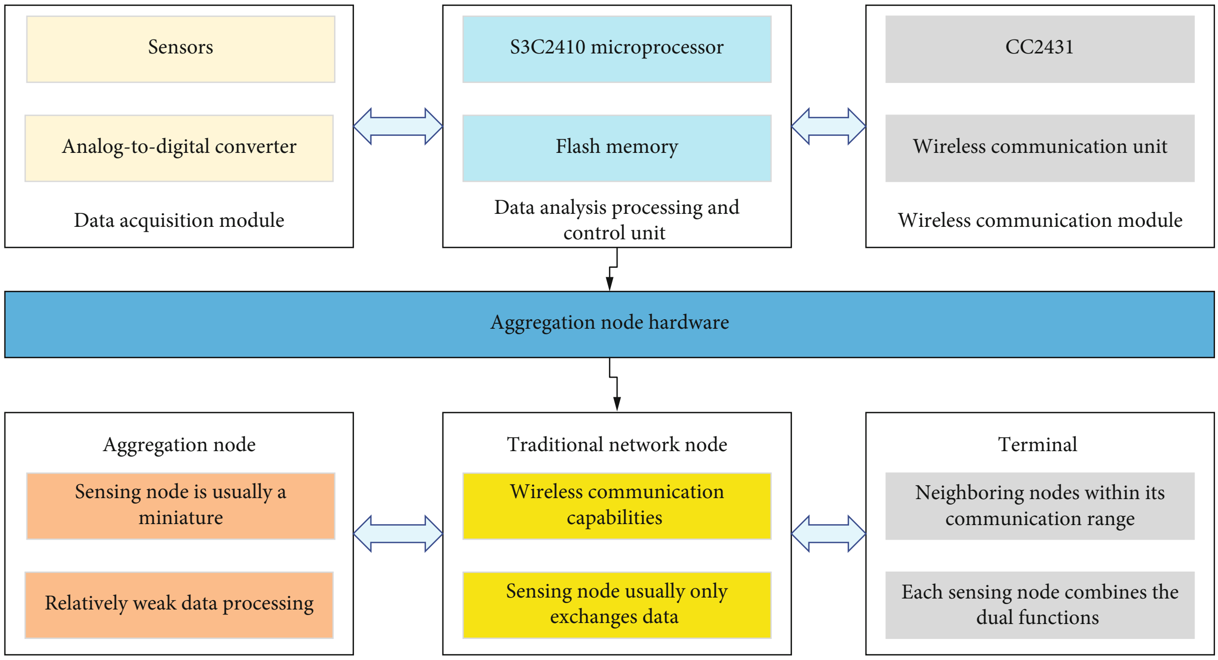

Figure 2: Aggregation node hardware.

with the bearer network as the boundary of the entire network divided into the railway computer network domain and the sensor network domain:

$$E_{\mathrm{Tx}} = \begin{cases} k \times E_{\mathrm{elec}} - k \times \xi_{fs} \times d^2, & d \geq d_0, \\ k \times E_{\mathrm{elec}} + k \times \xi_{fs} \times d^2, & d < d_0, \end{cases} \tag{1}$$

$$E_{\mathrm{Rx}} = k - E_{\mathrm{elec}}. \tag{2}$$

A local network is a local wireless sensor network built for a certain monitoring object forming the lowest layer of a terrestrial wireless sensor network, which is responsible for collecting the basic monitoring information. The network topology inside the local wireless sensor network is determined by the characteristics of the monitoring object. The corresponding local network topology is designed according to the needs of the monitoring object, which can be a flat network result, a hierarchical network structure, or a hybrid network structure. Nodes within each type of local wireless sensor network can communicate with each other, while nodes located in different local wireless sensor networks cannot communicate directly:

$$E_{\mathrm{total}} = \sum_{i=1}^{k} \left(E^i_{\mathrm{CH}} - \sum_{i=1}^{n} E^i_{\mathrm{CH+Non}} \right), \tag{3}$$

$$E^i_{\mathrm{CH}} = E^i_{\mathrm{CH\text{-}Rx}} - E^i_{\mathrm{CH+Dx}} - E^i_{\mathrm{CH\text{-}Sx}}. \tag{4}$$

The backbone network is a linear network consisting of fully functional sensing nodes of the local wireless sensor network, individual sensing nodes, relay nodes joined between sensing nodes, and aggregation nodes in the server room. The backbone network is responsible for transmitting the information collected by the local wireless sensor network to the convergence nodes. The design of the backbone network can unify the monitoring equipment of all the professions involved along the railway line for unified management and unified transmission of information, avoiding each profession to work separately and duplicate investment, and avoiding the problem of mutual seizure and mutual interference of wireless channels. The backbone network is a typical linear wireless sensor network. The architecture takes the service as the main line and crosses the railway computer network and wireless sensor network. As the original service provider, the perception node in the wireless sensor network registers the service it provides to the sink node. And the deployment location of each local wireless sensor network is determined by the inherent characteristics of the monitoring object, so how to reasonably deploy relay nodes among the fully functional sensing nodes (or sensing nodes) to enable the backbone network to have higher network efficiency, longer life cycle, and higher robustness becomes the key problem of this paper's research, as shown in Table 1.

