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Research Article

Wireless Sensor Networks of Infrastructure Health Monitoring for High-Speed Railway

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High-speed railways (HSRs) have been widely deployed all over the world in recent years and China has entered an era with both high investments and rapid expansion of HSR transport infrastructure. One of the most challenging issues is how to keep the security and safety of millions of HSR infrastructures. Meanwhile, the emerging sensing and wireless sensor network (WSN) technologies for infrastructure health monitoring (IHM) are being substituted for traditional tethered monitoring systems. This paper presents a two-layer architecture of WSN which will be appropriate for infrastructure health monitoring of HSR. The upper layer is named as tree access network and the lower layer is called star detection network. By adapting to the special characteristics of IHM network, we design a short network address and an optimized communication frame structure, which can satisfy the actual requirements and special characteristics of the IHM network. In order to implement a better transmission performance, we propose a novel transmission power based method which adopts the knowledge update mechanism to detect the optimization result. In the end, the details of address assignment and network construction are discussed, and the effectiveness of the proposed method is validated by a practical instance.

1. Introduction

High-speed railways (HSRs) have been widely deployed all over the world in recent years. High-speed trains with an operation speed of more than 300 km/h have been rapidly deployed all over the world. Particularly, bullet trains and high-speed trains have been widely used in China [1]. China has entered an era with high investments and rapid expansion of HSR transport infrastructure. In 2004, the State Council approved Medium and Long-Term Railway Network Plan 2005–2020 and adjusted it in 2008. According to the plan, the government will build a network of HSRs with four east-west lines and four north-south lines, which is also named as "four vertical and four horizontal corridors" [2]. By the end of 2014, there are more than 112 000 km of railway lines (including 16 000 km of HSR lines) in service and almost one thousand trains are running at a speed of 250 km/h or higher every day. As is shown in [3], Figure 1 gives the plan of China HSR program in 2020. With the quick development of HSR system, the security and safety of those huge systems will be the biggest concern for passengers. HSR infrastructure is an important part of HSR system, and how to keep the security and safety of HSR infrastructure is a crucial topic to deal with. Structural monitoring systems are widely used to monitor the behavior of structures during forced vibration testing or natural excitation. In recent years, there has been an increasing interest in the application of emerging sensing technologies for infrastructure health monitoring. Meanwhile, wireless sensors and sensor networks have begun to be considered as substitutes of traditional tethered monitoring systems in structural engineering and critical infrastructure surveillance fields [4]. As Flammini et al. [4] and Hadim and Mohamed [5] presented that different middleware platforms have been proposed for WSNs, such as software and tools, which provide an abstract of the system, therefore, the application programmer only needs to focus on the application logic

Figure 1: Plan of China HSR program in 2020.

without having to deal with lower level implementation details.

For the application studies of railway monitoring in HSR, Flammini et al. [4] presented a proposal of an early warning system based on WSN for railway infrastructure monitoring. The goal is to hedge detection capabilities in a complete framework for structural failures as well as security threats, including both natural hazards and intentional attacks. Lynch and Loh [6] explored the historical development of wireless sensors and sensor networks intended for health monitoring. A significant advantage of wireless sensor networks over traditional cable-based monitoring systems is the collocation of computational power with the sensing transducer. In essence, this feature transforms the wireless monitoring system into a genuine health monitoring system where damage detection is fully automated. Márquez et al. [7] pointed that increasing traffic and shortened maintenance windows require better approaches to turnout maintenance. They undertook the development of algorithms to detect gradual failure in railway turnout which should allow a move to a remote condition monitoring approach to the management of switch and crossing maintenance. The European Commission has estimated that by 2020 passenger traffic will double and freight traffic will triple compared with current volumes [8]. Márquez et al. [8] studied the life cycle costs for railway condition monitoring and the objective of their paper was to illustrate how the cost benefit of remote condition monitoring can be evaluated. In 2007, Márquez and Schmid [9] studied the application of remote condition monitoring to point mechanisms and their operation and identified algorithms which can be used to identify incipient failures. They proposed a Kalman filter for the linear discrete data filtering problem encountered when using current sensor data in a point condition monitoring system. Clark et al.

[10] discussed the various applications of ground penetrating radar and infrared thermography on the UK infrastructure, with concentration on the high-speed applications of these noninvasive techniques. Besides, other issues of HSR are also being paid close attention [2, 3, 11–14]. Monzón et al. [11] focused on efficiency and spatial equity impacts of high-speed rail extensions in urban areas, and they described an assessment methodology for HSR projects which follows this twofold approach. Efficiency impacts were assessed in terms of the improvements in accessibility resulting from the HSR project, with a focus on major urban areas; and spatial equity implications were derived from changes in the distribution of accessibility values among these urban agglomerations. Mu et al. [3] applied the theory on public values and the way various values were traded off against each other to the case of high-speed rail development in China. They developed a public value tradeoff matrix enabling us to identify and measure the various public values at play and to establish what changes took place in the prioritization of various public values over time. He et al. [2] investigated high-speed railway related public views, risk perceptions, and trust of Chinese residents living along the Beijing-Shanghai high-speed railway. Their results showed high public acceptance in high-speed railway, due to perceived low environmental and social risk and high economic and social benefits.

