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Energy-Efficient Chain-type Wireless Sensor Network for Gas Monitoring

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Abstract. As a supplement of current wired gas monitoring system, wireless sensor network can be used to cover the blind area, and to diagnose the faults of wired system. The concept of novel chain-type wireless sensor network (NCWSN) for gas monitoring in coal mine with multi-sections is defined. The connectivity of NCWSN is considered too. To focus on gas monitoring, the advantages of NCWSN for gas monitoring are introduced first, then two energy-efficient methods are adopted in gas monitoring NCWSN which are node scheduling and data fusion. The scheme of node scheduling can keep balance of the energy cost by transmitting energy distribution frame in certain section. The scheme of data fusion can reduce transmission data bits by adopting fuzzy sets. Finally, performances of NCWSN are investigated including energy efficiency and network capability. It is shows that energy efficiency is improved to double by adopting node scheduling and data fusion. In addition, it is important to keep the balance among energy cost, network capability and detection precision by choosing appropriate number of sections.

Keywords: Chain-type wireless sensor network; energy efficient; coal mine; gas monitoring; fuzzy set

1. Introduction

Wireless Sensor Network (WSN) is integration of sensor technology, embedded computer technology, distributed information process technology and communication technology. In wireless sensor network, information of environment in the network coverage area can be detected, sensed and gathered real time, and then send the processed information to users who need the information [1,2]. It makes the idea “Ubiquitous Computing” come true by wireless sensor network. Wireless sensor network can be widely used in national defense, military affairs, nation security, environment detection, traffic management, medical treatment, manufacturing, counter terrorism, etc.

At present, the situation of safe production in coal mine is very serious, and gas is always the most critical factor causing accidents. The traditional coal mine gas monitoring system uses the method of wire network, which is inherently restricted by time and space flexibility. To overcome these shortcomings of wired systems, WSN should be applied to gas monitoring as a supplement, and gas pre-alarm system would be established based on wireless method to detect gas more effectively and flexibly and it will decrease blind area and hidden danger, and enhance the safety of coal production which is very important to decrease and prevent accidents in coal mine.

Because of the geography character of coal mine, sensor nodes in laneway are deployed with chain-type topology along a relatively long range of distance, the existing schemes are not applicable to this application. Therefore, the concept of Chain-type Wireless Sensor Network (CWSN) [3, 4, 5] was proposed for this class of applications, which is often limited by their natural formation of landscape or manmade infrastructures of long ranges, such as coal mines, rivers, coastal lines, highways, and national land borders.

In this paper, a New CWSN with banded nodes distribution for coal mine gas monitoring is proposed. Two energy-efficient methods are adopted in gas monitoring NCWSN which are node scheduling and data fusion. Interrelated performances are also studied. As a supplement of wired monitoring system, it will improve the level of coal mine gas monitoring and pre-alarm greatly.

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2. Novel chain-type wireless sensor network in coal mine

2.1. Definition of new chain-type wireless sensor network

Literature [3, 4] defines the concept of CWSN from the angle of topology, where sensor nodes are strategically deployed in a line. However, the New CWSN is defined from the angle of communication in this paper, which is extended from the literature.

Definition 1 (NCWSN): In new chain-type wireless sensor network, sensor nodes can be randomly deployed in surveillance area, such as laneway. However, active nodes which have communication relations are nearly in a line. Therefore, the network is still in chain-type technically. Namely “banded topology, chain-type communication”.

2.2. NCWSN in coal mine

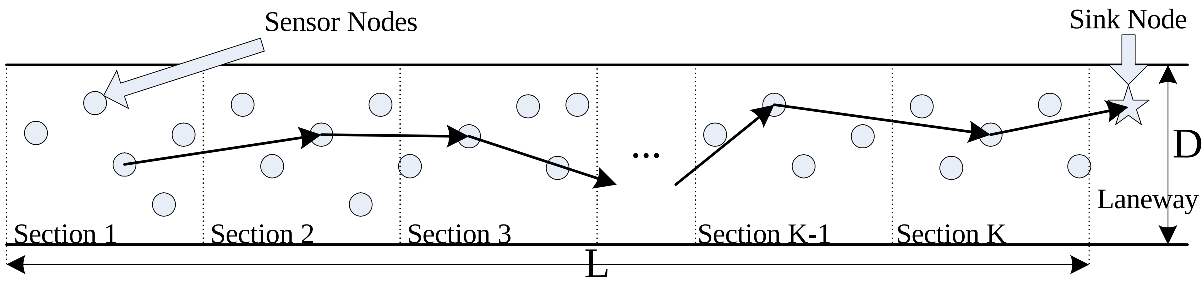

Figure 1. Sketch map of NCWSN in coal mine

As show in figure 1, N sensor nodes are randomly deployed in $L \times D$ laneway, resembling geographical adaptive fidelity routing algorithm (GAF) [6], divide laneway into K uniform sections with area $(L \times D)/K$, only one node will be active at certain time in certain section, rest nodes in that section will be sleep for saving energy. Alternately wake up a sleeping node to active state.

