A DOOR MONITORING SYSTEM FOR SUBWAY CARS BASED ON WIRELESS SENSOR NETWORK

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Abstract- The place and performance of wireless sensor networks are rapidly improving in the automotive industry, industrial and environmental monitoring. Uptake of this technology can be used in urban rail vehicle management system. Due to the difficult and time-consuming maintenance of vehicle management, a remote automatic monitoring system is needed. In this paper, it is proposed to design, develop and implement a remote automatic vehicle monitoring system. The complete system architecture includes a group of sensor nodes, some sink nodes, and a data centre. The sensor nodes are connected to the sink node, which is connected to a data centre through CDMA or General Packet Radio Service (GPRS) technologies. In order to improve the reliability of wireless transmission, retransmission and redundant path are discussed. The system has been tested for half a year and satisfactory results have been observed, which indicate that this system is useful for urban rail vehicle monitoring.

Index terms*: Wireless sensor networks, embedded operating system, remote monitoring, urban railway system, data centre.*

I.   INTRODUCTION

With the increasing proportion of the population residing in towns and the increasing private cars on the road caused a great burden to the current city traffic, people demands for an effective, green and low carbon travel mode. As a safe, convenient and fast transit mode, urban rail transportation system can alleviate traffic problems and meet the needs of people. The construction of the urban rail transportation system is costly, and the maintenance is also important and costly due to the safety. The most critical problem of safety is the vehicle door's correct running status, especially correct open/close. Since most vehicles lack of environment monitoring system to track the doors' running status and monitor the in-car environment variables, such as the temperature and humidity, staffs have to be on duty all day and especially work very hard at midnight due to management inefficiencies.

Wireless Sensor Network (WSN) is a modern technology integrates the knowledge of sensors, automation control, digital network transmission, information storage, and information processing. Currently, WSN technology has been mostly applied to environment monitoring[1-4], agricultural monitoring[5-6] and gaseous leakage monitoring[7]. In this paper, we propose a urban rail vehicle monitoring system, which can real-time collect each door's status information and environment variables, and deliver these information to the mobile Internet. The main contributions of this paper are: 1) design and implement a front-end monitoring device for each door by applying the existing technologies. The functions of the front-end monitoring device include collecting the door's various status and fault information from the Electronic Door Control Unit (EDCU) and the environment data from sensors, analyzing and packing the data, and storing it temporarily; 2) propose a chain-type topology in clustering-based networks and a routing protocol; 3) apply the retransmission and redundant path to combat wireless multi-path fading and improve the reliability.

II.   SYSTEM ARCHITECTURE

a. System Requirements Analysis

Each door of the vehicle is equipped with one wireless sensor node, and the node is connected to the temperature and humidity sensors to measure their values inside and outside the vehicle,

respectively. Besides, each node is embedded a front-end device to collect doors' status information, and the doors' status information can obtain from the Multifunction Vehicle Bus (MVB) of the Train Control Networks (TCN). Each sensor node transmit the packed data to a sink node, where they are packed and sent to the data centre on a predefined schedule in order to achieve real-time data release in the WEB. The sink node is placed in each metro car, where the sensor nodes can easily access.

This system can achieve the following functions: (1) automatic collection of monitoring data for all cars of the vehicle; (2) periodical transmission of the monitoring data and any alarm messages to sink nodes; (3) sending of the real-time door monitoring data to the data center via the CMDA or GPRS network; (4) rolling and displaying the information on the screen of the data centre.