From the studies of WSN, it is found that WSN has a series of advantages in terms of wireless communication, self-organizing, low cost, and low power, which will be suitable for implementing infrastructure health monitoring for HSR. Many literatures focus their study on topology control [15–22] and routing protocols [20, 23–29]. Chiwewe and Hancke [15] presented a new distributed topology control technique that enhances energy efficiency and reduces radio interference in wireless sensor networks. Topology control plays an important role in the design of wireless ad hoc and sensor networks; it is capable of constructing networks that have desirable characteristics such as sparser connectivity, lower transmission power, and a smaller node degree [15]. Liu et al. [16] proposed a novel probabilistic network model to implement topology control of WSN. Their experimental results showed that the network energy efficiency can be improved by up to 250% and the average node degree was reduced by 50%. Li et al. [17] conducted a comprehensive survey on topology control issues in WSNs and provided a taxonomy for the topology control techniques under this frame and reviewed existing works. Besides, they emphasized the basic principles of topology control to understand the state of the art, while exploring future research directions in the new open areas and proposing a series of design guidelines under this topic. Three different mathematical models whose solutions prescribe cluster head and sink locations and data routing from sensors to sinks in a period of a deployment cycle were developed by Üster and Lin [20]. They developed a heuristic solution algorithm which provided very small optimality gaps for the models and presented extensive numerical test results and analysis of the models and the solution approach. Vecchio and López-Valcarce [22] presented techniques to improve convergence speed of distributed average consensus algorithms in wireless sensor networks by means of topology design. Their methods effectively improved convergence speed for average consensus algorithms, with reduced energy consumption as an important side benefit. Al-Karaki and Kamal [25] studied the design tradeoffs between energy and communication overhead savings in every routing paradigm and also highlighted the advantages and performance issues of each routing technique. Zhang et al. [28] proposed an energy-balanced routing method based on forward-aware factor. What is more, some researchers have paid their attention to field applications [30–32], communication security [33], or energy conservation [34]. All of those achievements provide a good foundation to implement infrastructure health monitoring for HSR by taking advantage of WSNs.

Based on the problem considered in our paper, the goal of this research is (1) to find out a suitable architecture of WSN which can satisfy infrastructure health monitoring of HSR, (2) to identify a suitable kind of network address and communication frame for implementing efficient communication in the considered network in this paper, and (3) to obtain the optimal topology structure for the considered network which can reduce the communication jamming, extend the network lifetime, and improve the communication efficiency with the constraint of transmission power.

2. Architecture of IHM-WSNs for HSR

In order to transmit the real-time data of IHM network of HSR to data center (DC), the WSNs should be deployed in different detection areas via detection nodes and transmission points, such as end detectors (EDs), repeat points (RPs), and access points (APs). EDs are usually powered by storage batteries, and RPs and APs can be powered by storage batteries, solar batteries, or wired electric cables. The architecture of IHM-WSNs can be shown in Figure 2. The IHM-WSNs consist of several WSNs which are in charge of the health monitoring in different detection areas. Each WSN is in charge of a detection area around 500–1000 meters along railways. And each detection area is covered by a variety of sensors; some common types of sensors used in IHM-WSNs are shown in Table 1. Those sensors can detect a variety of state data required by health monitoring.

As is shown in Figure 2, an IHM-WSN contains two communication layers. The upper layer is a tree subnet which contains an AP and several RPs. In the tree subnet, the AP is a root node and the RPs are the leaf nodes. The upper layer can also be named as tree access network (TAN) which is in charge of retransmitting communication frames and ensures that the communication can be covered in the whole detection areas for IHM-WSNs. The lower layer contains several star subnets, one of which is made up of a RP and several EDs. The lower layer network can also be named as star detection network (SDN). In a SDN, the RP is a head node, which is in charge of fusing and retransmitting the data from EDs. EDs are in charge of detecting and monitoring the health state of infrastructure of HSR. In each IHM-WSN, the EDs adopt sleeping modes which can extend the lifetime of the whole IHM-WSN.

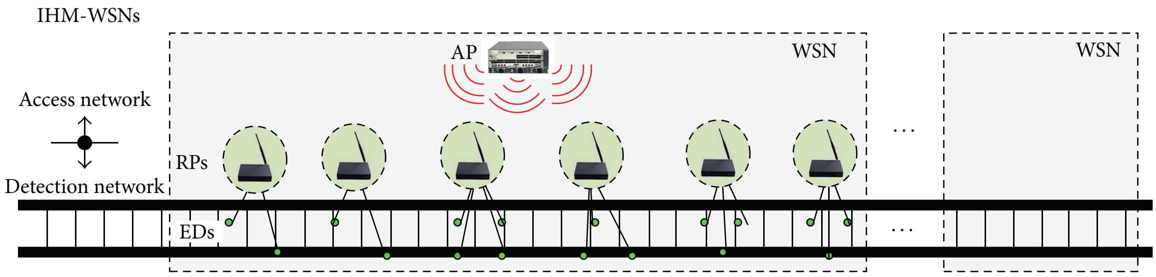

Figure 2: IHM-WSNs architecture for HSR.

Table 1: Common types of sensors used in IHM-WSNs.

Sensor type	Application purpose or monitoring strategy
Photoelectric switch	Monitoring of overhead line system
Electrical sensor	Safety monitoring of power supply system
Optical grating transducer	Monitoring of rapid slope
Water sensor	Monitoring of track settlement deform
Strain transducer	Monitoring of track longitudinal stress
Pressure sensor	Monitoring of track composite stiffness
Humidity sensor	Safety monitoring of power supply system
Temperature sensor	Monitoring of track longitudinal stress
Displacement sensor	Monitoring of track displacement and crawling

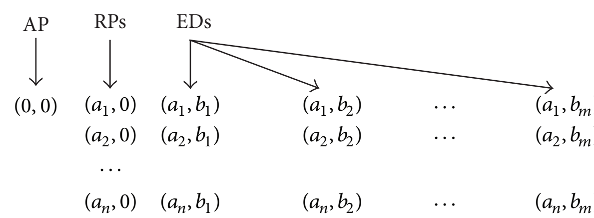

Figure 3: Address assignment of an IHM-WSN.

3. Network Address and Communication Frame of IHM-WSNs for HSR

3.1. Network Address Design. IHM-WSNs have some characteristics, such as low density of nodes, few amounts of information, and long communication distance between different nodes. Thus, a short network address (NA) will be fit for IHM-WSNs. In this paper, a CA contains only two bytes (16 bits) and is divided into a high byte part and a low byte part based on the two layers of IHM-WSNs. Then, a WSN in IHM-WSNs will contain no more than 255 RPs (an AP included), and a RP contains no more than 255 EDs. Compared with traditional network address (64 bits) used in WSN, a short CA will be more suitable for the actual application of IHM-WSNs, which can reduce the amount of communication data and the energy consumption greatly.

