The Design and Evaluation of a Wireless Sensor Network for Mine Safety Monitoring

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***Abstract* – This paper describes a wireless sensor network for mine safety monitoring. Based on the characteristics of underground mine gallery and the requirements for mine safety monitoring, we proposed a distributed heterogeneous hierarchical mine safety monitoring prototype system, namely HHMSM. This system is capable of monitoring methane concentration, and locating miner. We proposed a novel overhearing-based adaptive data collecting scheme which exploits the redundancy and correlation of the sampling readings in both time and space to reduce traffic and control overhead with a well-bounded offset error for large-scale sensor networks. This mechanism is easy to implement and low-cost compared to other more theoretically based mechanisms such as Kalman filter. Experimental results show that HHMSM achieves better performance on flexibility, correctness, coverage, and lifetime compared with other existing wireless mine safety monitoring systems.**

I. Introduction

Underground mining is inherently dangerous and its safety monitoring is a complex, interdisciplinary research area which spans several decades. In China, almost half of the local mine fatalities are caused by methane explosions [1]. Therefore, the essential function of mine safety monitoring system is to monitor and locate the methane leakage timely. Furthermore it should meet the requirements of low-latency, high data fidelity, fully and reliable coverage on the underground mining tunnels.

The current underground mine safety monitoring systems are of two kinds: wired systems and wireless ones. The wired safety monitoring systems have some inherent problems (e.g. lack of monitoring in the most hazard working area). Wireless sensor networks have the potential to effectively handle these problems [2]. In previous work, Lauri et al proposed a wireless solution which provides wireless and real-time connection with full coverage from underground mine to the enterprise information system [3]. However this system requires high bandwidth and a great amount of power consumption.

The goal of this work is to develop a large scale, energy-saving, low cost, reusable, and effective wireless sensor network to meet the practical requirements for the mine safety monitoring. It is capable of monitoring the change of methane concentration, and locating miners. To achieve this challenging goal we started by studying the existing underground mine safety monitoring systems and identifying their requirements and constraints. We then set up a hierarchical prototype system for underground mine safety monitoring, namely HHMSM.

The major contributions in this paper consist of the following aspects:

- We developed a heterogeneous hierarchical mine safety monitoring network prototype which is divided into three tiers to achieve system flexibility and coverage.
- We proposed a novel overhearing-based adaptive data collecting scheme which exploits the traits of the lower-tier sensor network--redundancy and correlation of the sampling readings in both time and space to select local sampling and transmission rules for the sensor nodes so that the performance of the system is optimized, including a better correctness and lifetime.
- We implemented the prototype system and conducted experiments with it.

The remainder of the paper is organized as follows: Section II discusses the related works in sensor network applications and underground mine safety monitoring systems. In Section III, we describe the overall architecture and design contributions of HHMSM system, and provide a high-level description of its functionality. Section IV describes the proposed efficient data and transmission scheme which drives our system's requirements and design. Then we present the experiment results and evaluate the performance of HHMSM in Section V. Finally, Section VI concludes the paper.

II. Related Works

Numerous sensor network applications have been proposed for the areas like habitat monitoring, structure monitoring [4, 5] and so on.

As to the mine safety monitoring system, many current underground systems are deployed by means of wireless communication technology. Ndoh et al. proposed a wireless propagation model [2] to validate that the realization of the wideband wireless LAN in a complex and diffracting rough mine is possible. Some researchers have implemented networks and topologies based on wireless LAN for underground mine communications [3]. Srinivasan et al. proposed a hybrid wireless network topologies along with heterogeneous communication protocols to support high and low bandwidth applications [6]. However, the wired basestations are only deployed in the relatively fixed mine corridors, and the wireless devices in the profile of mine working need high transmission power to communicate with basestations. So the key disadvantage of these systems is the high power consumption and cost of the wireless devices.

