A Multi-interface WSNs Based Hazardous Materials Transportation Monitoring System

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Abstract

The increased number of hazardous materials transportation accidents has caused a series of environmental and health problems across the world. In this paper, a hazardous materials transportation monitoring system (HMTM) is designed, implemented, and tested using multi-interface Wireless Sensor Networks (WSNs). In order to meet various state tanker transportation information collection, we designed a multi-interface sensor node. According to energy consumption and response time during clustering of Wireless Sensor Networks LEACH (Low Energy Adaptive Clustering Hierarchy) routing protocol, we proposed STATIC-LEACH routing protocol based on static clustering, it can effectively reduce energy consumption of the wireless sensor nodes and reduce network latency of cluster. The project is targeting a deployment on the vehicles. Ambient situation of the vehicles and also the state of the goods is monitored and is used to determine the safety status of the transportation.

Keywords: Wireless Sensor Networks, Hazardous Materials, Routing Method, Monitoring System

1. Introduction

The transportation of hazardous materials has the potential to cause serious environmental and health problems in the event of an accident. In addition, the delayed and unsuitable treatments will cause hazardous materials spread out in large areas, which will greatly damage the environmental system. These serious consequences necessitate effective transportation monitoring systems to provide timely and accurate danger warnings so that anomalies can be detected and corrected rapidly to humans and the environment.

Nowadays, several hazardous materials transportation monitoring systems have been deployed to serve different regions and countries. These systems include the standardized hazardous goods transport alerting field trail (SHAFT) system[1], monitoring and intervention for the transportation of dangerous goods (MITRA) system[2], tanker truck monitoring system[3], and any other systems as shown in[4][5]. These existing systems, however, face challenges in providing accurate accidents forecasting and timely warnings because they lack real-time observation capabilities from the goods, containers and vehicles, such as relative speed, humidity, surface temperature, and leak status etc. More specifically, the currently operational monitor systems, such as in [3,4], heavily rely on a single sensor to collect and transmit the special status like geographic information. Such a strategy is not feasible for hazardous materials transportation pre-warnings, which need more information about whole transportation process and participators. In addition, due to the high deployment complexity of wired solutions, the density of existing monitoring nodes is not sufficient to yield an acceptable coverage for accurately detecting the anomalies.

To address these challenges, hazardous materials transportation monitoring is required using low-cost, easy-deployment and long term monitoring devices. To this end, wireless sensor networks provide a promising solution to realize real-time transportation monitoring, multi-status coverage, on-site data processing, and rapid information delivery [6]. Specifically, WSNs can be easily deployed so that sensors are quickly and efficiently placed in the target area. After a wireless sensor network is deployed, the networked sensors can collaboratively collect real-time information such as pressure, temperature, humidity, wind speed, and goods status. The gathered information is then preprocessed, aggregated/compressed, and transmitted to a remote control center, where sophisticated forecasting models can utilize this information to initiate corresponding pre-warnings.

Despite the promising aspects of WSNs in hazardous materials transportation monitoring, there are still many open research issues remaining to be resolved for practical implementation. One of the major
issues is how to effectively deploy WSNs under the impact of transportation system. More specifically, it has been reported that many factors will cause the accidents during transportation [7], which implies the function of sensor nodes will be multiplicity and their placement is also a problem. In addition, due to the environment, the sensor nodes must be reliable and long term working ones.

Broadly, our goal is to develop a generic framework for monitoring hazardous materials transportation with wireless networks. In this section we discuss the problems of our monitoring system and some of the challenges in achieving our goal. The rest of this paper is organized as follows. Section 2 introduces the framework and implementation of the monitoring system. In Section 3, we describe the important issues of the network, then we give out the performance study and data visualization results in section 4. Finally, Section 5 concludes this paper.

2. Monitoring System

The proposed wireless sensor network for HMTM integrated into a broader multilayer monitoring system is illustrated in Figure 1. The HMTM system spans a network comprised of individual state monitoring systems that connect through the Internet to a server layer. The top layer, centered on a server, is built to service for the terminal users who care about the goods’ information. Each vehicle equips a number of sensor nodes that are strategically placed on the key points. The primary functions of these sensor nodes are to sample vital signs and transfer the relevant data to an onboard sink node through wireless.