The high byte part of CA describes the address assignment of the RPs. Since an AP controls all the RPs in an IHM-WSN, the high byte addresses of RPs in the same IHM-WSN are different. The high byte address of the AP is set as 0. The low byte address of the RP is set as 0. All of the EDs with the same parent RP have the same high byte address which is also the high byte address of the RP. The low byte part of CA describes the address assignment of the EDs in a WSN. All of the EDs with the same parent RP have the same high byte address but different low byte addresses. However, the low byte addresses of different EDs are the same if these EDs are assigned in the same column even though they belong to different parent RPs. The address assignment of an IHM-WSN is shown in Figure 3.

3.2. Communication Frame Design. IHM-WSNs are a kind of wireless network which contains several WSNs. These WSNs implement the function of IHM at different areas in real time. These nodes in WSN communicate with each other via communication frames (CFs). According to the actual requirements and special characteristics of IHM-WSNs, a CF contains nine parts shown in Table 2. These nine parts are Head, Length, CtrlInfo (control information), DSTAddr (destination address), SRCAddr (source address), Port, Trans ID (transmission ID), Security, APP Payload, and FCS (Frame Check Sequence). Among all the 9 parts, we will focus on seven which reflect the particularities of IHM-WSNs; the details are described as follows.

(1) Head and Length. Head and Length fields are designed by the CF format of IEEE 802.15.4 in physical layer. The Head field has 5 bytes and is inserted by the radio hardware. It contains the first 4 bytes of preamble field and the last 1 byte of synchronization field. The Head field serves to initialize the receiver circuitry of network nodes upon reception of an incoming frame. The preamble allows signal sensing, signal amplitude control, and initial clock synchronization. The synchronization field provides absolute symbol synchronization and qualification of signal detection based on the preamble. The Length field is inserted before the node is sending a frame and contains 1 byte. This is the byte after the last synchronization byte which is expected to be the length of the frame (not including the Length byte itself). If such an option

Table 2: Communication frame structure.

Head	Length	CtrlInfo	DSTAddr	SRCAddr	Port	Trans ID	Security	APP Payload	FCS
5 bytes	1 byte	2 bytes	2 bytes	2 bytes	1 byte	1 byte	2 bytes	n byte	2 bytes

Table 3: CtrlInfo bit values.

Bit	Name	Description
15	AckReq	1: acknowledgment request, 0: no acknowledgment request
14	AckRep	1: acknowledgement reply, 0: no acknowledgement reply
13	Sleeping	0: no sleeping, 1: sleeping enabled
12-11	Node Type	00: ED, 01: RP, 10: RP-R, and 11: AP
10	Direction Flag	0: from child to parent, 1: from parent to child
9–7	Depth	The depth value of the node that retransmits the frame recently, the maximum value is 8
6	Security	0: no encryption, 1: encryption enabled
5–0	Reserved Bits	Reserved

exists, the radio will be able to send and receive variable length frames.

(2) CtrlInfo. CtrlInfo field of a CF has 2 bytes and consists of AckReq (acknowledgment request), AckRep (acknowledgement reply), Sleeping, Node Type, Direction Flag, Depth, Security, and Reserved Bits. The CtrlInfo bits are defined as follows (Table 3).

Table 3 shows the CtrlInfo bit values. Each field of AckReq, AckRep, and Sleeping contains one bit. The first two bits concern the acknowledgment request and reply of the CF, and the third bit concerns the type of the receiver node, with sleeping enabled or not. The Node Type field describes the type of the sender node of the frame. There are four kinds of nodes in an IHM-WSN which are ED, RP, RP-R, and AP. EDs detect the infrastructure health state data and send it to a RP. A RP will receive data from EDs, other RPs, or RP-Rs, but a RP-R just receives data from other RPs or RP-Rs. All the RPs and RP-Rs will send the data from other nodes to another RP or RP-R or the AP. Direction Flag field describes the communication direction in an IHM-WSN. 1 represents the frame from a child node to its parent node; 0 represents the frame from a parent node to one of its child nodes. Depth field has 3 bits and describes the depth value of the node that retransmits the frame recently. Since the high byte of a CA is 1 byte (8 bits), the maximum depth will be 8 which is 111 (binary). Similarly, 000 (binary) represents the depth that is 1. Security field describes whether the frame is an encryption frame or not.

(3) DSTAddr and SRCAddr. Each address has 2 bytes. DSTAddr field describes the destination address of a CF and SRCAddr field tells us where the frame will be sent to. The destination and source addresses are treated as byte arrays. Each node has a unique initial CA to be used during the process of topology optimization and it will have a new CA during the process of network construction.

(4) Port. Ports are conceptual abstractions that specify the target application handling the frame. Each port has one byte. In an IHM-WSN, Port numbers 0x00-0x2F are reserved or assigned as "well known Ports" with specific services. They are intended for use by network management. Port numbers 0x30-0x9F are mapped to user handlers and Port numbers 0xA0-0xFE are reserved. Port 0xFF is a broadcast port to be used when the sending device has not been explicitly linked to the receiving device or the sending device needs to send a frame to all devices in the network.

(5) Trans ID. Trans ID field is used to add robustness to the communications. It can be used to match replies to outstanding messages or to help recognize a duplicate frame. Each sending side maintains its own transaction ID discipline.

A short CA can reduce network communication costs, save network resources, and lessen communication energy consumption. The design of communication frame adapts the actual requirement of transmission and receiving nodes. The nodes in an IHM-WSN transmit monitoring data by using the designed network address and communication frame above. However, to implement optimal transmission performance of IHM-WSNs, the network topology optimization should also be done.

4. Topology Optimization Method of IHM-WSNs

The topology structure of a communication network has a huge influence on transmission performance. A good topology structure is able to reduce the communication jamming, extend the network lifetime, and improve the communication efficiency. For IHM-WSNs with fixed layered structure and motionless nodes, a transmission power based method is proposed to optimize the topology structure. Since the lower layer of the IHM-WSNs is made up of SDNs (Figure 2), their topology structures are known. Here, the main optimization object is the upper layer, which contains an AP and a number of RPs.