Recently, many researchers have investigated how to make the continuous monitoring in sensor networks more energy-efficient by exploiting the correlation in both time and space of the readings. Chu et al. proposed the *Ken* [7] framework which uses a joint probability model to reduce the communication overhead. The *Ken* exploits spatial correlations across nodes to improve compression of the data communicated to the basestation without imposing undue communication burdens to maintain the models. However temporal correlation cannot be fully exploited in the *Ken.* By monitoring a combination of individual values and relation- ships between neighboring values, CONCH [8] exploits spatio-temporal correlations in data much more effectively. However, most of these mechanisms cannot guarantee a bounded error exponent while aiming at minimizing the total communication consumption. One of our contributions is to fully exploit the potential of spatio-temporal correlation in minimizing the energy cost with a well-bounded error exponent.

III. Mine Safety Monitoring Using Sensor Networks

In this section, we discuss the design of HHMSM, the underground mine safety monitoring system, which is motivated by the requirements of a typical underground mine surveillance application.

A. Hardware

To meet the design requirements of nodes in hierarchical architecture, we used the EASINET series hardware developed in house [9] to build HHMSM prototype system. The wired basestation, which is composed of the communication board EZ210 and the gateway board EZ511, access the CAN field bus via a CAN adaptive module. The EASINET mote includes EZ210 which is compatible with TinyOS and a sensor board EZ310 which supports analog gas sensor (LXK-3). The mote uses an 8-bit micro-processor running at 8MHz, and a data rate of 38.4 Kbps operating at 433MHz radio.

B. System Architecture

We now describe the system architecture, functionality of individual components and how they operate together. The main tunnels in the underground mine are kilometers long and well equipped with wired or fiber cables. Connected with main tunnel are small branch tunnels called drilling tunnels. HHMSM is designed to be implemented at the profile of mine working and to be integrated with main cables. The heterogeneous tiered architecture is depicted in Fig.1.

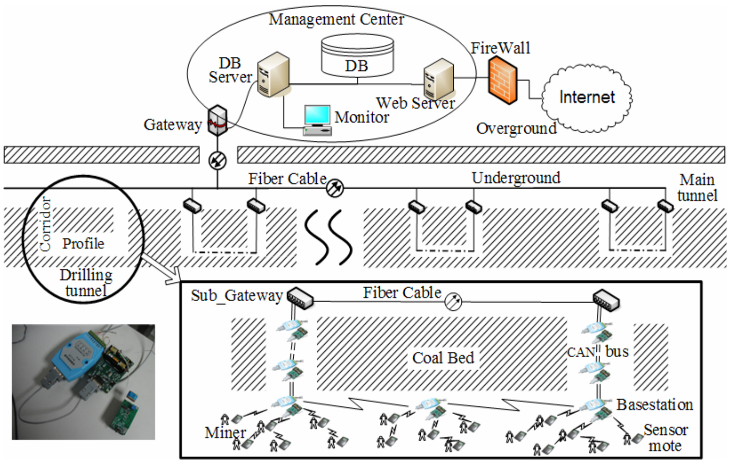


Fig. 1. HHMSM system architecture and hardware platform

The HHMSM hierarchical architecture consists of three layers. The lower tier is a network of mote-class wireless sensor nodes that can be densely deployed. This tier has the lowest computing capability and significant limitations on radio bandwidth and battery capacity. Each mote, which is equipped with a sensor board that has methane and acoustic sensors on it, may be attached to a miner, and therefore is mobile in nature. The middle tier forms the backbone of the entire sensor network. As shown in Fig.1, it is composed of individual basestations which have significantly more communication and power capacity than those motes in the lower tier. These basestations which are deployed in each drilling tunnel offload the burden of communications from the lower tier. To guarantee the reliability and reusability of this system, the basestations at the mine corridor are linked by a CAN field bus while the basestations at the profile of mine working communicate with each other by radio. The upper tier is the sensor network's interface to the operator. The console of the upper tier can generate external alarms to indicate methane leakage, and show the locations of all the miners.