The monitoring and alarm process mainly can be divided into three stages: data collection stage; data processing stage; decision-making and alarm stage. Our conceptual framework and data flow are shown as follows:

**Figure 1. Data Flow of the System**

2.1 Multi-interface WSNs monitoring nodes hardware implementation.

We divided the monitoring nodes into three kinds: Environmental nodes, Vehicle nodes and goods nodes.

**Environmental nodes:** for environmental monitoring, equipped with simple analog temperature, relative humidity, and light sensors.

**Vehicle status sensing nodes:** this kind of nodes sensing the attitude, pressure, location of the vehicle, equipped with acceleration MEMS sensor, GPS device, and pressure sensor.

**Goods status sensing nodes:** this kind of nodes sensing the leakage status, surface temperature of the goods.

The sensor nodes are composed of the node platform with an independent sensor. Multi-interface wireless sensor nodes use Atmega1281 microprocessor chip and AT86RF230 RF chip to form a small
wireless embedded measurement system and the nodes running the Tiny Operating System (TinyOS)[8,9].

Sensor interface in the node is responsible for connecting various sensors, and transfer signals to the processor. Processor module is responsible for the operation of the network nodes, to handle the data collected by itself and data sent by other nodes for secure communication protocol. RF modules are responsible for communicating with other nodes to exchange information and data. Power supply module is responsible for providing power nodes to work, in order to extend the life cycle of nodes the Power module typically use lithium batteries.

In order to meet various state tanker transportation information collection, In this paper, the sensor interface integrated into a variety of wireless nodes. This includes temperature sensor DS18B20 IO interface, ISL29001 light sensor IIC interface, CS-2TAS-04 dual-axis inclinometer RS232 interface, 8-channel ADC interface of combustible gas concentration sensor (or 4 differential ADC interface) and JTAG interface for download the program to debug. Wireless sensor nodes to connect different sensors that can capture the different tanker state information.

2.2 WSNs' software implementation.

TinyOS kernel implements the activities of sensing, timing, communication, data preprocessing and power management. In central server, it provides the service of database, remote management, monitoring software and warnings.

(a) Cluster Head Node Flow Chart
TinyOS operating system and its applications are developed by relatively few NesC code languages. Wireless sensor node software is the role of regular collection of data-aware objects, according to TinyOS-specific routing protocol, sent to the ROOT node. As the monitoring system for each node of the program code will be slightly different, following the combustible gas concentration sensor node as an example to introduce the software process as shown in Figure 2.

In order to reduce the energy consumption of wireless sensor nodes, wireless nodes switch between in active mode and sleep mode, and most of the time in sleep mode. Cluster head node is responsible for receiving and processing the child nodes of the sensor data concurrent to the ROOT node, the other, the cluster head node also serves as the task of collecting sensor data; child node within the cluster is responsible for periodically collecting sensor data, concurrent sent to cluster head node. Wireless sensor nodes based on the sensor data acquisition cycle to modify the data collected frequency, thereby increasing the number of critical data collection to ensure the timeliness of critical data.

2.3 On vehicle deployment.

As shown in Figure 3, we deployed 10 nodes plus the sink node on a tank truck. Sink is placed at the cab, the only spot guaranteeing access to the external GPRS network. The sensor position is chosen to detect early symptoms of deterioration of the transportation.

Firstly, we take the finite element analysis method of fluid-solid coupling simulation to obtain the maximum point of transient stress under all the working condition of truck to monitor structural changing information. Secondly, at the theoretical gravity center, we arrange the gyroscope to monitor the vehicle attitude information. Thirdly, the oil-in and oil-out are regarded as the mainly leakage...
monitoring points. Finally, temperature sensors placed on the surface of the container for monitoring
the temperature anomaly.

![Sensors Layout](image)

**Figure 3. Sensors Layout**

3. Important network issues

3.1. Routing strategy.

The first significant question which arises here is what is the expected stability of the routing tree, that is how often this tree changes. Routing protocol is one of the key technologies of Wireless sensor
network, responsible for sending the collection data packets along the optimal path from the source
node to destination node. Common routing protocols are: Flooding protocol, SPIN protocol, LEACH
protocol, TEEN protocol, PEGASIS protocol, Random Walking protocol and so on[10.11]. LEACH
protocol is the first level routing protocols of data aggregation, and has self-organizing, adaptive and
automatic clustering features. Other clustering routing protocols (such TEEN, PEGASIS, etc.) are
mostly based on LEACH protocol.