Definitions

Transmission Power Based Method. By changing the transmission power and location of each node, a connected graph with all the nodes of an IHM-WSN will be obtained. The aim of this method is to minimize the total power consumption.

Adjacent Node. For each node P in an IHM-WSN, P's adjacent nodes are the nodes which are able to communicate with P directly when P is set at a certain transmission power. When P's transmission power is set as a maximum allowable power, all of P's adjacent nodes will be obtained.

Neighbor Node. After the process of topology optimization, the nodes which are able to communicate directly with P are P's neighbor nodes.

4.1. Power Cost of Links with Adjacent Nodes. Each node in the TAN can send probe comments using a broadcast frame by different transmission power from low to high value automatically. Firstly, each node sends probe comments with current transmission power; meanwhile, it receives probe comments from other nodes. If node P receives several probe comments from node Q, the probe comment from node Q with minimum transmission power will be responded by node P. When node Q receives an acknowledgment from node P which has received node Q's probe comment before, the address of node P and corresponding minimum transmission power will be recorded by node Q. This minimum transmission power is named as the power cost between two nodes. Then, node Q has a new adjacent node P and the power cost between node Q and its adjacent node P has been obtained. As the transmission power of node Q increases, the signal coverage of node Q will be extended. Then, the number of node Q's adjacent nodes will increase. When node Q has its maximum allowable power, it will obtain all of its adjacent nodes and corresponding power costs. Based on those node addresses and power costs, node Q can build its power cost table (PCT). By this method, each node in the TAN will have its initial PCT. The PCTs of these nodes will be the method's inputs.

4.2. Topology Optimization of TAN. The optimization object of the transmission power based method is to achieve the direct or indirect communication between two random nodes in a TAN and minimize the total power consumption. Considering the nodes in a TAN as the vertexes of an undirected graph and the power costs of PCTs as the weights of the links between two corresponding nodes, the problem of topology optimization for IHM-WSNs is to find a minimum spanning tree (MST) in an undirected graph.

The AP in a TAN starts the process of topology optimization by broadcasting an activated comment. When a RP receives the activated comment, it will turn on an activated state to wait for subsequent comments from the AP or other RPs. Since there are some constraints of nodes' allowable transmission power and location, not all of the nodes in the TAN can receive the activated comment directly or indirectly, although these nodes have built some subnets and their own PCTs in the process of power cost acquisition. Given the PCT of each node in the TAN, the undirected graph will not always be a connected graph. Therefore, an improved prim algorithm (IPA) is proposed to address the problem of topology optimization for IHM-WSNs. The IPA realizes topology optimization by starting with an AP and just making use of the local information of each node. It adopts the knowledge update mechanism to detect the optimization result and judge whether the parameters (power or location) of the nodes in an IHM-WSN should be changed. Thus, the IPA can work without knowing the connectivity matrix of the TAN. The process of the IPA is as follows.

Step 1. Each node in the TAN implements the process of power cost acquisition of links with adjacent nodes to obtain its local information, for example, its own PCT.

Step 2. For each node in the TAN, sort the power costs of PCT in ascending order.

Step 3. Initialize a local node set N_s with an only element AP and a local link set L_s with empty element.

Step 4. Select a link with minimum power cost between a node in N_s and one of its adjacent nodes which is not in N_s; add the link into L_s and the node which is not in N_s into N_s.

Step 5. If the nodes in N_s have their adjacent nodes, return to Step 4; or else, go to Step 6.

Step 6. If the local node set N_s includes all of the nodes in the TAN, end; or else, start up the knowledge update mechanism and change the allowable transmission power or the locations of the nodes which is not in N_s and return to Step 1.

Utilizing the IPA, a MST of the TAN can be obtained, in which the set N_s contains all the nodes in the TAN and the set L_s contains all the directly communication links of the TAN. In the MST, randomly selecting a node P, the nodes which can communicate with node P directly are named as P's neighbor nodes. Then, node P will use the transmission power with the maximum power cost between node P and its neighbor nodes to send broadcasts or communicate with its neighbor nodes directly.

5. Address Assignment and Network Construction

5.1. NA Assignment and TAN Construction. After topology optimization, the work of TAN construction will start. IHM-WSNs are layering networks with the upper layer being a tree-topological structure (TAN) and the lower layer being a star-topological structure (SDN). In a TAN, the AP is the TAN's root, and the RPs are the subroots or leaves. Each subroot or leaf node has only one parent node. Each subroot node is able to build a tree-topological subnet with itself as a subroot.

There are plenty of communication information and monitoring data to be transmitted. The TAN is charged with major communication tasks. Besides a good NA design, a reasonable NA assignment is necessary and important to reduce broadcast storms and ensure a unique and smooth communication route from the source node to the destination node. As described in Communication Frame Design, the low byte of NA is always 0 for the RPs; therefore, the high type of NA will be assigned for a TAN.

The specialty of communication route between two random nodes is determined by the tree-topological structure of the TAN. In order to relieve broadcast storms, each node in the TAN needs to judge whether the received CF has been

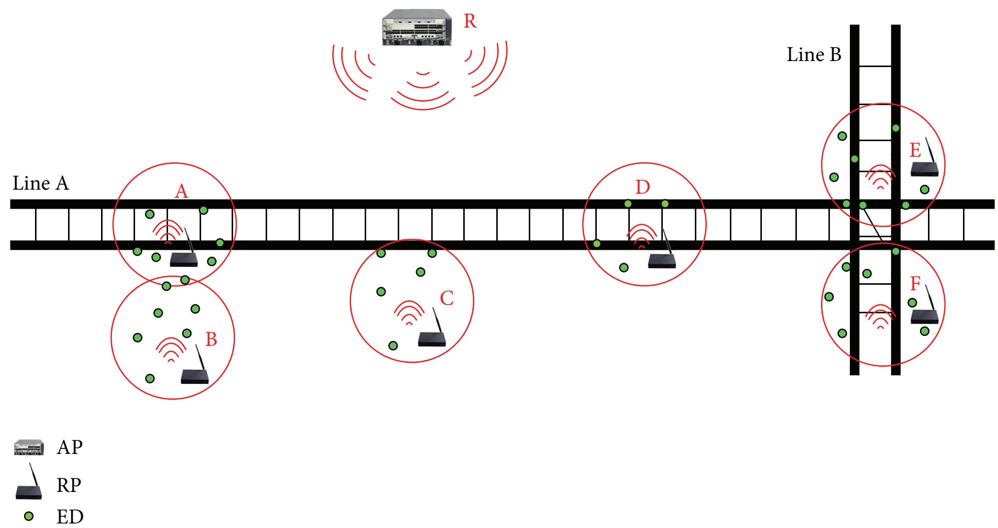

Figure 4: A practical instance for IHM of HSR.