The profiles of mine working are harsh wireless environments where connectivity varies with time. Miners with sensor motes move around while working. Engineering a basestation placement to guarantee each sensor node within one hop of a base is difficult and costly. So different from the existing solutions, we propose to adopt multi-hop wireless sensor networks for communications at the middle tier. This structure can accommodate the mobility of miners and the relocation of the profile of mine working efficiently. If a sensor node finds it can not communicate with any other node, it will enhance the transmission power temporarily in order to deliver data to basestation successfully.

C. Functionality design and implementation

C.1 Data sampling and collection

The key function of the HHMSM system is to collect the data of methane concentration. The motes equipped with gas sensor sample the methane concentration in the underground mine periodically and transmit them to the monitoring server. There are a large number of motes in the system and they are randomly distributed in the mine, which will cause large redundant traffic. This traffic may exploit most of the limited bandwidth, which will interrupt other applications (e.g. miner localization). In order to solve this problem, we proposed some measures to reduce the unnecessary traffic at a minimized cost. Specifically, we proposed a distributed overhearing-based adaptive data collecting scheme described in section IV to reduce traffic significantly.

C.2 Miner localization

In the underground mine, the basestations are deployed linearly along the drilling tunnel. Based on this characteristic, we proposed a lightweight scheme that locates motes based on the basestation it is close to. A mote sends its location information to the miner localization server on the ground periodically. The information sent to the server consists of the miner's identification, hops to the basestation(s) it is associated with and radio signal intensity of received packet, which allow the server to learn relatively fine-grained location of the miner. As the locations of the basestation nodes are known to the server, the location of the mote can be pinpointed.

TABLE I
NOTATIONS

Notation	Description
C(x, t)	The function of concentration diffusion process
$\tilde{C}(x, t+\tau)$	The observation of *C(x, t)* at the server
X	The distance of the diffusion process in *C(x, t)*
t	The time of the diffusion process in *C(x, t)*
D	The diffusion coefficient
τ	The duration of sampling result delivering
Δ	The offset error of sampling result at the server
$\triangle t$	The sampling interval
Φ	The maximal acceptable offset error

IV. OVERHEARING-BASED ADAPTIVE DATA COLLECTING SCHEME

In the underground mine, the methane diffusion process follows Fick's second law, as shown in equation 1. From that law we can see that there exists a strong correlation in both time and space in terms of the concentration of methane, and the correlation changes dynamically along with the move of sensor nodes and the changing speed of gas concentration. Based on this characteristic, we proposed an overhearing-based data collecting scheme via interpolation method. The gist of the scheme is to select and activate sensors to satisfy the desired detection performance with the minimum amount of sensor data since the number of activated sensors is directly related to the energy consumption of the entire network. The scheme includes two parts: a lightweight overhearing-based data collecting algorithm which exploits data redundancy and correlation in space, and an adaptive data sampling rate adjusting mechanism that exploits correlation in time.

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} \qquad (1)$$

A. Lightweight overhearing-based data collecting algorithm

In our algorithm, the region of the entire sensor network, which can be treated as roughly linear along the profile of mine working, is partitioned into several overlapping zones as shown in Fig. 2. A zone consists of a zone leader and all its direct neighbors. The sensor node whose sampling data value is the highest among its direct neighbors is the zone leader, which is the center of the zone. With the change of sampling values of each sensor, the boundary of a zone and its leader change dynamically. Sensor nodes which are not a leader can be within multiple overlapping zones. In our algorithm, a sensor does not transmit its sampled data unless the value of its sample is higher than any of its direct neighbor's data it overheard during the last period, i.e. a sensor will become the leader automatically if its sampled value is higher than the values it overheard from its neighbors. Unlike general cluster formation and maintenance algorithms [10], our algorithm, in which each sensor node decide whether to be a zone leader just by overhearing the messages derived from its direct neighbors, does not incur any additional traffic and control overhead. This overhearing technique exploits correlation in space in a very simple and efficient way.