2.3. Connectivity of NCWSN

For ensuring the connectivity of NCWSN, enough communication range and nodes should be provided.

Supposed that node can always cover its section. It is obviously that the communication range r of sensor nodes should satisfy the inequation $r \geq \sqrt{D^2 + \left(\frac{2L}{K}\right)^2}$.

At the same time, due to the random deploying, number of nodes N in certain section should be ensured from the angle of probability. The probability of sensor node’s number n in certain section is given by

$$p\{X = n\} = C_N^n \left(\frac{1}{K}\right)^n \left(\frac{K-1}{K}\right)^{N-n} .$$

According section number K, adequate sensor node’s number n and probability p, number of nodes N can be obtained from this equation.

3. NCWSN for gas monitoring

3.1. Advantages of NCWSN for gas monitoring as a supplement

In coal mine, the operating managers need to obtain the consistency of gas in each monitoring site during monitoring, so they can analyze and forecast the distribution of gas in the whole monitoring area. Moreover, the monitoring network should give an alarm in time when gas consistency is over the danger mark. However, some failures, which are insurmountability, influence the reliability of wired gas monitoring system [7], such as sensor fault, communication fault, work station fault, software fault and so on.

In the other hand, although the existing wired system has some shortcomings, WSN can not be instead of the wired system entirely at the present time. The reasons are as follows. First of all, the technology of wired gas monitoring is mature, and the technician has accumulated a wealth of experience. Secondly, interrelated equipments are also self-contained in coal mine. Thirdly, the communication quality in coal mine is unstable. Therefore, constructing NCWSN for gas monitoring as a supplement of existing wired system is practical and effective.

3.2. Energy-efficient NCWSN for gas monitoring in coal mine

As a supplement of existing wired gas monitoring system, NCWSN can analyze the state of wired system by comparing consistency of gas. Dispersive multi-sensor nodes team up to overcome the shortage of wired system, which the areas turn to be blind section when the single work station is fault.

Due to the character of supplement, NCWSN should prolong working hours of network as possible as it can. Therefore, two energy efficient methods are adopted in gas monitoring NCWSN which are node scheduling and data fusion.

3.2.1. Energy-efficient node scheduling of NCWSN

It is shows that node idle energy cost is as much as receiving energy cost [8]. Therefore, adopting node scheduling can save energy. As show in figure 2, for section i with n_i nodes, supposed that each node have the same initialization energy E ; initialized the section by choosing a node randomly and activating the node; established *energy distribution frame* (EDF)

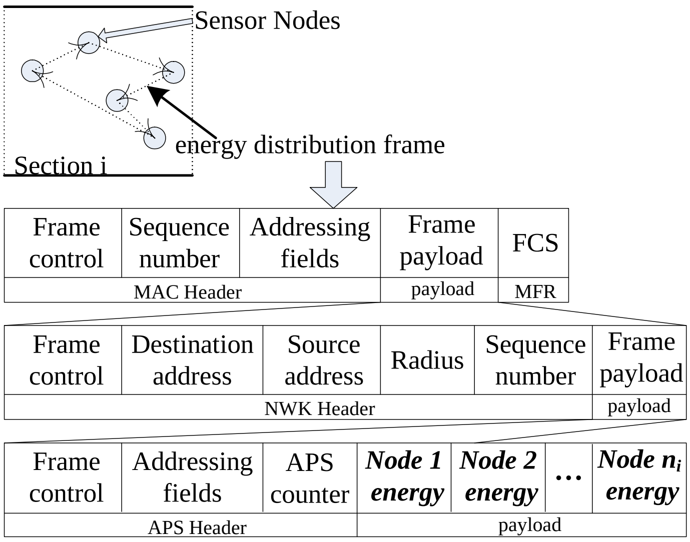

Figure 2. Node scheduling and energy frame

which contains remain energy of each node in section; computed remain energy of the node and updated the frame; elected node who has the most energy; activated that node and sent the frame to it, then current active node turn to be sleeping, new activated node charge the section.