retransmitted by other nodes and whether the node's depth is larger than that of the CF. Besides the depth, each node has a NA and a subnet mask (SM). The SM is used to implement an "AND" operation with the high byte address of the CF that the node receives. The results of this operation can judge whether the node is the destination node of the CF.

The step of topology optimization enables every node to obtain its neighbor nodes. For each node P in the TAN, if it knows its depth, NA, and SM, it will send a request to its entire neighbor nodes (not including its parent node). The request asks for these neighbor nodes to join a subnet whose subroot is the node P. When the node P receives all of these neighbor nodes' acknowledgments, it will compute the values of depth, SM, and CAs for these neighbor nodes and then send these values to these neighbor nodes which will be the node P's child nodes in the subnet. The child nodes with the same parent node will have the same depth and SM, but different CAs.

Given a parent node's depth, NA, and SM, the depth, SM, and regions of NA of its child nodes can be calculated as follows:

$$\begin{aligned} D_c &= D + 1, \\ L_c &= L + \log_2 (x + n + 1), \\ R_c &\in \left\{ R + \mathbf{R} \times 2^{8-L_c} \quad \left(\mathbf{R} \in \left[1, 2^{(L_c - L)} - 1 \right] \right) \right\}, \end{aligned} \tag{1}$$

where D, L, and R are the depth, the length of SM, and the NA of the parent node, respectively, D_c, L_c, and R_c are the depth, the length of SM, and the NA of its child nodes, respectively, n is the number of child nodes, x is the number of NA reserved for the subsequent child nodes, which makes it easy for the parent node to add new nodes, and $\mathbf{R}$ is an integer vector related to L and L_c.

As the root of the TAN, AP has a minimum depth value 1 and its NA and SM are both 0x00. Given the optimal topology structure of the TAN, AP starts the work to construct the TAN and assigns the values of depth, NA, and SM to its child nodes according to (1). Then, each child node does the same work as its parent node until all the nodes have their depth, NA, and SM. Here, the TAN has been constructed and it can be used to send CFs from each node to another.

5.2. NA Assignment and SDN Construction. If the construction work for the TAN has been done, the AP will start the construction work for SDNs. When the RPs receive the comments to construct SDNs from the AP, they will send invitation comments to the EDs by their maximum allowable transmission power. After initialization, each ED is at listening state; thus, the EDs can receive RP's invitation comments. Sometimes, each ED will receive invitation comments from multiple RPs, but it will respond to only one RP with a maximum received signal strength indicted by the ED. Then, the ED will send an access message with a network token and a hardware flag to its parent RP. The RP will check the validity of the network token and hardware flag. If they are valid, the RP will distribute a unique number (1–255) to the ED as the ED's low byte address. The high byte address of the ED is the same as its parent RP.

If a RP cannot receive any access message from new EDs within a setting time, then a star subnet with the RP as the root node will be constructed. When all the RPs have possessed their subnets, the construction work of the SDN is done.

6. Practical Instance

A practical instance for IHM of HSR is shown in Figure 4. An IHM-WSN will be built to implement IHM near the area of two HSRs. There are six detection areas. Each RP covers a detection area to access the data from the EDs in this area. The six RPs are denoted by A, B, C, D, E, and F. The root node of the IHM-WSN is an AP which is represented as R.

Firstly, the topology optimization and NA assignment of the TAN will be done based on the transmission power based method and IPA. As an initialization parameter, the NA of

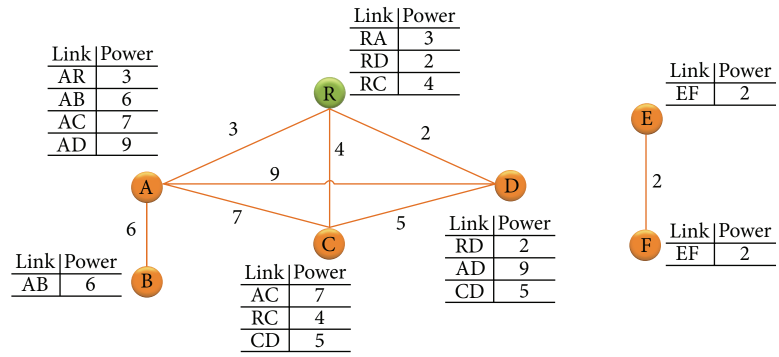

Figure 5: Link power and PCTs of the TAN in the example.