b. System Architecture Design

The overall architecture of the urban rail vehicle remote monitoring system is shown in figure 1. The system mainly consists of three parts: 1) a group of sensor nodes and some sink nodes, installed next to every EDCU, have functions of real-time collecting each door's status and fault information, analyzing and storing the collected information locally, and the sink nodes are also responsible of uploading the information to public network, such as the mobile Internet; 2) the wireless transmission channels. To guarantee transmission reliability, the sensor nodes and sink nodes embedded wireless transceiver modules compose a special ad hoc network, with layered cluster & chain topology. Due to the variable propagation loss, it need to propose a propagation model suitable for the in-car environment[8]. Furthermore, retransmission and redundant path should be applied to improve the transmission reliability; 3) the data centre, which has functions of receiving, accessing data from the mobile Internet. Furthermore, rolling and displaying the information or drawing statistics curves, and et al.
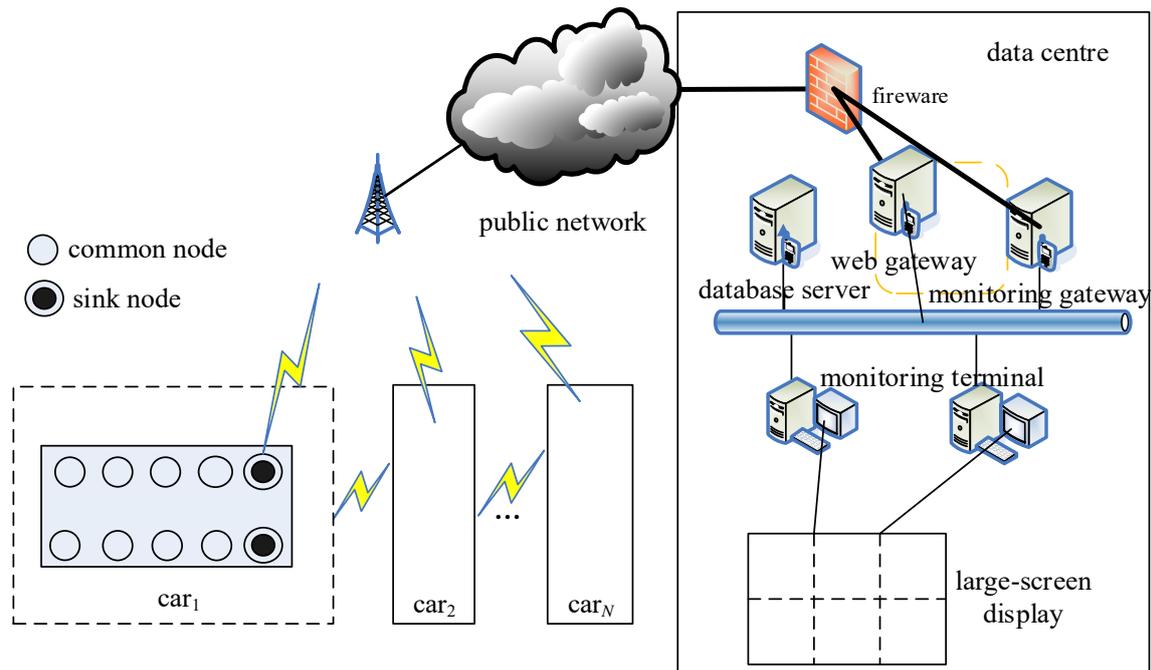
Figure 1. Architecture of the monitoring system

To illustrate more details in one car (the others are similar), we will take the metro vehicle as an example. According to the internationally standards, there are three specification metro vehicles: A, B and C. Specification of A-type metro vehicle is 3 meters in width and 21-24 meters in length; specification of B-type is 2.8 meters in width and 19-21 meters in length; specification of C-type is 2.6 meters in width and 15-19 meters in length. If specification of A-type vehicle is applied, there are six cars. Each car has 10 doors, and then a total vehicle has 60 doors. For each car, there are 8 sensor nodes and 2 sink nodes distributed in both sides. Each door has its own electronic control unit executing the instruction ordered by the train control system and reporting the door's status information to the vehicle communication bus of the train control system.

c. Chain-type Topology in Clustering-based Networks

As we mentioned above, there are totally six cars of one vehicle. Each car has 10 doors, and a vehicle has 60 doors. So, there are 60 front-end devices with wireless transceiver modules distributed at each door. These devices are constructed in a chain-type with cluster topology, shown in figure 4. The chain-type with cluster topology is selected due to decrease the cost. If each front-end device is connected to the mobile Internet through the 3G CDMA module, the

communication costs are high. As the front-end devices with wireless transceiver module, we call them wireless nodes, and classify them as follows.

(1) common nodes, denoted as "○" in figure 2, are equipped with 2.4GHz short-range wireless communication module, and responsible for data collection and transmission;

(2) sink nodes, denoted as "◉" in figure 2, are equipped with 2.4GHz short-range wireless communication module and also 3G CDMA module. The sink nodes are responsible for collecting the information in one cluster and transmitting it to the mobile Internet, also the error detection and retransmission control problems.