In LEACH protocol [11], the network run as a round way, each round is divided into the
construction phase and steady-state phase. During the construction phase, the node is divided into
several clusters, and play as a cluster head node according to the energy level of a cyclical rotation, so
that each node's energy consumption is uniform; in the steady-state phase, the main task is data
transmission, data from non-cluster head node sent to the cluster head, then sent to the rood root after
handling. However, LEACH protocol cannot guarantee the number and location of the cluster head
nodes in the process of clustering, the number of cluster head nodes deviate from the expectation and
the position focus on one side of the network region. So that a large number of cluster child nodes and
head nodes consume more energy and bring greater latency response because of long distance

Against the shortages of LEACH protocol clustering, including complexity algorithm, large energy
consumption and long delay, combine the diverse types and relatively fixed position of tanker’s sensor
nodes, and different type sensor using different sampling frequencies and packet sizes, this paper
presents a STATIC-LEACH routing protocols based on the wireless node static clustered. The system
uses different type sensors. STATIC-LEACH protocol discards the complex automatically clustering
operations of protocol LEACH, the protocol assigns the same type of sensors to the same static cluster,
the entire network forms the tree topology and the cluster is the basic unit, shown in Figure 5.

There is no communicate between two different clusters, the cluster child nodes change information
and data packets to ROOT bode through cluster head nodes.

For STATIC-LEACH protocol, the first step is static clustering, nodes divided into several static
clusters according to space arrangement and types of sensors, each cluster initializes a cluster head
node; and then periodically run as a basic unit of round, each round including the construction phase of
steady-state phase, and construction phase including the request phase, the selection phase and the
release phase, steady-state phase is same with of LEACH protocol, shown in Figure 4.
Operations of STATIC-LEACH protocol at all stages of the construction phase are described below:

1. The request phase: When nodes first enter the network or the steady-state phase is completed, the cluster head node releases request signal to cluster child nodes, requires to send their energy information, shows it is a new round.

2. The selection phase: the child nodes sent their residual energy and node ID to the cluster head node after AD converter; cluster head node selects the node with the maximum energy value as the cluster head of next round.

3. The release phase: The old cluster head node releases the node ID of new cluster head, show it enters the steady-state phase.

There are several characteristics of network routing algorithm based on STATIC-LEACH protocol:

1. Because off cluster-based hierarchical routing protocol, it reduces conflict between cluster nodes, improves network data security.

2. The cluster head node is responsible for integration the data of cluster child nodes sent to the ROOT node, it effectively alleviates the data congestion problem of ROOT node;

3. Selecting cluster head node as round polling mode, to ensure that each node has a uniform energy distribution, and extend the life of wireless sensor networks.

4. Against to the construction phase of LEACH protocol, static clustering method reduces energy costs and response delay because of the instability caused by the clustering.

3.2. Time synchronization.

Since the data within a vehicle are correlated, we need time synchronization across the nodes, to time-align the data. The accuracy of time synchronization required is determined by the time period of oscillation above, which is minimum for the highest frequency component present in that data i.e. 20 Hz. For this frequency, the time period is 50ms, so a synchronization accuracy of about 5ms (1/10 of the time period) should be sufficient. Here we use RBS method[12-16] for network synchronization.
4. Data visualization and performance study

4.1. Data visualization.

Effective access to the information gathered by the system is crucial in supporting pre-warnings analysis. To this end, we provide a custom graphical user interface, shown in Figure 6, 7. The GUI shows the current network topology and serves as a control center. Moreover, it displays the data collected, which are also persistently stored in a database.

Figure 6. Data visualization      Figure 7. Three-Dimensional Model Vehicle

4.2. Performance study.

To assess the effectiveness of our system, we report on two key performance issues:

**Reliable and timing delivery:**

Nodes in the hazardous materials transportation monitoring system, are relatively stationary, we assess the performance of WSN by modifying some parameters about the network, mainly relying on the Node Number and Packet Size. With a period of simulation, we do the comprehensive evaluation after taking an average of several experimental data. The result of evaluation is shown in Table 1.