The analysis of the parameters in Table 1 and the research described above show that the communication transmission needs to be compared in many aspects and based on the environmental problems faced by the railway freight trains in the actual driving process such as no power supply device and no additional power input that requires low power consumption of the equipment; the train driving process instability factors lead to signal susceptibility to interference, and the number of nodes with the carriage needs to be above 2 digits, etc. EnOcean technology will be widely used in various industries in the future, but at this stage, it is too costly and cumbersome to maintain, so it is

Table 1: Technical parameters of short-range wireless transmission communication.

Name	EnOcean	Zigbee	Z-Wave	Bluetooth	WiFi
Working frequency (Hz)	38	34	48	90	35
Wireless standard	136	83	92	104	148
Power requirement	149	88	50	20	162
Maintenance time	104	158	82	57	181
Maximum transmission rate	82	163	88	140	73
Interference effect	99	104	49	67	84

not suitable for freight railways [20]. WiFi has the advantages of fast transmission rate and low cost, but due to more uncertainties in railway freight, the WiFi transmission signal is more unstable, and its power consumption is too large, also not suitable for the transmission of the goods-based railway freight system. Zigbee technology has low power consumption, relatively long transmission distance, easy to self-organizing network, network node capacity, and better security features that can be used. Through the above wireless communication transmission technology for comprehensive comparison, and combined with the technical characteristics of the railway wagon and transport environment involved in this paper, Zigbee technology will be selected as the wireless transmission scheme between freight trains, as shown in Figure 3.

The request indicates that a service primitive action is passed from the N-layer entity to the $N-1$ layer to initiate the service primitive action. Acknowledgment indicates that the $N-1$ layer protocol entity responds to the previous request action of the N-layer protocol entity, indication primitive indicates that the $N-1$ layer protocol entity sends a notification to the N-layer entity that a new action has arrived, and response primitive indicates that the N-layer protocol entity responds to the indication sent by the $N-1$ layer protocol entity. The request and response actions are implemented by calling the function mapped by the corresponding entity when interacting messages between the corresponding protocol entities. In the process of train position update, a positioning device with higher positioning accuracy is selected as the reference system, and then, the positioning performance is evaluated and verified. Acknowledgment and indication actions are implemented through message mechanisms or callback functions when interacting messages between corresponding protocol entities. The monitoring data from the site and the train location information are analyzed and processed to provide information on the safety assessment of the area along the railway line and the tracking interval of the train. In this way, the monitoring center or the operating train achieves macroscopic proficiency in the status along the railway line, including the front and rear positions of trains and information on the monitoring area along the railway line. The assessment information is transmitted to the train control center to provide the basis for traffic scheduling and speed restrictions, stops, etc. The operation department sends the determined plan to the onboard convergence node through the monitoring subcenter and wireless sensor network transmission platform layer, which serves to prevent train accidents; at the same time, the plan is notified to the relevant railway departments. The lifting of control measures is also promptly notified to train drivers and relevant departments along the line through the information distribution system:

$$R_P(d) = R_P(d_0)^2 \left(\frac{d_0}{d}\right), \tag{5}$$

$$P_L = \text{long} \ln \frac{P_r^2}{R_P}. \tag{6}$$

In the clustered communication routing protocol, the energy consumption of cluster head nodes is much larger than that of noncluster head nodes; therefore, the cluster head is reselected before the start of each round of communication, to effectively ensure the balance of energy consumption among sensor nodes and avoid the failure of cluster head nodes due to excessive energy consumption. In the process of cluster head selection and rotation probability modeling, this paper integrates the node cluster head candidate probability, node residual energy rate and cluster head predicted energy consumption rate, etc., and the cluster head selection based on the integrated probability model can effectively reduce the probability of undercapable nodes selected as cluster heads [21]. After multiple rounds of communication, the residual energy of each sensor node within the subnet will be different from each other because the energy consumption of cluster head nodes and noncluster head nodes is different. The number of nodes and the amount of data transmitted within each cluster varies, and the distance from each cluster head to the aggregation node varies, resulting in uneven energy consumption among the cluster head nodes. The difference in the distance from each noncluster head node to the cluster head and the amount of data transmitted leads to uneven energy consumption among the noncluster head nodes. In the cluster head selection and rotation process, the node with more residual energy has a higher probability of being selected as the cluster head, as shown in Figure 4.