The nodes at the same side in one car are constructed one cluster, as the dotted ellipse in figure 2. To provide collision-free packet transmission with quality-of-service (QoS) support in one cluster, we select TDMA (Time Division Multiple Access) technology [9-11]. Then in one cluster, time is divided into equal-length frames, and each frame is composed of a fixed number of unit-length transmission slots.
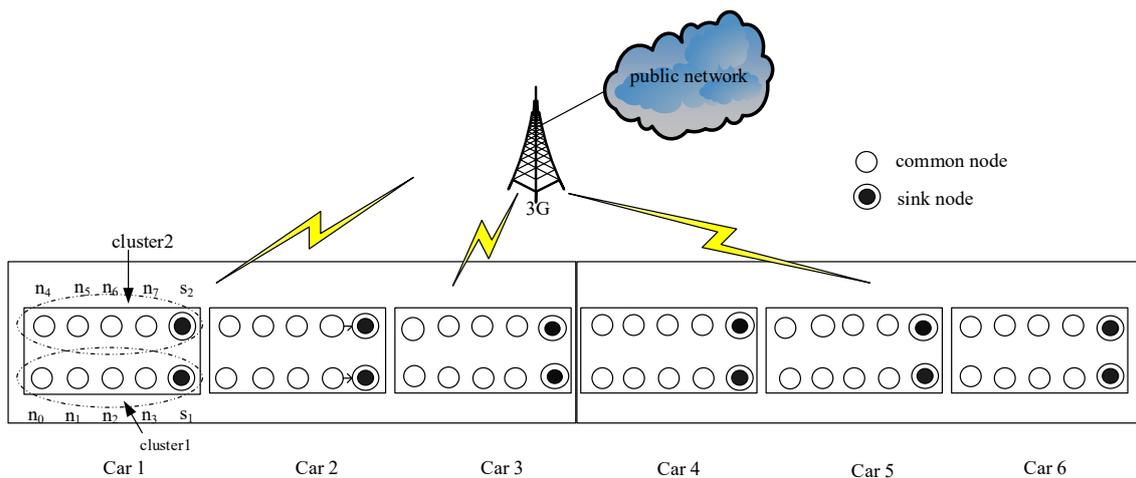

Figure 2. Chain-type topology in clustering-based networks

III.   SYSTEM FUNCTIONAL MODULES

a. Sensor Node Module Hardware and Software Design

The functional block diagram of the sensor node is shown in figure 3, mainly consists of RS485-232 conversion module, ARM processing unit, 2.4G wireless transceiver module, and power source unit. The implementation of the sensor node is shown in figure 4.

a.i RS485-232 Conversion Unit

The RS485-232 conversion unit is responsible for level conversion. Because the train bus provides RS-485 interface and the EBD9260 ARM developing system of Shenzhen Embedall Company can only provide RS-232 interface, so the RS485-232 conversion unit is needed to converts RS-485 bus signal to RS-232 signal.

The temperature and humidity data and the data collected from the train bus are collected by ARM processing unit. The ARM unit will packed the data, and transmit the data to the sink node through 2.4G wireless transceiver module.
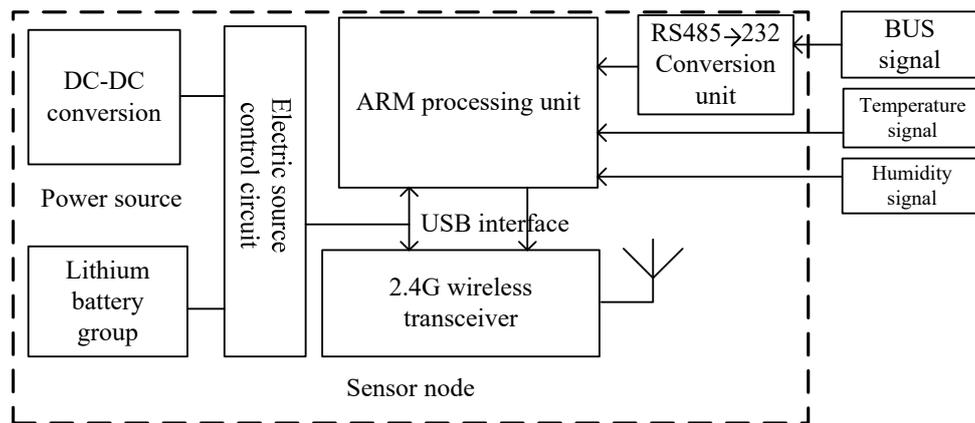

Figure 3. Functional block diagram of the sensor node

Figure 4. An encapsulated sensor node

a.ii Design of Node Power Management System

The node power management system is shown in figure 5. The power control circuit can supply double power: the main power supply is DC 110V which from the DC-DC conversion module; the auxiliary power supply is provided by the lithium battery group. When the main power supply provide power, the power control circuit output to the ARM processing unit and CDMA module.

When the main power goes off, the power supply control circuit switches to the auxiliary power for constant power supply to the ARM unit and CDMA module, and ensures reliable data storing and transmission. After data has transmitted and some other related tasks have completed, the power supply control circuit will cut off the supply to the ARM unit and the CDMA module. The power control circuit switches to the low power consumption standby mode. PB17 and PB18 of GPIO J5 port of ARM processing unit are two signals for power control.

