Long distance wireless sensor networks applied in coal mine

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Abstract

To remedy the deficiency of the present monitoring systems in coal mine, this paper designs the integrated mine network composed of wireless sensor networks and other technologies, and analyzes the problems of wireless sensor networks applied in long distance roadway. Different from wireless sensor networks in common wide area environment, topology of network in long roadway is zonal structure, which leads the nodes near Sink to have high energy consumption and become “bottleneck node”. To improve the bottleneck phenomenon, strategies of uneven fixed cluster and Mixed routing based on the features of long roadway are proposed. Simulation based on Matlab shows that these strategies balance the global energy consumption and have a better performance on the network lifetime and connectivity, which proves they are suitable for mine environment.

Keywords: wireless sensor networks; coal mine; long distance; routing; uneven cluster

1. Introduction

Mine monitoring system is very important for coal mine safety. With the increase of coal mine mechanization and mining scale, the limitations of widely adopted monitoring systems \cite{1} in mine are becoming increasingly prominent: The interactive communication between different kinds of systems is difficult; Equipment interconnection and power supply are by the wired mode, which may break down the whole system once an accident happens; Traditional systems are performed with poor flexibility and expansibility. To improve the monitoring ability effectively, it is necessary to introduce new technology in coal mine.

Wireless sensor networks \cite{2} have characteristics of self-organization, wireless communication, distributed autonomous and simple maintenance, which make it showing itself in the research of mine monitoring system. Up to now, wireless sensor networks have attracted lots of researches at home and abroad, but only a few researches involve application in coal mine. The environment underground is bad and complex, and accidents occur frequently. The particularity of environment determines that in mine, it not only needs to consider network construction and cost as in common environment, but also has to adapt to requirements and features of coal mine environment.

This paper designs the structure of integrated mine network with wireless sensor networks, and analyzes the

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deficiency of conventional algorithms in long distance roadway. Then the strategies of uneven advanced node deployment and routing are simulated by Matlab. And conclusions and future work of wireless sensor networks applied in coal mine are given.

2. Integrated mine network

Wireless sensor networks are more flexible and have better perceptive function than wired network, but it is inferior to wire communication in transmission capacity, rate and reliability. Therefore, we design an integrated mine network [3] composed of wireless sensor networks and other communication technologies. Integrated mine network uses fiber as the backbone network, and uses wireless sensor networks in roadway where monitoring is needed. If necessary, other communication techniques can be designed depending on the actual needs, such as leaky cable, PHS network and so on. Wireless sensor networks connect other networks by gateway node, realizing systems interconnection and information interaction of aboveground networks and underground networks. Fig. 1 shows the structure of integrated mine network.

The advantages of integrated mine network by adopting wireless sensor networks [4] are as follows:
1) Integrated network makes full use of the existing network in mine which costs low maintenance.
2) Wireless sensor networks do not need lay lines for communication and power, which make it more flexible.
3) Nodes can be placed optionally and compactly, so it is possible to monitor corner and anyplace in mine.
4) It is expandable. Nodes can entry and exit the network freely when coal face advances, roadway is abandoned or new roadway is set up.
5) Nodes can be moved, make it convenient to monitor the moving equipment in mine.

3. Long distance wireless sensor networks applied in mine

Wireless sensor networks in mine are generally used to monitor the long roadway. The height of roadway is about 3–5 meters and the width is about 10 meters, while the length often reaches to hundred meters, so the topology of networks in roadway is chain-like. Multi-path Fading, Shadowing Fading and interference are serious in roadway, therefore, the radio propagation distance of nodes are limit [5]. The environmental conditions of roadway determine the particularity of wireless sensor networks, which needs some particular deployment and routing protocol. The simulation is based on Matlab, and the parameters are listed in Table 1, others are the same as [6].

3.1. Analysis of conventional routing algorithms [7] used in long roadway

Conventional routing protocols used in long roadway: Plane routing has great waste of energy and bandwidth, and the maintenance of routing table is complex, which do not meet the requirements of mine system; Geographic routing and energy-aware routing have high cost, and it is difficult to get the theoretical effect and stability in harsh
environment underground; Hierarchical routing reduces the communication conflict, furthermore, it has better expansibility and energy efficiency. While nodes have restrictions due to energy and communication ability underground, which make it impossible to communicate with Sink by single-hop in roadway. Therefore, it is suitable for long roadway to use the method that normal nodes transmit data to its cluster head by single-hop in each cluster, and cluster-heads manage routing to Sink by multi-hop between clusters. Because data are transmitted from source nodes to Sink, data quantity is duplicated many times with the length of networks [8], shown as Fig. 2.