Through these steps, the onboard computer can calculate its position. Then, the onboard convergence node sends its position information to the upper layer information transmission platform of the wireless sensor network through wireless communication technology. In this way, the onboard convergence node can receive the location information of other trains nearby through the neighboring

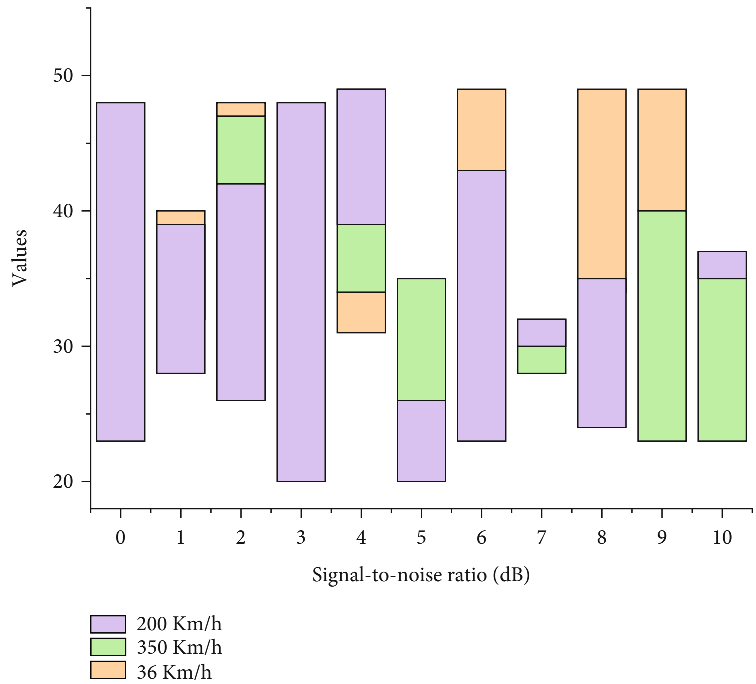

Figure 3: BER at different operating speeds.