The power control unit applies AT89C2051 control circuit based on SCM. When the main power supply is working, the lithium battery group is charged through a boosting circuit based on LM2577ADJ chip. The charging circuit is based on MAX1873SEEE charging chip, and the electronic switch is designed on AO4435 based on PMOS tube. The typical transistor threshold voltage VGS(th) is -2.3V, and the drain source voltage VDS is -30V. The gate source voltage VGS is set to -10V, the drain the current ID is set to -10A, and the drain source resistance RDS(ON) is less than 18mΩ. The gate source voltage is controlled to make AO4435 in switching status to control the output voltage.

The main technical indexes of the DC-DC module are as follows: input DC is 66V-160V, output is 12.75V (3.9A); ripple noise peak to peak voltage is 100mV; 1500V isolation voltage. Besides, the circuit is safe with short circuit and overcurrent protection, and passes the EMC testing and vibration impact test requirements. Lithium batteries use Sanyo specifications 18650 for three series battery, the full charge voltage is 12.6V, and the capacity is 2200mAH with short circuit and overcurrent protection.

Figure 5. The composition of the node power management system

a.iii Software Implementation of Node Modules

1) Data format

Before they are sent to the sink node, the data are collected through nodes in certain format, which is shown in Table 1. The data flow-process diagram is shown in figure 6.

2) Working process of sensor node

To reduce the communication conflicts resulting from nodes simultaneously sending networking information, TDMA technology is applied. The nodes will delay sending the information based on their own serial numbers, such as node n1 sending the network information after 5 ms, node n2 sending information after 10 ms, etc.. If a node does not receive the confirmed information from the sink node by sending network information within 500 ms, the system will judge the networking times; once it is exceeded 5 times, the system will stop networking and directly go into a state of hibernation, a redundant path will be chosen.

Table 1: Data format

Field	Length(Byte)	Meaning
DLE	1	Regular byte 0x10(DLE)
File Begin	1	Regular byte 0x02(STX)
Frame_id	2	1~N
Total Frame Number	2	N
Terminal_id	2	Terminal identifier
Data type	1	0x00: real-time message 0x01: control message 0x02: file transmission
Data length	2	Raw data length, MAX=512Byte
Data	>0	Data of sensors are concerned about temperature, humidity and metro door's status
DLE	1	Regular byte 0x10 (DLE)
End of Frame	1	Regular byte 0x03(ETX)
Check code	1	Check Sum

If the node network is successfully built, the current time and the parameters are obtained from the confirmed information sent through the sink node networking to update the node configuration information and the current time; then it starts sampling the sensors and recording the sampling time; the node packs the sampling data, transfers it to the sink node and waits for its confirmation; if it does not receive the confirmed information from the sink node by sending the

data within 500 ms, which means the data delivery failed, and if it fails to send data after three tries, then the link breaks down and the system will choose a redundant path.
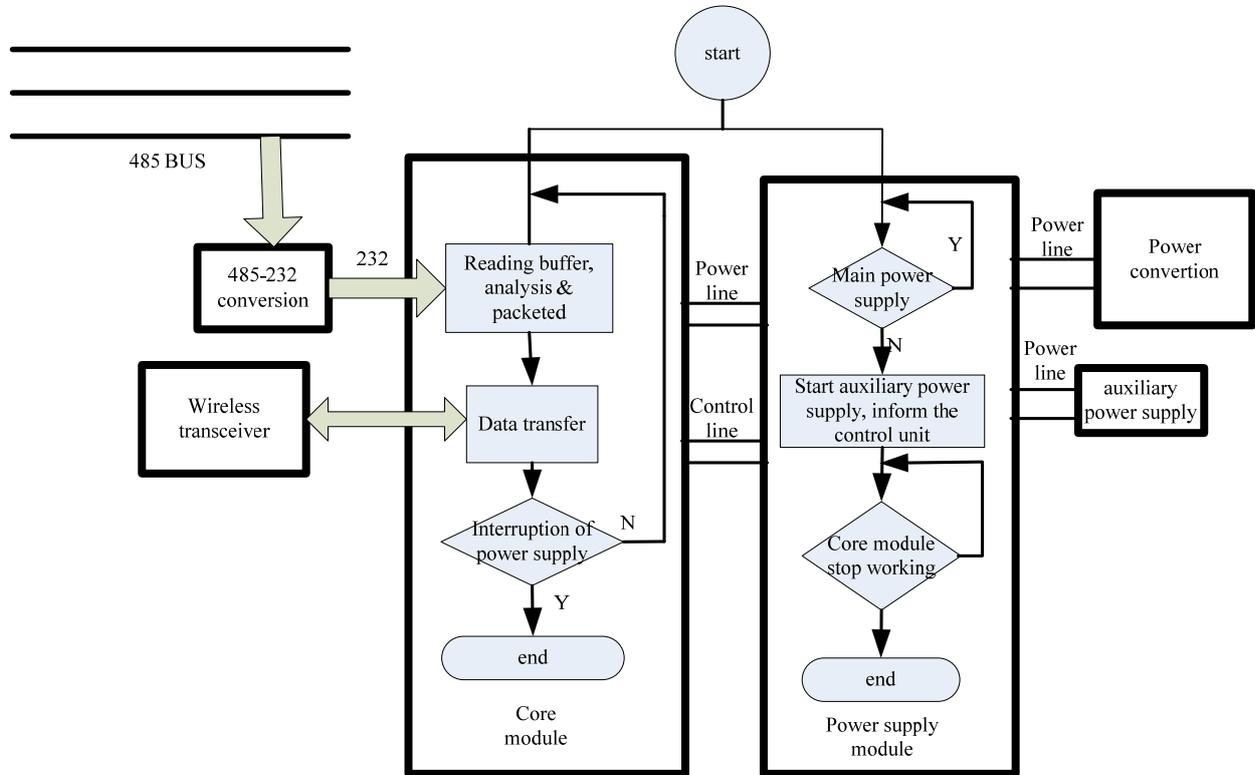