Table 1. Main simulation parameters setting

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width and Length of coverage area</td>
<td>W=10m L=200m</td>
</tr>
<tr>
<td>Nodes number</td>
<td>n=40</td>
</tr>
<tr>
<td>Maximum communication radius of advanced node</td>
<td>R=40m</td>
</tr>
<tr>
<td>Communication radius of normal node</td>
<td>r=30m</td>
</tr>
<tr>
<td>Initial energy of normal node</td>
<td>Eo=0.5J</td>
</tr>
<tr>
<td>Percentage of advanced node</td>
<td>ma=30%</td>
</tr>
<tr>
<td>Energy ratio of advanced and normal node</td>
<td>a=5</td>
</tr>
<tr>
<td>Convergence coefficient of M-type network</td>
<td>a1=0.29</td>
</tr>
<tr>
<td>Convergence coefficient of M-type network</td>
<td>a2=1.49</td>
</tr>
</tbody>
</table>

Fig. 2. Data quantity of long networks

The most main defect is common routing algorithms can not balance global energy consumption in long roadway. These algorithms based on common areas can not eliminate the higher energy consumption near Sink caused by long distance, which makes Sink can not communicate with other areas and the whole network is forced to die. Moreover, these routing algorithms have great variation of topology and coverage. Although the algorithms designed for common environment work well in some situations, they can not be used in long roadway directly.

3.2. Long distance wireless sensor networks

In long roadway, the farthest part to Sink is the “distal” of network. The hop number of node to “distal” is defined as the “degree” of node. Nodes with large “degree” have much more forwarding data quantity and energy consumption than nodes with small “degree”. In general environment, the length-width ratio of wireless sensor networks is rather small in comparison with that of underground roadway, and it has many nodes with large “degree”, so the death of one large “degree” node only leads failure to a small part of networks. While in long roadway environment, network topology is chain-like structure, the death of node often causes the chain fracture; especially the death of large “degree” node makes the network to be separated into several parts with small “degree”. This node whose death breaks the chain and makes the whole network fail is called “bottleneck node” [9]. To alleviate the bottleneck effect, a long distance heterogeneous network based on fixed uneven cluster and farthest forwarding node routing is proposed for mine wireless sensor networks.

3.2.1. Fixed uneven cluster

The mechanism of nodes becoming cluster head by turns makes energy consumption disperse in different node perfunctorily, but large “degree” node is essentially “bottleneck node”. However, fixed cluster not only reduces consumption of rebuilding cluster and updating routing table, but also increases the stability of network. And in the
monitoring area of mine, nodes can be completely placed with fixed deployment by workers. So we fix advanced nodes as cluster heads, which have more functions than normal nodes. And normal nodes are placed randomly and join cluster based on the communication cost. Fixed even and uneven networks are compared, and meaning of variable is in Table 2.

Table 2. Meanings of variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>K</td>
<td>Data quantity of a packet</td>
</tr>
<tr>
<td>DQ(s)</td>
<td>Forwarding data quantity of node with “degree” of s</td>
</tr>
<tr>
<td>D</td>
<td>Distance of one hop</td>
</tr>
<tr>
<td>d(i)</td>
<td>Distance between node i and Sink</td>
</tr>
<tr>
<td>k(i)</td>
<td>Weight of node i in routing</td>
</tr>
<tr>
<td>k1</td>
<td>Weight of residual energy in routing</td>
</tr>
<tr>
<td>k2</td>
<td>Weight of communication cost in routing</td>
</tr>
<tr>
<td>k3</td>
<td>Weight of distance to node in routing</td>
</tr>
<tr>
<td>C(i)</td>
<td>Cost of communication to node i</td>
</tr>
<tr>
<td>Eri</td>
<td>Energy of node i</td>
</tr>
<tr>
<td>Am(s)</td>
<td>Density of advanced node with “degree” of s</td>
</tr>
</tbody>
</table>

If the cluster head is placed evenly, the data quantity \( DQ \) of forwarding is as Formula 1.

\[
DQ(s) = \sum_{i=2}^{L} D \times \frac{n}{L} \times K = D \times \frac{n}{L} \times K \times (s - 1) = D \times \frac{n}{L} \times K \times \left( \frac{L - d}{D} \right)
\]

But if the density of cluster head \( Am(d) \) is

\[
Am(d) = \frac{1}{DQ(d)}
\]

the influence of increasing data quantity can be counteracted. We compare the even and uneven cluster [10] strategy in long roadway, the forwarding data quantity with different “Degree” is shown as Fig. 3.

Fig. 3. Forwarding data quantity of even and uneven cluster

We design M-type network and the deployment of cluster head is simplified to two lines. But in the real application of mine environment, the deployment is more crowded and complex. Cluster head can adjust its communication radius with the “degree”. And the initial energy of advanced node is set with the principle of making cluster heads alive until the majority of normal nodes die. Advanced node coordinates of M-type network are expressed as Formula 2 and the result of clustering is shown as Fig. 4.
The advantages of M-type uneven heterogeneous network are that: it reduces the cost and complexity of mine WSN system; it lightens the load of “bottleneck node”; it maintains more ways to Sink, which increase the network robustness and dependability; it reduces the interference between nodes and have better coverage.