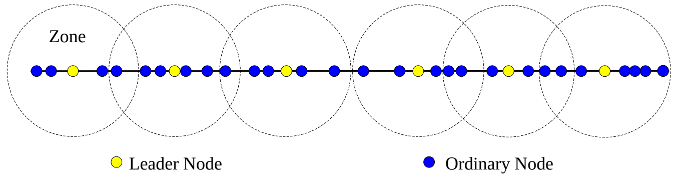


Fig. 2. An overhearing-based network for HHMSM

B. Adaptive data sampling rate adjusting machanism

As the network being partitioned into zones, the traffic in a given area is a function of the updating frequency of zone, which equals to the sampling interval of the nodes in that zone. Therefore, we proposed a distributed algorithm which employs interpolation method and spatio-temporal correlation of methane concentration initiated by Fick's second law to obtain an adaptive data sampling rate adjusting strategy. In this algorithm, each node can calculate the optimized sampling interval periodically based on the local information to minimize the traffic throughout the network within an acceptable offset error. First, we define some notations that are used in the formulation as shown in TABLE 1.

In methane monitoring, the main cause of server observation's offset error is the duration of sampling result delivering τ. If a node sends the sampling reading at time t, the server will receive that observation at time $t+\tau$. To reduce the offset error, we add an estimate value to the observation based on the latest observations:

$$\tilde{C}(t+\tau) = C(t) + \frac{C(t) - C(t-\Delta t)}{\Delta t}\cdot\tau \qquad (2)$$

Then, the observation offset error δ can be calculated through Lagrange interpolating polynomial as follows:

$$\begin{aligned}\delta &= \left|C(t+\tau) - \tilde{C}(t+\tau)\right| \\ &= \left|\frac{\tau^2}{2}C_t''(\xi_1) - \frac{\Delta t\cdot\tau}{2}C_t''(\xi_2)\right| \\ &\le \frac{\tau}{2}C_t''(\xi_3)\cdot(\Delta t+\tau)\end{aligned} \qquad (3)$$

where $\xi_1 \subset (t-\Delta t, t), \xi_2 \subset (t,\tau), \xi_3 \subset (\xi_1, \xi_2)$.

By using equation 3, we can extend the offset error constraint to the following:

$$\begin{aligned}&\delta \le \frac{\tau}{2}C_t''(\xi_3)\cdot(\Delta t+\tau) \le \varphi \\ &\Rightarrow \Delta t \le \frac{2\varphi}{\tau\cdot C_t''(\xi_3)} - \tau\end{aligned} \qquad (4)$$

and the optimized sampling interval is:

$$\Delta t = \frac{2\varphi}{\tau\cdot C_t''(\xi_3)} - \tau \qquad (5)$$

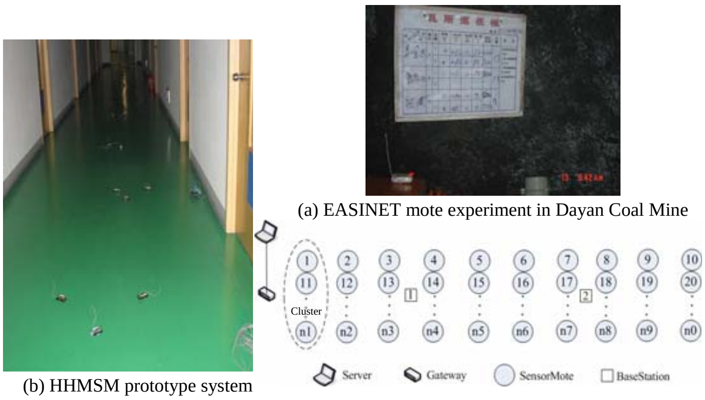
here, $C_t''(\xi_3)$ is second-order partial derivative of concentration diffusion function with respect to time t. From the equation 1 we can induce that each node can calculate the approximate value of $C_t''(\xi_3)$ periodically just based on the overheard sampling results sent by its adjacent neighbor nodes, i.e. calculate the second-order partial derivative with respect to time t using second-order partial derivation with respect to space x. This will make the estimate of the second-order partial derivative with respect to time t faster and more accurate because the methane concentration change in one area is caused by the concentration gradient at its adjacent areas. And the nodes can then get the optimized sampling interval Δt. Our approach is clearly much simpler than approaches such as Kalman filter which is too complex to be implemented in a mote.