Figure 6. The flow chart of program in the sensor node

b. Sink Node Module Design

The sink node module consists of an ARM processing unit, a CDMA communication module, a 2.4G wireless transceiver module and a power source unit. We use an ARM9 microprocessor embedded ZKOS operating system to achieve data influx, system configuration and remote data forwarding [12-13]. The proprietary embedded operating system ZKOS has a small amount of code, and is less dependent on system hardware features such as stacks, registers, timers and interrupters. Therefore, it can be implemented on different types of mono-chips[12]. Transactions are managed by the sink node module through ZKOS operating system. We select ZTE MC8630 module as CDMA module for remote communication.

ZKOS contains a timer that periodically sends a command through a serial port to the 2.4G wireless transceiver module to transmit door's current status and current temperature and humidity. After the command is sent, ZKOS is kept in the awaiting status. When it gets data, the

data will be packed, processed, and sent to the GRPS/CDMA module after a predefined interval so that the specified host can obtain the data through the China Mobile network.

When the sensor nodes are initialized, they start building the network, and wait for their successful communication with the sink nodes. The sensor nodes collect the door's status information and the environment data, and then send this information to the sink node. After initialization, the CDMA module in the sink node is turned on, and the TCP/IP connection with the remote server is conducted. If the connection fails a couple of times, it will automatically turn off and repeat the above steps. When the connection is fulfilled, the networking maintaining communication is repeated every 5 minutes.

The sink node initializes the node management list, and then waits for the sensor node to upload door's status information and sample data. The sink node also sends this information to the server via CDMA module. The flow chart of program in the sink node is shown in figure 7.
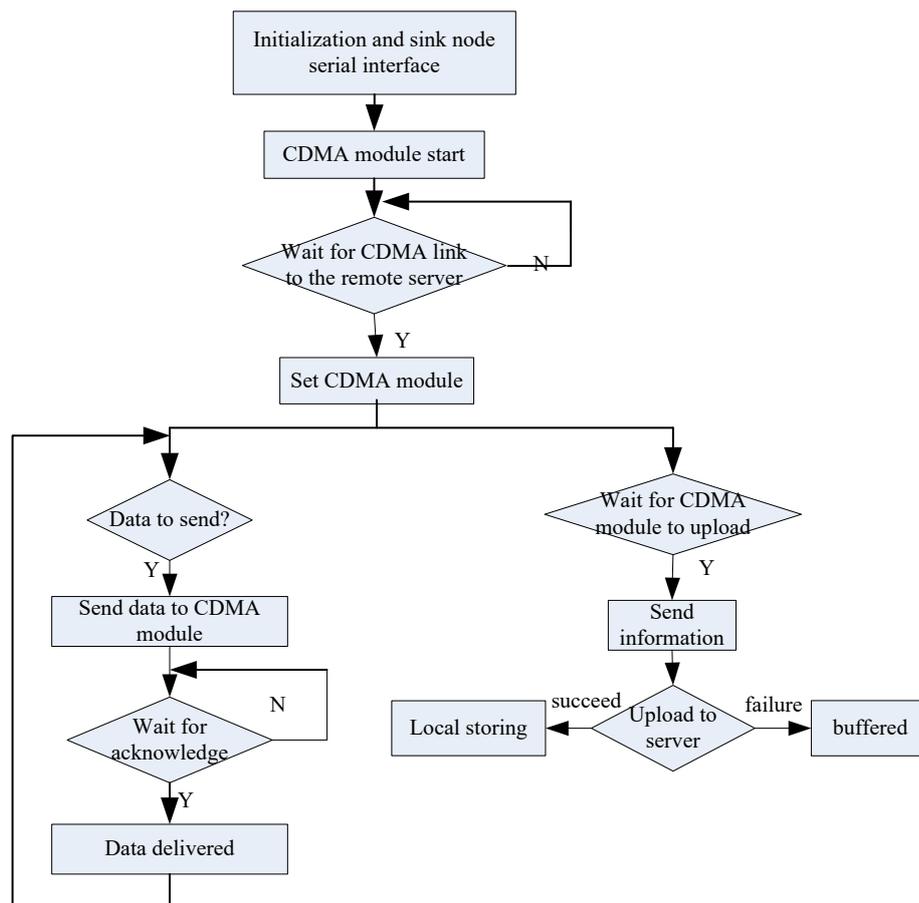
Figure 7. The flow chart of program in the sink node