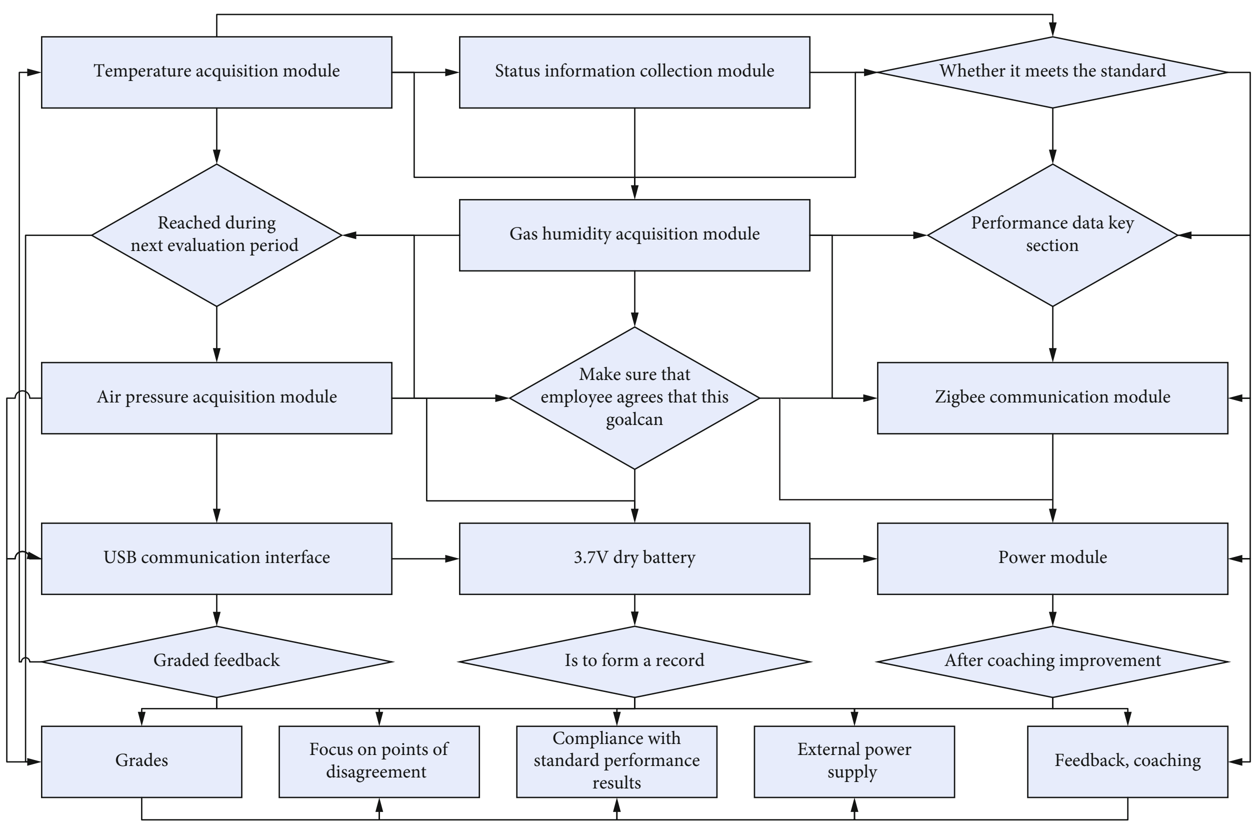

Figure 4: Design scheme of state information simulation detection unit.

ground convergence nodes. The onboard convergence node inputs the received train location information into the onboard safety computer, and after the computer information is parsed, the absolute physical coordinates of the train are matched with the latitude and longitude coordinates of the railway GIS electronic map. The computer converts the train's position coordinates into screen coordinates after doing Gaussian projection conversion. The onboard

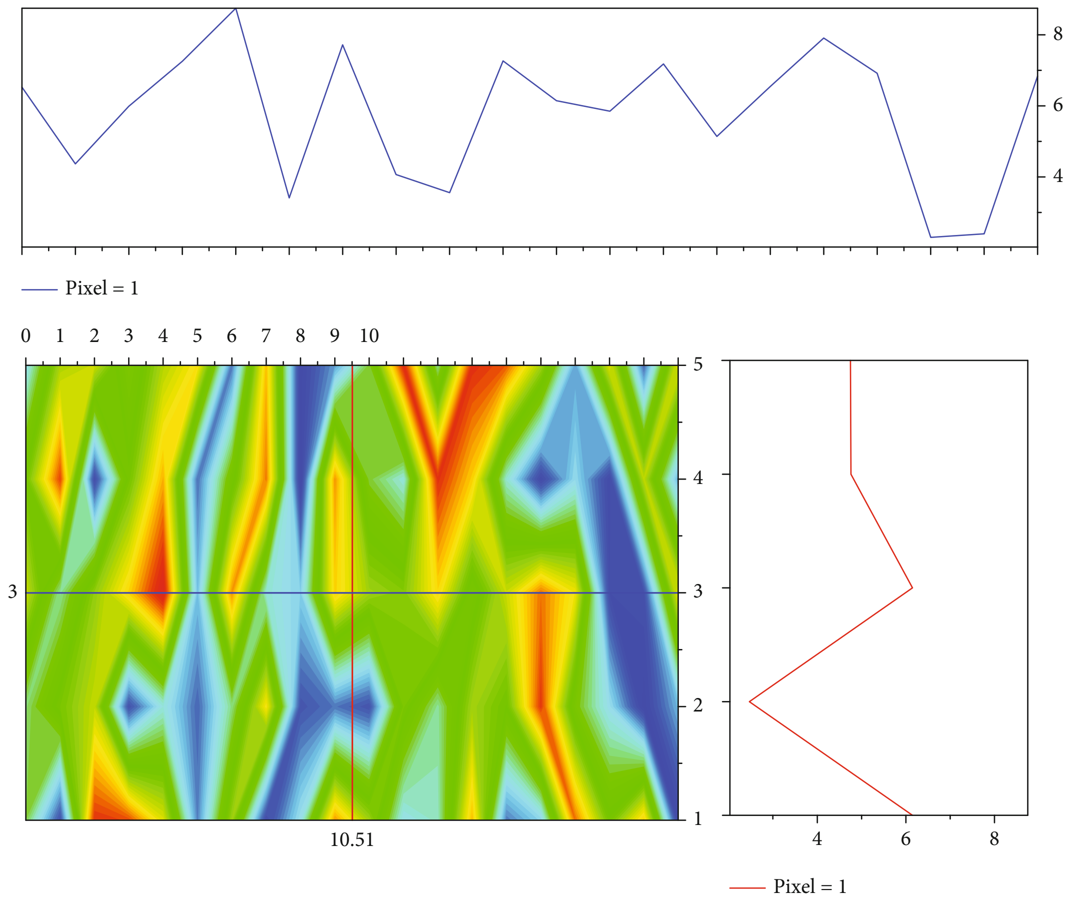

Figure 5: Plot of packet count versus priority.

computer converts the plane coordinates to pixel point coordinates according to the map scale. The position information of the front and rear trains and this train is displayed in real time on the electronic map of the onboard computer. The onboard computer calculates the spacing of the tracking train by integrating the line parameters and displays it on the screen. If the distance between the front and rear trains is less than the train braking distance or if a dangerous situation occurs, an alarm message can be sent in real time on the monitoring center and the onboard computer. The driver will be reminded to slow down the train by regular braking or emergency braking, thus effectively preventing accidents from happening.