Normally, all values of sampling data are under the dangerous threshold, and in each zone only the highest value of sampling data (i.e. the data from the zone leader), which can be used to predict the methane leakage timely, is transmitted to the gateway in the drilling tunnel. However, in case of methane leakage, more sampling data beyond the dangerous threshold will be transmitted to the monitoring server directly. With enough sample data in a dangerous area, the server can apply large deviation technique to accurately predict and locate the methane concentration and leakage in a mining zone [11, 12].

V. Performance Evaluation

A. Current Results

We have experimented with the EASINET motes for several times in Dayan Coal Mine, Inner Mongolia province. As shown in Fig.3(a), sensor nodes operated at different radio frequencies were tested to obtain the communication capacity which helped to design a more feasible and efficient system. We have also deployed a 3-basestation HHMSM prototype system in a lab corridor (see Fig. 3(b).) which is similar to the drilling tunnel in underground mine.



(a) EASINET mote experiment in Dayan Coal Mine

(b) HHMSM prototype system deployed in a lab corridor

(c) HHMSM prototype system architecture

Fig. 3. HHMSM prototype system experiments in a corridor

Fig. 3(c) shows the layout of our network and also depicts the topology in the experiments. There are 10 mote-clusters in the network. Each cluster consists of the same number of sensor motes. For different experiments, the density of the network can be varied by changing the number of motes in each cluster. One mote can communicate with other motes both in its own cluster and its direct neighboring clusters. The data from the left four clusters will be transmitted to the No.1 basestation. The data from the right four clusters will be transmitted to the No.2 basestation. The data from the middle two clusters will be transmitted to both basestations. During experiments, we manually actuated a device to release a proper amount of methane to change the methane concentration, which can be regarded as a methane leakage.

B. Evaluation of Methane Concentration Monitoring

In order to examine the effectiveness of HHMSM system in monitoring the variation of methane concentration, detecting the methane leakage timely and studying the impact of our proposed overhearing-based adaptive data collecting algorithm on the monitoring performance, we compared HHMSM system with a reference system named ORDINARY in which all the sampling results will be transmitted to the server. In our experiments, firstly we investigate the performance of the two systems under the same conditions by changing the density of motes, and then compare the two systems under different conditions.

B.1 Change density of motes

In this monitoring experiment, each mote sampled the methane concentration every 5 seconds. We varied the number of direct neighbors of each mote from 2 to 11. Fig. 4 shows how the number of sampling packets received by the No.1 basestation during a 100-second experiment varies with the mote density. It demonstrates that when the mote density increase from 2 to 11, the number of sampling packets transmitted in ONDINARY system increases steadily because each mote may send a sampling packet periodically while the number in HHMSM system remains almost at a relative fixed value. These results indicated that our proposed data collecting algorithm, resulting from organizing the motes into zones dynamically, significantly reduces the traffic volume during monitoring. The sampling traffic volume in our HHMSM is virtually independent from the density of motes in the system, which leads to much less energy consumption in the data transmission especially in a dense case.

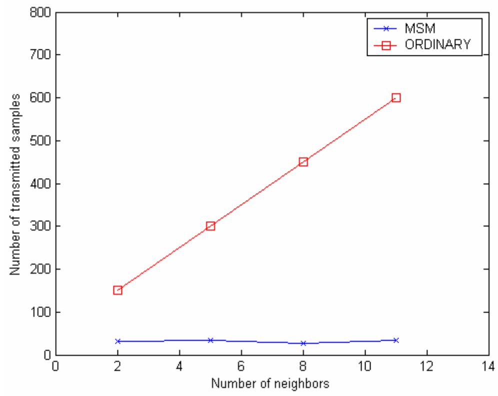


Fig. 4. Impact of network density on transmission overhead

B.2 Change methane concentration

In this experiment, each cluster consists of 3 sensor motes. We varied the methane concentration. Our goal is to analyze the monitoring accuracy and the corresponding transmission overhead under different conditions.