IV. TRANSMISSION RELIABILITY TASK

a. Message Loss Handling

To avoid losing messages, the system establishes retransmission scheme, including message numbering and message acknowledging [14-15]. All the data messages correspond to a specified response message; when a node is sending messages, it must receive its response message, thus it can be considered as a successful communication; each message has a message numbering; when communication is finished, 1 will be automatically added to the message numbering; when the response is not received within a fixed time interval or an error prompts into the response message, the message will be re-transmitted; if the received message numbering is greater than the previous one, this message will be identified as a valid message processing; if it is determined to be an invalid one, it should send the corresponding response message in order to inform the sending terminal on whether the current communication is normal.

b. Redundant Path

Considering wireless channel, the data-link L_i can be described as 2-state Markov chain, shown in figure 8. G_i and B_i denote successful communication status. Let q_{Gi} and p_{Gi} denote the successful and failure probability respectively, while the previous slot communication is success. Let q_{Bi} and p_{Bi} denote the successful and failure probability respectively, while the previous slot communication is failure. If the interruption is random, then $q_{Gi} = q_{Bi} = q_i$, $p_{Gi} = p_{Bi} = p_i = 1-q_i$. Then we can use Bernoulli model to describe L_i: let s_i denote the slots number distributed to L_i (including retransmission slots), R_i denote the success possibility of one sub-link which can be calculated as

$$R_i(q_i, s_i) = 1 - \prod_{j=1}^{s_i}(1-q_i) \qquad (1)$$

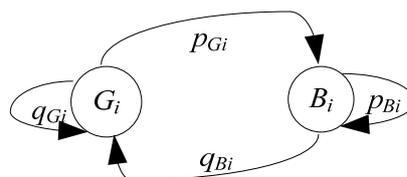where $p_i = 1-q_i < 1$, and R_i increases with d_i.

Figure 8. 2-state Markov chain of data-link L_i

In order to further increase link's reliability, the redundant path is used [16-17]. As we can see from figure 2, whenever one node is disabling, the neighbor node can serve as a relay and forward the data to the destination, shown in figure 9. The node r_1 is the redundant relay node. When the communication between n_0 and n_1 is failure, the sub-link from n0 to r1 and r_1 to n_2 are enabled, which denote as L_{11} and L_{12} respectively. The $n_0{\rightarrow}r_1{\rightarrow}n_2$ path is the redundant path.

(a) redundant route of single hop

(b) redundant route of multi-hop
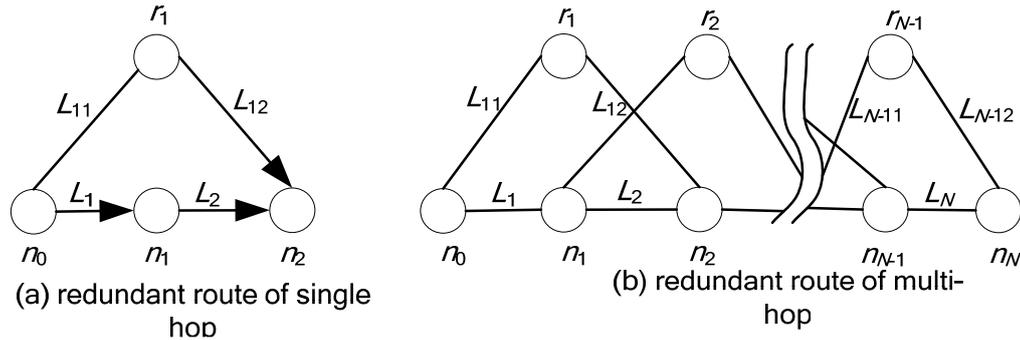
Figure 9. Redundant path