Table 1. The evaluation for the performance of WSN

<table>
<thead>
<tr>
<th>Network</th>
<th>Frequency (MHz)</th>
<th>Node Number</th>
<th>Packet Size(Byte)</th>
<th>Time Delay(ms)</th>
<th>Packet Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network 1</td>
<td>2450</td>
<td>8</td>
<td>1024</td>
<td>0.012150</td>
<td>0.014680</td>
</tr>
<tr>
<td>Network 2</td>
<td>2450</td>
<td>12</td>
<td>1024</td>
<td>0.013486</td>
<td>0.066186</td>
</tr>
<tr>
<td>Network 3</td>
<td>2450</td>
<td>8</td>
<td>512</td>
<td>0.008564</td>
<td>0.002862</td>
</tr>
<tr>
<td>Network 4</td>
<td>2450</td>
<td>12</td>
<td>512</td>
<td>0.009483</td>
<td>0.002895</td>
</tr>
</tbody>
</table>

RBS algorithm does not exceed the max synchronization error of 50us[12], and the max clock drift of our platform is 20ppm, that is, one minute drift 1.2ms(s). To minimal the power consumption we synchronize the every minute, the maximum time the system error is: 50us+1*1.2ms=1.25ms. Still meet the synchronization accuracy and also achieve a balance of precision and power.

**Energy consumption and lifetime:**

Since the wireless sensor networks need to execute data collection in unsupervised environment, within limited energy, the power consumption of wireless sensor networks is of great significance. According to the report of Deborah Estrin for the Mobicom conference in 2002 [10], the majority energy consumption of wireless sensor node is the communication module. Therefore, we had done some experiments by using low-power RF chip AT86RF230, to measure the energy consumption in different states, which are composed of four conditions: sleep, idle, receiving and sending.

By adding a module for energy measurement to the TOSSIM simulator, provided by the University of California, we contributed a Power-TOSSIM simulator to monitor the power consumption of sensor nodes. Also, for the node powered by 3.3v Li-Battery, the energy simulation is shown in Figure 8.
In Fig 8, the energy consumption of sleep state is very small and the current consumption is about 7\mu A, which is half to MICA’s. The energy consumption in idle state, less than 15mA, is nearly equal to that in receiving state. And the current in transmission is less than 20mA. So the lower current consumption leads to a longer life cycle for wireless sensor networks, satisfying the low power requirements.

Here focuses on the power consumption of sensor nodes. Due to the time synchronization interval period of 1 minutes, take one minute cycle as power analysis, according to the maximum operating current of Atmeg 1281 CPU, in 1 minute, the overall power consumption is: \[(0.024*14mA+0.976*7.5\mu A)+(0.024*16.5mA+0.976*20nA)]*62 ( mAs ) = 45.84 ( mAs ). In an hour, the overall power consumption is 45.84mAs * 60 = 2750.345mAs = 0.764mAh When using the battery capacity of 2500mAh, the system will work continuously 136 days.

**Performance of STATIC-LEACH Routing:**

Due to the different communication protocols in network self-organizing, data transmission and forwarding, great changes took place in the work status, the response time and energy consumption [11].

Using NS2 (Network Simulator Version 2) to the STATIC-LEACH routing protocol simulation, the analysis has been done for the delay time from cluster selection and the energy consumption in different routing protocols, e.g. the LEACH protocol. In a range of 100 * 100m 100 nodes were evenly deployed, the results are shown in Fig. 9 and Fig. 10, and the time unit in Fig.9 is the data transmission time for one byte.

The simulation results, in Fig.9 and Fig.10, have proved the superiority of the STATIC-LEACH routing protocol in terms of clusters, the average delay time and the energy consumption, compared with the LEACH protocol.

**7. Conclusion**
This paper presents a framework and implementation of HMTM, a wireless sensor network based system for long term multi-status monitoring of road transportation. The paradigm we have followed is that of application specific design.

In the design of HMTM, we identify the requisite set of functionalities from the application’s perspective, and we propose mechanisms to achieve these. Our novel contributions are three aspects: (1) Static LEACH routing method, (2) a plan for onboard sensors placement, and (3) long term working and low power consumption monitoring system: with the battery lasting for over 3 months.

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9. References