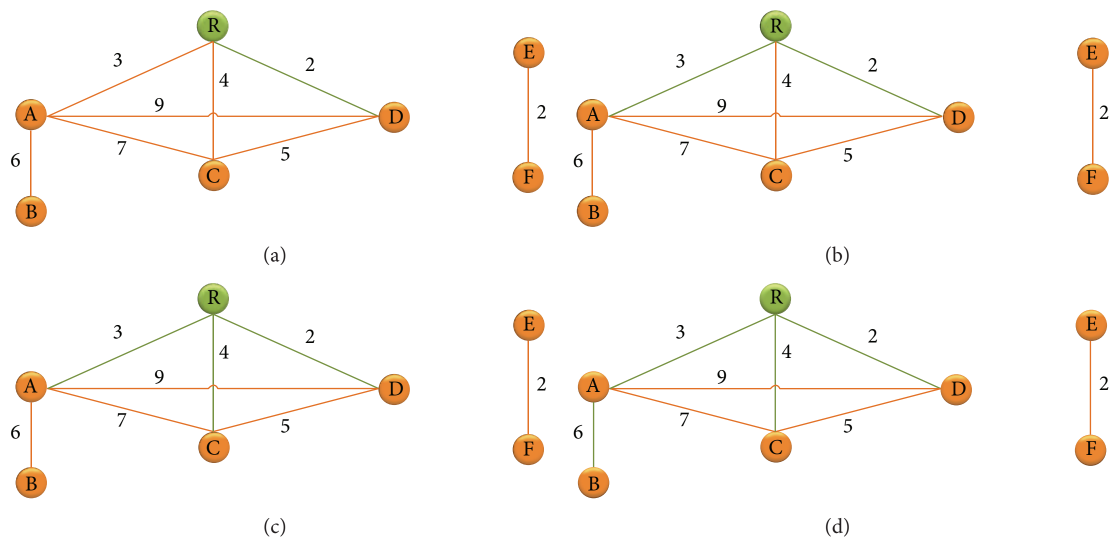

Figure 6: Process of the IPA on the basis of Figure 5.

node R is 0x0000. By the step of power cost of links with adjacent nodes, each node will obtain its PCT which is shown in Figure 5.

Then, the IPA will be used to implement the topology optimization of the TAN. Based on the initializing topology of the TAN, Figure 6 shows the process of the IPA on the basis of Figure 5. When it comes to Step 5 of the IPA, the AP (node R) will find only four RPs in its network, instead of the setting value six; therefore, we should start up the knowledge update mechanism and change the allowable transmission power or the locations of the nodes which are not in the network. Finally, the new link power and PCTs of the TAN are shown in Figure 7. Given Figure 7, Figure 8 shows the new process of the IPA and the final topology structure of the TAN. In Figure 8, there are six RPs in the TAN with the AP being the root node, and then the optimal topology structure of the TAN has been obtained, which is shown in Figure 9.

As the AP of the TAN, the NA, the SM, and the depth of node R are 0x0000, 0, and 1, respectively. Let the number of NAs reserved for the parent node be 1; that is, $x = 1$. For node R, $n = 3$. Through (1), we know that the depth of node R's children nodes is 2, the length of SM is 3, and seven CAs are used by node R's children nodes. Those CAs are 32, 64, 96, 128, 160, 192, and 224. Then, 32, 64, and 96 can be assigned to the CAs of nodes A, C, and D, respectively. Similarly, we have the depth of nodes B and F which is 3 and the depth of node E is 4. Figure 10 shows the detail information of each RP in the TAN.

After constructing the TAN, the AP starts to send command frame to each RP for constructing the SDN. Through the steps of NA assignment, each node of the whole IHM-WSN will have one NA and depth. Figure 11 shows the final network topology and NA assignment of the IHM-WSN in the example.

7. Conclusions

A novel network architecture for IHM of HSR has been described in this paper and the different layers of IHM-WSNs have their own functions. The responsibilities of the lower layer are detecting and collecting the state information of HSR infrastructures, and the high layer is primarily responsible for data transmitting and fusion. The special design of NA and CF enables IHM-WSNs to implement

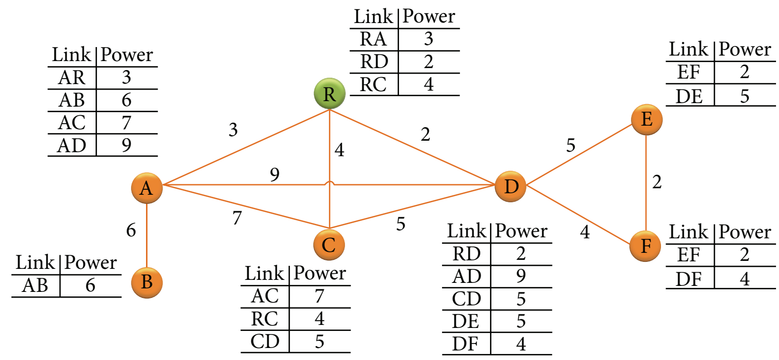

Figure 7: New link power and PCTs of the TAN in the example.