Let L_1 and L_2 denote the sub-links of the main link, the success probability are q_1 and q_2 respectively; L_{11} and L_{12} denote the sub-links of the redundant link, q_{11} and q_{12}. The success probability $R(n_0/n_2)$ of n_0 to n_2 is

$$R(n_0 / n_2) = q_1 q_2 + (1-q_1)q_{11}q_{12} \qquad (2)$$

Obviously $R(n_0/n_2)>q_1q_2$, the redundant path can increase the link reliability. For multi-hop link, let $R(n_i/n_j)$ denote the success probability from node i to node j, then the link reliability can be calculate as

$$R(n_{N-1} / n_N) = R_{L_N}$$
$$R(n_{N-2} / n_N) = R_{L_{N-1}}R(n_{N-1} / n_N) + (1-R_{L_{N-1}})R_{L_{N1}}R_{L_{N2}}$$
$$R(n_{N-3} / n_N) = R_{L_{N-2}}R(n_{N-2} / n_N) + (1-R_{L_{N-2}})R_{L_{(N-2)1}}R_{L_{(N-2)2}}R(n_{N-1} / n_N) \qquad (3)$$
$$...$$
$$R(n_0 / n_N) = R_{L_1}R(n_1 / n_N) + (1-R_{L_1})R_{L_{11}}R_{L_{12}}R(n_2 / n_N)$$

When the communication of n_i is failure, and the retransmission time is decrease to zero, the redundant path $n_i{\rightarrow}r_{i+1}{\rightarrow}n_{i+2}$ is enabled.

4.3 Reliability Model for Our System

Without loss of generality, the multi-hop link consists of $N+1$ nodes and N-hops. Let $N=\{n_0, n_1,..., n_N\}$ denote wireless nodes, n_0 is the source node, n_N is the destination node, L_i is the sub-link between n_{i-1} and n_i, $i \in \{1, 2, ..., N\}$.

As mentioned above, the success probability of L_i can be calculated by (1). For N-hops link, let $S=\{s_0, s_1, ..., s_N\}$ denote the distributed slot, $Q=\{q_0, q_1, ...,q_N\}$ denote each sub-link reliability, then the whole link reliability is described as

$$R(Q,S) = \prod_{i=1}^{N} R_i(q_i, s_i) \tag{4}$$

Assume that the perceived link reliability is constant during one communication period, (4) can be written as

$$R(S) = \prod_{i=1}^{N} R_i(s_i) \tag{5}$$

The reliability optimization problem is to maximize $R(S)$ in (5). Considering about the time constraint, assume the max delay from n_0 to n_N is S slots, and then the optimization problem can be described as

$$\begin{cases} \max_{S} R \\ s.t. \quad \sum_{i=1}^{N} s_i = S \end{cases} \tag{6}$$

To solve this optimization problem, we define the sub-link gain function as $G_i(s_i) = \dfrac{R_i(s_i+1)}{R_i(s_i)}$, which describe the reliability gain of sub-link L_i if it is distributed one more slot. Then we can prove that $G_i(s_i)$ is a decreasing function of s_i.

$$G_i(s_i) = \frac{R_i(s_i+1)}{R_i(s_i)} = \frac{R_i(s_i) + (1-R_i(s_i))R_i(s_i)}{R_i(s_i)} = 2 - R_i(s_i) \tag{7}$$

then

$$G_i(s_i+1) = 2 - \{R_i(s_i) + [1-R_i(s_i)]R_i(s_i)\} = 2 - R_i(s_i) + R^2_i(s_i) \tag{8}$$

$$G_i(s_i+1) - G_i(s_i) = R_i(s_i)[R_i(s_i)-1] < 0 \tag{9}$$

Proposition 1. If each retransmission slot is distributed to the sub-link with max $G_i(s_i)$, then the link reliability $R(S)$ is maximized.

Proof: Suppose the allowed max delay is S slots, then the available re-distributed slots $m=S-N$. Considering that Q is constant during one communication period, from (2) and the definition of $G_i(s_i)$, the link reliability $R(S)$ can be described as

$$R(S) = \prod_{i=1}^{N} R_i(1) \prod_{i=1}^{N} \prod_{j=1}^{s_i-1} R_i(1) G_i(j) \qquad (10)$$

i.e. $R(S) = f(G_i(j))$

Each sub-link gain function has mN possible values, and m is the available retransmission slots can be distributed to $G_i(j)$ with number m. During the distribution of retransmission slots, for every j increases from 1 to s_i, $G_i(s_i)$ is decreasing with s_i, therefore $G_i(j)$ is decreasing with j. Then, let $i = \arg \max_{i=1,2,...,N} G_i(j)$, if m retransmission slots are distributed to those sub-links with m most significant $G_i(s_i)$ values, the link reliability $R(S)$ is maximized.

V. EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

The use of the proposed system has been adapted to monitor door's status and interior environment of subway cars. In order to valid the transmission reliability of the proposed TDMA scheme outperforms the traditional TDMA; we do many experiments in Nanjing #1 Metro under our testing platform. We evaluate the traditional wireless TDMA transmission and the proposed TDMA transmission with retransmission slots distributed and redundant paths. The experimental parameters are: the initial transmission power of each node is set to 0dBm; the receiving threshold is set to -85dBm. The gains of transmitting and receiving antenna are 5dB. The frequency is 2.4GHz; communication distance depends on the actual metro car. On the same side in the same car, the space between two doors is 5m; the space between the neighbor cars is 3m. The data rate is 13.02KB/s. The number of sub-link N is 4. The maximum retransmission time is 3. The link attenuation model is calculated by

$$L(d) = L(d_0) + 20 * \lg(\frac{d}{d_0}) + \sum_{j=1}^{J} N_{wi} L_{wj} + \sum_{i=1}^{I} N_{Fi} L_{Fi} \qquad (11)$$

Before experimenting, the nodes in one car are numbered from n0 to n8 and s1 to s2, as shown in figure 4. Under different service status of Nanjing #1 Metro: idle, normal and crowded, the transmitting rate and packet loss rate from n0, n1, n2 and n3 to s1 are tested respectively. When

the testing packet size is set to 32Bytes, the results under different service status of Nanjing #1 Metro are shown in Table 2.

Table 2: The experimental results

Service status	Source → destination	Transmission rate(KBs/s)	Traditional TDMA		Proposed TDMA	
			Receiving rate(KBs/s)	Packet loss rate(%)	Receiving rate(KBs/s)	Packet loss rate(%)
idle	$n_0 \rightarrow s_1$	13.02	12.80	1.69	12.86	1.23
	$n_1 \rightarrow s_1$	13.02	12.87	1.15	12.90	0.92
	$n_2 \rightarrow s_1$	13.02	12.90	0.92	12.95	0.51
	$n_3 \rightarrow s_1$	13.02	12.92	0.77	13.01	0.11
normal	$n_0 \rightarrow s_1$	13.02	12.58	3.36	12.64	2.79
	$n_1 \rightarrow s_1$	13.02	12.74	2.12	12.80	1.49
	$n_2 \rightarrow s_1$	13.02	12.84	1.36	12.85	0.61
	$n_3 \rightarrow s_1$	13.02	12.87	1.15	12.91	0.44
crowded	$n_0 \rightarrow s_1$	13.02	12.21	6.52	12.29	4.61
	$n_1 \rightarrow s_1$	13.02	12.51	4.92	12.62	3.07
	$n_2 \rightarrow s_1$	13.02	12.64	2.92	12.74	2.15
	$n_3 \rightarrow s_1$	13.02	12.72	2.30	12.81	1.61

The curves of packet loss rate are plotted in figure 10 for clearly comparison. It can be seen that the packet loss is low when propagation distance is short than 10m. The packet loss rate will increase when the propagation distance increases. When the passenger number increases, the packet loss rate will increase. Furthermore, we can see from the curves, our proposed scheme outperforms the traditional transmission scheme in 0.6%-1.9% packet loss rate less.
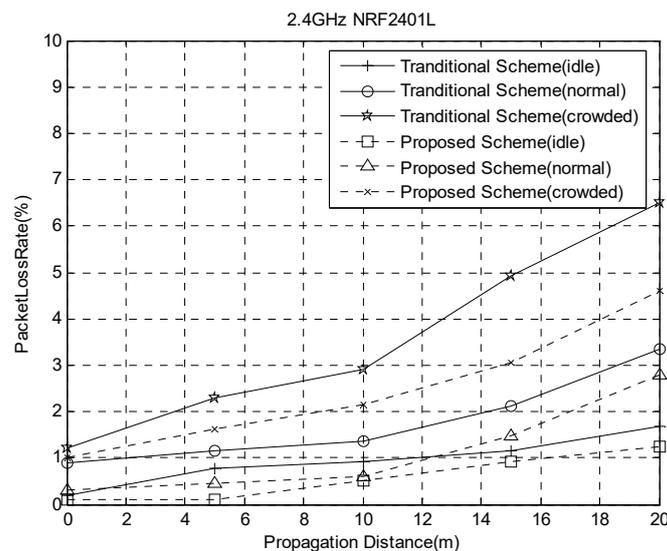

Figure 10. Curves of packet loss rate under different service status

VI. CONCLUSIONS

This paper presented a remote monitoring system for urban rail vehicle to decrease the maintenance costs and improve system running reliability. The system is developed on an independently-developed wireless sensor network platform, and it is a successful combination of wireless sensor network technology and the mobile communication technology. This system is low-cost, scalable and reliable with good processing capability. Especially, the device has passed the EMC testing and vibration impact test, so it has no influence on the primary system.

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