3.2.2. Mixed routing

Based on clustering, routing is among the cluster heads. This paper compares three concrete multi-hop routing algorithms in long roadway.

- Algorithm 1 Minimum energy consumption routing: Generate link matrix of network topology, which is valued by the energy cost. Then use Dijkstra algorithm to find the minimum consumption path to Sink.
- Algorithm 2 Minimum hop routing [11]: When distance is less than the transmission range, the valuation of hop matrix is 1, and then adopts the path which has the minimum hops.
- Algorithm 3 Farthest forwarding node routing: Once a data packet is going to send, choose the farthest nodes within its transmission range as the next forwarding node.

Minimum energy consumption routing and Minimum hop routing can save energy, but they often result in frequent use of a certain path which makes the nodes on this path die earlier. And all of these three routing algorithms have not considered the “bottleneck node”. So we use Mixed routing based on residual energy, communication cost and distance. Weight of routing is as Formula 3. Choose the node with highest weight and higher “Degree” as the next forwarding node. Only when the chain is broken and there is no cluster head to support, the routing update is request.

$$k(i) = k_1 \cdot \frac{E_r(i)}{E_0} + k_2 \cdot C(i) + k_3 \cdot d(i)$$

Different from Minimum energy consumption routing and Minimum hop routing, Mixed routing chooses path depending on the cost and distance, and none of the paths is used all the time, which prevents energy depletion. And roadway is long and narrow, and the zonal structure limits the direction of routing pointing to Sink, not to other direction. So Mixed routing can get the approximate optimal path as Minimum energy consumption routing and Minimum hop routing. And Mixed routing makes maximization to transmission distance with the same energy consumption, just like Farthest forwarding node routing. Different from Minimum energy consumption routing and Minimum hop routing needing global information, Mixed routing only needs information within some hops, which causes less packet and faster selection. Mixed routing protects the nodes with less energy; therefore it avoids the use of “bottleneck node”.

Further more, based on the importance of communication in mine, it adopts some efficient approach: K-fold spare nodes, start up spare nodes are when the chain is broken; Data is Local preserved for the fails is temporary, and send data when link is recovered; Use more Sink [12] to converge data of long road way sectionally.

4. Simulation results and analysis

Wireless sensor networks with three different kinds are simulated in long roadway area based on Matlab. They
are networks with uneven clusters and Minimum hop routing (ECMHR), uneven cluster and Minimum hop routing (UCMHR), uneven cluster and Mixed routing (UCMR). In order to be fair, the total energy and normal nodes distribution are the same. The number of dead nodes within 1000 rounds is shown as Fig. 5, and Network connectivity is shown as Fig. 6. The number of communication per round is shown in Fig. 7.

Analysis on simulation results is as follows:

Fig. 5 shows that these three kinds of networks have difference on the number of dead nodes; UCMR has the least number, while ECMHR has more dead nodes in the same round. Mixed routing makes full use of node transmitting capacity and considers the residual energy. Uneven cluster balances the load of nodes near Sink, so it protects the “bottleneck node” as expected and prolongs the network lifetime significantly.

In Fig. 6, M-type UCMR based on particularity of forwarding data quantity, makes an efficient clustering and increase connectivity rate, while ECMHR have poor effect. Network connectivity is
The number of nodes which can link to Sink is \( \frac{\text{number of nodes}}{\text{number of alive nodes}} \), but sometimes this ratio may also increase for the decrease of alive nodes. The chain with even cluster is easy to be broken, so even if there are alive nodes, it can not link to Sink and make the whole fail. But uneven cluster achieves the effect of improving the problem of network division.

Fig. 7 shows UCMR has the most communication number, while ECMHR has the least. The result indicates that with the same energy and time, network based on uneven cluster and Mixed routing can transmit more information, which results in effective communication.

In short, the main idea of fixed uneven cluster and Mixed routing is that: control the cluster size near Sink to light the load of “bottleneck node”; and maintain more ways to Sink to increase the network robustness. The simulation results verify that this idea can make wireless sensor networks more suitable for mine environment.

5. Conclusions

On the basis of the present mine system, we propose integrated mine network, which have the advantages of both wireless sensor networks and wired network. Long distance wireless sensor networks for mine are designed with fixed uneven cluster and Mixed routing. The simulation results verify that algorithms based on long roadway can balance global energy consumption and have better connectivity, which proves it more suitable for coal mine.

Wireless sensor networks will be a promotion factor to monitoring and emergency rescuing in mine. This paper only gives the preliminary conception of wireless sensor networks applied in coal mine, while it needs further study on wireless transmission characteristics and practical working of underground environment.

Acknowledgements

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References