4. Analysis of Results

4.1. Passive Wireless Sensor Network Detection Network Performance. The data from different sensors are first preprocessed, i.e., patio-temporal synchronization, and fault detection isolation, and then, data fusion is performed on the preprocessed data. Preprocessing and data fusion together are called data processing. During the train position update process, a positioning device with high positioning accuracy is selected as a reference system, which in turn is used for performance evaluation and verification of positioning. The combined positioning system provides positioning information for high-speed trains but is not the only positioning system. When the distance is greater than 72 meters, since the energy consumption of data processing is less than the energy consumption of data transmission, the life cycle of the subnet system based on the CR algorithm is longer. The combined positioning system can be applied to high-speed train positioning only after it has high accuracy, safety, and reliability. When the onboard aggregation node does not receive the position information from the wireless sensor node, the odometer is used for train localization. The odometer positioning error is corrected after positioning by the wireless sensor beacon node. The positioning accuracy based on the combination of wireless sensor node and odometer positioning depends mainly on the spacing of the wireless sensor beacon nodes and the success rate of the mobile convergence node in collecting coordinate information, as shown in Figure 5.

In actual transmission, after forming a good network and route establishment successfully, set the router and terminal node to collect data every 15 s and send the information to the coordinator that is the main control unit. Due to the specificity of the transmission situation of railway wagons, the nodes of the wagons far from the head need to transmit the status information to the coordinator in multiple hops, according to the design of the above routing algorithm; in the case of direct transmission, the routing nodes directly

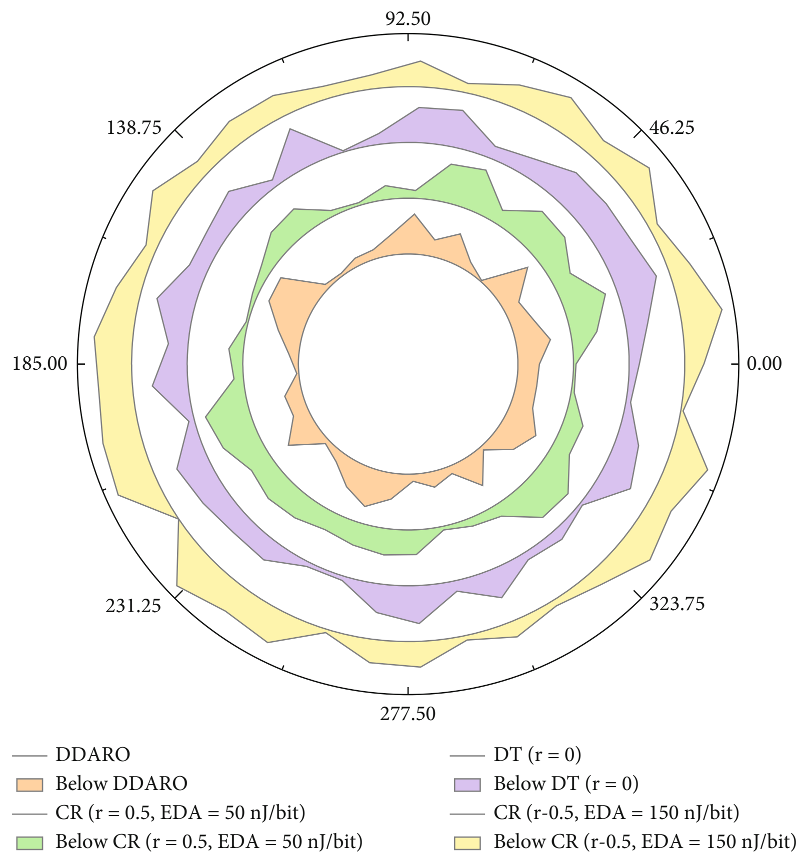

Figure 6: Relationship between subnet life cycle and change in distance from subnet to aggregation node.

transmit the information to the coordinator, if not directly, according to the routing search table, select the loss of routing overhead comparison to select the reverse routing node with the lowest overhead, generally the adjacent node perform the transmission. The status information parameters of axle temperature, relative temperature, and humidity of gas in the compartment and brake gas pressure detected by each compartment detection unit encapsulated and transmitted to the coordinator through routing, as the nodes use the same channel and there is a CSMA/CA mechanism in Zigbee technology, i.e., to prevent conflicts when sending data, the nodes listen to the channel first when sending data. When the channel is idle the data is sent directly and when the channel is busy, the detection unit is set to wait after a delay and reconfirm the channel condition until the data transmission is completed. If the multihop transmission is required, the data information is sent to the upper node and then the same operation is performed until the data is sent to the coordinator. At the end of transmission, to prevent data problems or transmission failure, a tail check is set and if the check is wrong, the data is discarded and waited for resending. The total number of packets transmitted during the entire lifetime of the network is divided by the number of nodes in each column called node utilization. Solving for this gives the relationship between node utilization and the number of nodes in each column if there are five columns of relay nodes in the network. As the number of nodes in each column increases, the utilization of nodes becomes less and less.