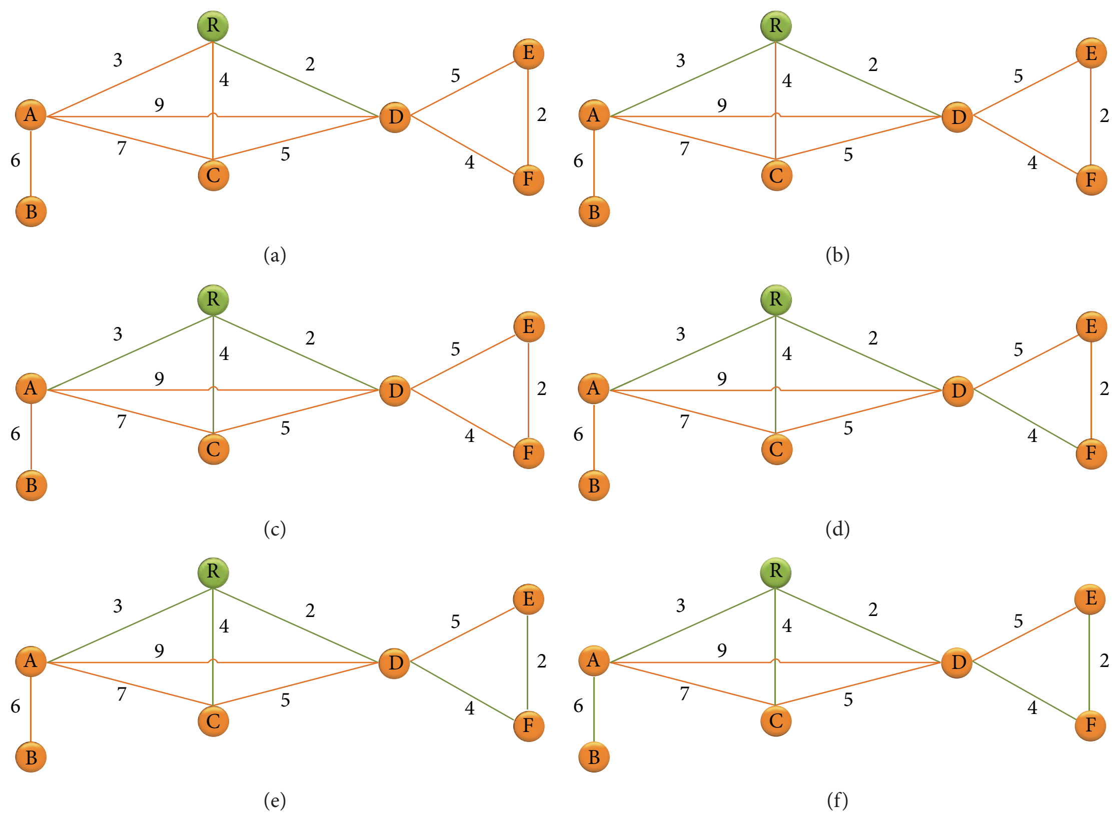

Figure 8: New process of the IPA and final topology structure of the TAN given in Figure 7.

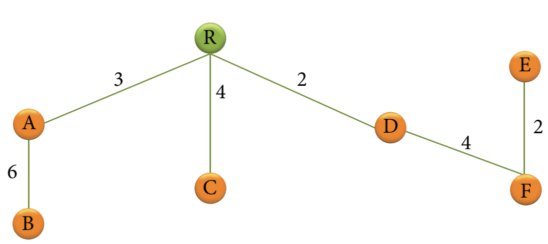

Figure 9: Optimal topology structure of the TAN.

communication between different nodes with less energy consumption and lower memory space in the network. Besides, the proposed method is able to obtain an optimal topology based on local information of each node and it is proved that the IPA can solve the topology optimization problem. The proposed IPA can also deal with the situation of disconnected graph using the knowledge update mechanism which is another advantage of the IPA. This mechanism can detect the optimization result and judge whether the parameters (transmission power or location) of the nodes in IHM-WSNs should be changed. Moreover, the process of NA assignment and network construction will get a complete IHM-WSN which is composed of EDs, RPs, and an AP. This network can availably reduce broadcast storms and ensure a unique and smooth communication route from the source

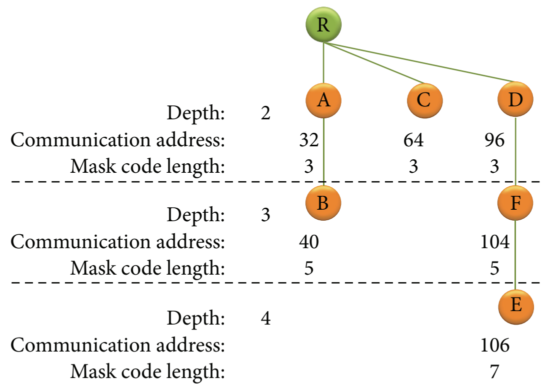

FIGURE 10: Node information of RPs in the TAN.

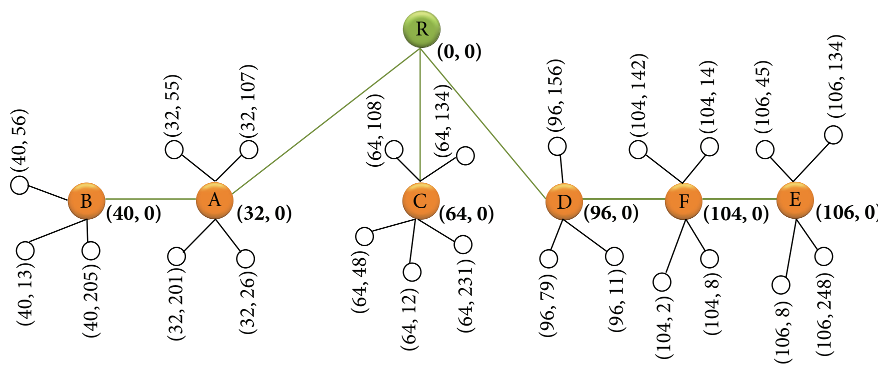

FIGURE 11: Optimal topology and node address of the IHM-WSN in the field example.

node to the destination node. The practical instance demonstrates that the proposed method can be used to implement topology optimization and network construction for IHM-WSNs, which validates the applicability and effectiveness of our method.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] Y. Dong, P. Fan, and K. Ben Letaief, "High-speed railway wireless communications: efficiency versus fairness," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 2, pp. 925–930, 2014.

[2] G. He, A. P. Mol, L. Zhang, and Y. Lu, "Environmental risks of high-speed railway in China: public participation, perception and trust," *Environmental Development*, vol. 14, pp. 37–52, 2015.

[3] R. Mu, M. De Jong, Y. Ma, and B. Xi, "Trading off public values in High-Speed Rail development in China," *Journal of Transport Geography*, vol. 43, pp. 66–77, 2015.

[4] F. Flammini, A. Gaglione, F. Ottello, A. Pappalardo, C. Pragliola, and A. Tedesco, "Towards wireless sensor networks for railway infrastructure monitoring," in *Proceedings of the International Conference on Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS '10)*, Bologna, Italy, October 2010.

[5] S. Hadim and N. Mohamed, "Middleware: middleware challenges and approaches for wireless sensor networks," *IEEE Distributed Systems Online*, vol. 7, no. 3, pp. 1–23, 2006.

[6] J. P. Lynch and K. J. Loh, "A summary review of wireless sensors and sensor networks for structural health monitoring," *Shock and Vibration Digest*, vol. 38, no. 2, pp. 91–128, 2006.

[7] F. P. G. Márquez, F. Schmid, and J. C. Collado, "A reliability centered approach to remote condition monitoring. A railway points case study," *Reliability Engineering and System Safety*, vol. 80, no. 1, pp. 33–40, 2003.

[8] F. P. G. Márquez, R. W. Lewis, A. M. Tobias, and C. Roberts, "Life cycle costs for railway condition monitoring," *Transportation Research Part E: Logistics and Transportation Review*, vol. 44, no. 6, pp. 1175–1187, 2008.