Fig. 5 shows the methane concentration data collected from the No.1 basestation. When these values are under normal condition, the value of the sampling result in HHMSM system is slightly higher than that value in ORDINARY system. When the value of sample result is above the dangerous threshold, both systems have the same sampling results, and the sampling rates of both systems were increased adaptively. In HHMSM, only the highest value of sampling data in each zone is transmitted to the gateway in the drilling tunnel. Yet in the ORDINARY system all the sample data will be transmitted. Thus in the HHMSM system the sample data collected by the monitoring application on the ground are higher than that of the ORDINARY system, whose sampling results are the average values of all sample data. However, our goal of monitoring methane concentration is to predict the methane leakage, which is only concerned with those high sampling data, so that the collected sampling data normally in HHMSM system is enough to predict a methane leakage. When the sampling data is beyond the dangerous threshold, the sampling rate in our HHMSM system is increased and all the dangerous sampling data are transmitted to the monitoring application on the ground allowing timely and accurate prediction for the methane leakage.

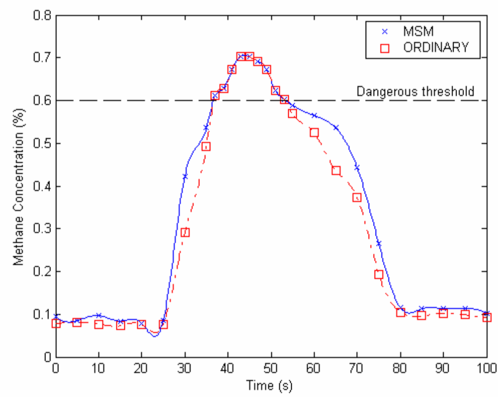


Fig. 5. The methane concentration data collected from the No.1 basestation

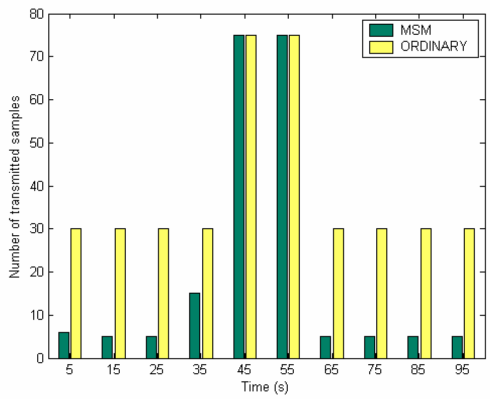


Fig. 6. The transmission overhead from the No.1 basestation

Fig. 6 shows the transmission overhead during this experiment. The two systems have the same transmission overhead only when the sampling data is beyond the dangerous threshold. While for most part of the experiment, the transmission overhead of ORDINARY system is much larger than that of the HHMSM system. That is to say, the HHMSM system is more efficient in power consumption than ORDINARY system.

The above discussion demonstrates that the HHMSM system which uses different data collecting measures under different conditions can monitor methane concentration and predict methane overproof timely with less bandwidth and energy consumption than existing wireless solutions.

VI. Conclusions And Future Work

This paper presents a heterogeneous hierarchical prototype system for underground mine safety monitoring, namely HHMSM. This system can meet multiple requirements for the applications such as monitoring the methane concentration, and miner localization. To realize the hybrid architecture, we also designed and implemented an overhearing-based adaptive data collecting scheme which exploits the redundancy and correlation of the sampling readings in both time and space to reduce traffic volume and control overhead within a bounded offset error. We have experimented with HHMSM system in corridor environment with dozens of sensor motes to evaluate the performance of this prototype system. The HHMSM system has several advantages comparing to the existing systems, such as full coverage to underground mine, fault tolerance and reliability, energy and bandwidth efficiency, low cost, and maintainability.

Acknowledgements

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