Table 2: Node communication test results.

Test environment	Communication distance (m)	Packet loss rate (%)
Indoor	142	42
Indoor	39	20
Outdoor	161	29
Outdoor	95	46
Outdoor	87	47
Indoor	105	40

When the distance from cluster head nodes to aggregation nodes is too large, data fusion is needed before data transmission to reduce the energy consumption of data transmission. Different cluster head nodes have different distances to the convergence nodes, so it is necessary to use different fusion rates for data fusion at different cluster head nodes and to optimize the multihop communication links to balance the energy consumption of each cluster head node, thus extending the life cycle of the subnet system, as shown in Figure 6.

From Figure 6, the communication energy consumption of each cluster head node increases greatly as the distance from the subnetwork to the aggregation node increases, thus shortening the life cycle of the system. In this paper, the maximum data fusion rate is set to 0.5 during simulation and validation, so the lifecycle of the fusion algorithm

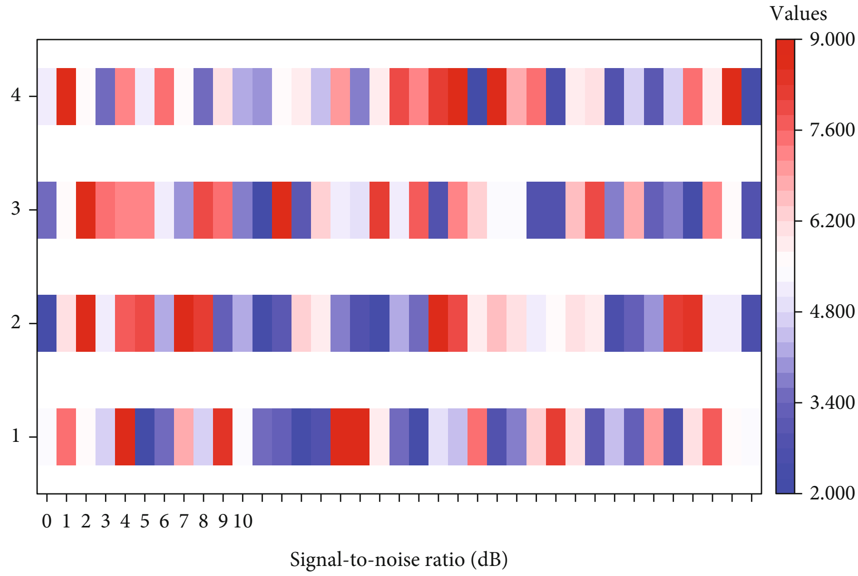

Figure 7: PDF values of the phase during the motion period.

proposed in this paper is close to that of the DR-based algorithm when the distance between nodes is increasing (both data fusion energy consumption rates are 50 nJ/bit). When the distance is less than 72 m, the DT-based algorithm has a longer life cycle than the CR-based algorithm with a data fusion energy consumption rate of 50 nJ/bit, while when the distance is greater than 72 m, the CR-based algorithm has a longer life cycle for the subnetwork system because the energy consumption for data processing is less than that for data transmission. The data fusion energy consumption of the cluster head nodes within the subnet is determined by the amount of data processing, the data fusion rate, and the data fusion energy consumption rate together, while the energy consumption rate of data processing is positively related to the fusion rate. Therefore, it is necessary to adjust the data fusion rate adaptively to reduce the total cluster head energy consumption according to the changes in the communication load and communication distance of the cluster head nodes and the changes in the data fusion energy consumption rate and to balance the energy consumption among the cluster heads utilizing multihop optimization, which in turn improves the lifecycle of the subnet system.

4.2. Results of In-Transit Health Status Monitoring of Rail Transport. In the MAC payload, to see the data sent for the address to the address of the coordinator, the section only intercepted a transmission of a small section for demonstration, in the actual test, in the case of setting the transmit state unchanged for a long-time packet capture test, according to the number of packets shown with the time to calculate its system packet loss rate less than 1%. Then follow the same process to lengthen the communication distance and change the test environment, after several test-specific parameters as shown in Table 2.