[9] F. P. G. Márquez and F. Schmid, "A digital filter-based approach to the remote condition monitoring of railway turnouts," *Reliability Engineering & System Safety*, vol. 92, no. 6, pp. 830–840, 2007.

[10] M. Clark, M. Gordon, and M. C. Forde, "Issues over high-speed non-invasive monitoring of railway trackbed," *NDT & E International*, vol. 37, no. 2, pp. 131–139, 2004.

[11] A. Monzón, E. Ortega, and E. López, "Efficiency and spatial equity impacts of high-speed rail extensions in urban areas," *Cities*, vol. 30, no. 1, pp. 18–30, 2013.

[12] B. Chang and A. Kendall, "Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system," *Transportation Research Part D: Transport and Environment*, vol. 16, no. 6, pp. 429–434, 2011.

[13] X. Feng, "Optimization of target speeds of high-speed railway trains for traction energy saving and transport efficiency improvement," *Energy Policy*, vol. 39, no. 12, pp. 7658–7665, 2011.

[14] X. Li, C.-F. Chien, L. Li, Z. Gao, and L. Yang, "Energy-constraint operation strategy for high-speed railway," *International Journal of Innovative Computing, Information and Control*, vol. 8, no. 10, pp. 6569–6583, 2012.

[15] T. M. Chiwewe and G. P. Hancke, "A distributed topology control technique for low interference and energy efficiency in wireless sensor networks," *IEEE Transactions on Industrial Informatics*, vol. 8, no. 1, pp. 11–19, 2012.

[16] Y. Liu, L. Ni, and C. Hu, "A generalized probabilistic topology control for wireless sensor networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 9, pp. 1780–1788, 2012.

[17] M. Li, Z. Li, and A. V. Vasilakos, "A survey on topology control in wireless sensor networks: taxonomy, comparative study, and open issues," *Proceedings of the IEEE*, vol. 101, no. 12, pp. 2538–2557, 2013.

[18] N. Xu, A. Huang, T.-W. Hou, and H.-H. Chen, "Coverage and connectivity guaranteed topology control algorithm for cluster-based wireless sensor networks," *Wireless Communications and Mobile Computing*, vol. 12, no. 1, pp. 23–32, 2012.

[19] S. Rizvi, H. K. Qureshi, S. Ali Khayam, V. Rakocevic, and M. Rajarajan, "A1: an energy efficient topology control algorithm for connected area coverage in wireless sensor networks," *Journal of Network and Computer Applications*, vol. 35, no. 2, pp. 597–605, 2012.

[20] H. Üster and H. Lin, "Integrated topology control and routing in wireless sensor networks for prolonged network lifetime," *Ad Hoc Networks*, vol. 9, no. 5, pp. 835–851, 2011.

[21] M. Younis, I. F. Senturk, K. Akkaya, S. Lee, and F. Senel, "Topology management techniques for tolerating node failures in wireless sensor networks: a survey," *Computer Networks*, vol. 58, no. 1, pp. 254–283, 2014.

[22] M. Vecchio and R. López-Valcarce, "A greedy topology design to accelerate consensus in broadcast wireless sensor networks," *Information Processing Letters*, vol. 115, no. 3, pp. 408–413, 2015.

[23] K. Akkaya and M. Younis, "A survey on routing protocols for wireless sensor networks," *Ad Hoc Networks*, vol. 3, no. 3, pp. 325–349, 2005.

[24] L. J. G. Villalba, A. L. S. Orozco, A. T. Cabrera, and C. J. B. Abbas, "Routing protocols in wireless sensor networks," *Sensors*, vol. 9, no. 11, pp. 8399–8421, 2009.

[25] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: a survey," *IEEE Wireless Communications*, vol. 11, no. 6, pp. 6–27, 2004.

[26] A. M. S. Saleh, B. M. Ali, M. F. Rasid, and A. Ismail, "A survey on energy awareness mechanisms in routing protocols for wireless sensor networks using optimization methods," *Transactions on Emerging Telecommunications Technologies*, vol. 25, no. 12, pp. 1184–1207, 2014.

[27] K. Narendra, V. Varun, and G. H. Raghunandan, "A comparative analysis of energy-efficient routing protocols in wireless sensor networks," *Lecture Notes in Electrical Engineering*, vol. 248, pp. 399–405, 2014.

[28] D. Zhang, G. Li, K. Zheng, X. Ming, and Z.-H. Pan, "An energy-balanced routing method based on forward-aware factor for wireless sensor networks," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 1, pp. 766–773, 2014.

[29] M. Hammoudeh and R. Newman, "Adaptive routing in wireless sensor networks: QoS optimisation for enhanced application performance," *Information Fusion*, vol. 22, pp. 3–15, 2015.

[30] M. Collotta, M. Denaro, G. Scatà, A. Messineo, and G. Nicolosi, "A self-powered wireless sensor network for dynamic management of queues at traffic lights," *Transport and Telecommunication*, vol. 15, no. 1, pp. 42–52, 2014.

[31] S. K. Ghosh, M. Suman, R. Datta, and P. K. Biswas, "Power efficient event detection scheme in wireless sensor networks for railway bridge health monitoring system," in *Proceedings of the IEEE International Conference on Advanced Networks and Telecommuncations Systems (ANTS '14)*, pp. 1–6, IEEE, New Delhi, India, December 2014.

[32] T.-H. Yi, G. Song, S. C. Stiros, and B. Chen, "Distributed sensor networks for health monitoring of civil infrastructures," *Shock and Vibration*, vol. 2015, Article ID 271912, 3 pages, 2015.

[33] K. Banerjee, H. Sharma, and B. K. Chaurasia, "Secure communication for cluster based wireless sensor network," in *Proceedings of the International Conference on Computational Intelligence and Communication Networks (CICN '14)*, pp. 867–871, Bhopal, India, November 2014.

[34] S. N. Pai, *Energy Conservation Protocols for Wireless Sensor Networks*, Manipal Institute of Technology, Manipal, India, 2014.