It can be compared and analyzed that in the case of increasing communication distance, the communication effect then becomes worse, and its transmission effect is better indoor. Considering the actual railway wagon, affected by speed and environmental factors, its actual sensitivity and packet loss rate will change accordingly, but in the case of adjacent carriages or separated by a short distance, wireless network transmission has a better transmission. This part uses the router node to connect the temperature sensor, pressure sensor, and temperature and humidity sensor to simulate the status information detection of a single carriage, and transmits to the coordinator node through the Zigbee wireless network, and then relies on the GPRS communication module to send the information to the ground monitoring center, to set up a simple and convenient simulated railway wagon monitoring system to simulate the normal work of the system and ensure that all functions can be achieved. Due to the constraints of laboratory conditions and working time, the test is conducted by simulating measurements instead of actual detection of wagon status information. Only one routing node is used for information collection in this test, and the rest of the nodes are in the group network state. When the system is simulated and tested, if each state parameter can be detected without operational errors, it proves that the design function can be implemented and tested without errors. For the axis temperature detection test, due to the relatively harsh environmental conditions of the axle temperature, it is not easy to achieve; this time, only a temperature sensor detects the ambient temperature around to simulate the detection of axle temperature information, and the test of the temperature sensor can detect the temperature normally; if the temperature sensor can accurately detect the ambient temperature, it represents the design of the truck axle temperature detection function to achieve and test success, as shown in Figure 7.

The KL discrete values quantify the similarity of the phase trend within two continuous windows, and we divide the phase flow into periods of motion as well as periods of rest as defined above. During the stationary period, the phase values will show fluctuations in the range of stable horizontal values. Therefore, if both consecutive windows are in the stationary period, their KL dispersion values will be small. Conversely, if at least one window is in a period of motion, the PDFs of these two windows should be significantly different and their KL dispersion values are large. Using this property, we determine whether the current window is in a stationary period by checking the KL dispersion value, and after finding all the stationary period windows, the remaining ones are in the motion period. There are four labeled items in the scene, and the volunteer picks up the items labeled 1 and 2 in turn, and the item picked up first, on the time axis, is the first to fluctuate and then shows the same trend of fluctuation, while the remaining two labels have a clear dissimilarity in fluctuation. Therefore, in this section, we first introduce a method to measure the similarity between two data series.

5. Conclusion

Based on the actual situation of high-speed train operation environment monitoring, this paper fully investigates and analyzes the current situation and business requirements of existing high-speed train operation environment monitoring and brings into play the advantages of wireless sensor networks, proposing a new idea of applying wireless sensor network technology to the field of high-speed train operation environment monitoring. And through the Zigbee wireless network, it transmits to the coordinator node and then relies on the GPRS communication module to send the information to the ground monitoring center, thus forming a simple and convenient simulated railway freight car monitoring system to simulate the normal operation of the system to ensure that various functions can be achieved. The topology of the ground-based wireless sensor network is designed; the node deployment strategy and routing protocol of the linear wireless sensor network are studied; the vehicle-ground communication performance of various wireless communication technologies is tested in a real high-speed railway environment, and a transmission scheme of the vehicle-ground wireless sensor network based on relay transmission is designed and verified in the field test. The natural disaster and foreign object intrusion monitoring system was designed. Because of the large variety of wireless communication technologies, most of them have no practical applications or test cases in high-speed train operation scenarios. In this paper, a "point-to-point" transmission scheme is designed to test the vehicle-to-ground communication performance of various wireless communication technologies in a real high-speed train operation environment and to determine the most suitable wireless sensor network communication technology for high-speed train movement scenarios. In this paper, we design a vehicle-to-ground wireless sensor network transmission scheme based on relay transmission and optimize the communication module program to improve the vehicle-to-ground communication performance of the communication module. Experimental verification in indoor, outdoor, and real train high-speed operation scenarios shows that the scheme has strong scalability and transmission stability and can significantly improve the data transmission volume of the vehicle-ground wireless sensor network. The problem of low communication reliability and a small amount of data transmission is effectively solved by the "point-to-point" transmission method, which only has one communication opportunity when the train passes the ground communication node rapidly.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] W. Loga-Księska, J. Sordyl, and A. Ryguła, "Long-term urban traffic monitoring based on wireless multi-sensor network," *Open Engineering*, vol. 10, no. 1, pp. 197–208, 2020.

[2] J. V. Anand, "Automatic traffic control technologies for remote monitoring of unmanned railway gates," *Journal of Electronics*, vol. 2, no. 1, pp. 30–37, 2020.

[3] P. Li, Z. Long, and Z. Yang, "RF energy harvesting for batteryless and maintenance-free condition monitoring of railway tracks," *IEEE Internet of Things Journal*, vol. 8, no. 5, pp. 3512–3523, 2021.

[4] H. Mohapatra, S. Rath, and S. Panda, "Handling of man-in-the-middle attack in wsn through intrusion detection system," *International Journal*, vol. 8, no. 5, pp. 1503–1510, 2020.

[5] N. Bosso, M. Magelli, and N. Zampieri, "Application of low-power energy harvesting solutions in the railway field: a review," *Vehicle System Dynamics*, vol. 59, no. 6, pp. 841–871, 2021.

[6] S. Dey, R. Bhattacharyya, S. E. Sarma, and N. C. Karmakar, "A novel "smart skin" sensor for chipless RFID-based structural health monitoring applications," *IEEE Internet of Things Journal*, vol. 8, no. 5, pp. 3955–3971, 2021.

[7] S. Godala and R. P. V. Vaddella, "A study on intrusion detection system in wireless sensor networks," *International Journal of Communication Networks and Information Security*, vol. 12, no. 1, pp. 127–141, 2020.

[8] G. D. OMahony, J. T. Curran, P. J. Harris, and C. C. Murphy, "Interference and intrusion in wireless sensor networks," *IEEE Aerospace and Electronic Systems Magazine*, vol. 35, no. 2, pp. 4–16, 2020.

[9] Z. Pu, M. Zhu, W. Li, Z. Cui, X. Guo, and Y. Wang, "Monitoring public transit ridership flow by passively sensing Wi-Fi and Bluetooth mobile devices," *IEEE Internet of Things Journal*, vol. 8, no. 1, pp. 474–486, 2021.

[10] F. Afroz and R. Braun, "Energy-efficient MAC protocols for wireless sensor networks: a survey," *International Journal of Sensor Networks*, vol. 32, no. 3, pp. 150–173, 2020.

[11] S. Mustapha, Y. Lu, C. T. Ng, and P. Malinowski, "Sensor networks for structures health monitoring: placement,

implementations, and challenges—a review," *Vibration*, vol. 4, no. 3, pp. 551–584, 2021.

[12] L. Costanzo, T. Lin, W. Lin, A. L. Schiavo, M. Vitelli, and L. Zuo, "Power electronic interface with an adaptive MPPT technique for train suspension energy harvesters," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 9, pp. 8219–8230, 2020.

[13] S. Ryu, B. B. Park, and S. el-Tawab, "WiFi sensing system for monitoring public transportation ridership: a case study," *KSCE Journal of Civil Engineering*, vol. 24, no. 10, pp. 3092–3104, 2020.

[14] T. Korbiel, R. Rumin, J. Blaut, S. Czerwiński, and J. Kania, "Analysis of the vibration measurement and reduction possibilities in linear infrastructure for vacuum rail technology," *New Trends in Production Engineering*, vol. 3, no. 1, pp. 450–461, 2020.

[15] R. Vikram, D. Sinha, D. de, and A. K. Das, "PAFF: predictive analytics on forest fire using compressed sensing based localized ad hoc wireless sensor networks," *Journal of Ambient Intelligence and Humanized Computing*, vol. 12, no. 2, pp. 1647–1665, 2021.

[16] J. Hu, J. Fang, and Y. Du, "Data acquisition and transmission scheme for large projects based on LoRa internet of things using improved linear integer programming model," *International Journal of Wireless Information Networks*, vol. 27, no. 2, pp. 215–225, 2020.

[17] M. Yin, K. Li, and X. Cheng, "A review on artificial intelligence in high-speed rail," *Transportation Safety and Environment*, vol. 2, no. 4, pp. 247–259, 2020.

[18] Ş. Fatih İzzet, A. Gökhan Nurettin, S. Panić, Č. Stefanović, M. Yağanoğlu, and B. Prilinčević, "Covid-19 risk assessment in public transport using ambient sensor data and wireless communications," *Bulletin of Natural Sciences Research*, vol. 10, no. 2, pp. 43–50, 2020.

[19] C. Tarawneh, J. Montalvo, and B. Wilson, "Defect detection in freight railcar tapered-roller bearings using vibration techniques," *Railway Engineering Science*, vol. 29, no. 1, pp. 42–58, 2021.

[20] H. Dong, F. Chen, Z. Wang, L. Jia, Y. Qin, and J. Man, "An adaptive multisensor fault diagnosis method for high-speed train traction converters," *IEEE Transactions on Power Electronics*, vol. 36, no. 6, pp. 6288–6302, 2020.

[21] Y. Jin, K. S. Kwak, and S. J. Yoo, "A novel energy supply strategy for stable sensor data delivery in wireless sensor networks," *IEEE Systems Journal*, vol. 14, no. 3, pp. 3418–3429, 2020.