3.2.2. Energy-efficient data fusion of NCWSN

Reducing transmission data bits is another way to save energy. As a supplement of wired system, gas monitoring NCWSN should transmit a few data when wired system is in order and consistency of gas is safety for industry. Therefore, data fusion based on fuzzy sets is imported to discriminate the gas consistency.

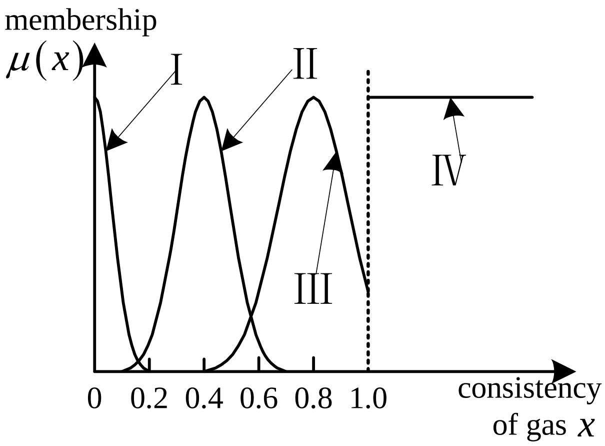

Figure 3. Membership function of each fuzzy set

Definition 2 (Fuzzy Sets for Gas Monitoring): According to “gas consistency could not exceed 1.0%” which is stipulated in coal mine safety regulation, combining industry condition. Divided gas consistency set $U=[0,\infty]$ into four fuzzy subsets as follow, Ⅰ(High safety factor set), Ⅱ(Medium safety factor set), Ⅲ(Low safety factor set) and Ⅳ(Alarm set). Membership function of each set is show in figure 3, fuzzy set are as follow by Zadeh representation.

$$\mathrm{I} = \int_{0\le x\le 0.2} \frac{6.6\times\exp\left(-138.9x^2\right)}{x} + \int_{x>0.2}\frac{0}{x}$$

$$\mathrm{II} = \int_{0\le x\le 1} \frac{4.9\times\exp\left(-78.1(x-0.4)^2\right)}{x} + \int_{x>1}\frac{0}{x}$$

$$\mathrm{III} = \int_{0\le x\le 1} \frac{3.3\times\exp\left(-34.7(x-0.8)^2\right)}{x} + \int_{x>1}\frac{0}{x}$$

$$\mathrm{IV} = \int_{0\le x\le 1}\frac{0}{x} + \int_{x>1}\frac{1}{x}$$

Bits: 2
Fuzzy set code: (00)
Payload when $x \in$ Ⅰ

Bits: 2	8
Fuzzy set code: (01)	Membership code (int)
Payload when $x \in$ Ⅱ	

Bits: 2	32
Fuzzy set code: (01)	Consistency value (float)
Payload when $x \in$ Ⅲ	

Figure 4. Payload of data frame

The structure of *data frame* (DF) is similar with EDF, only payload is different. As show in figure 4, if gas consistency $x \in \mathrm{I}$, only fuzzy set code should be transmitted with two bits, else if $x \in \mathrm{II}$, not only fuzzy set code, but also membership should be transmitted. When $x \in \mathrm{III}$, integrated consistency value should be sent to sink node. Specially, when $x \in \mathrm{IV}$, the DF should be transmitted at full steam, and all other DF whose consistency $x \in \mathrm{I}$ or II or III should be discarded to ensure transmission rapidly.

4. Performances of NCWSN

4.1. Energy efficiency

The energy model used in this work is adopted from [9]. The transmitting and receiving energy cost are given by

$$E_{Tx}(k,d) = E_{elec} \times k + \varepsilon_{amp} \times k \times d^{\alpha}$$

$$E_{Rx}(k,d) = E_{elec} \times k$$

Where k denotes data bits, d denotes communication distance, E_{elec} denotes transmitter and receiver electronics, ε_{amp} denotes transmit amplifier.

In our experiments, the influences of node scheduling and data fusion are studied by using Monte Carlo method with MATLAB. Interrelated parameters are as follow, length of laneway $L = 500m$, width $D = 3m$, the initial energy of sensor node E is $15120000J$ (two batteries with $2 \times 1.5V$, $3000mAh$), $E_{elec} = 50nJ/bit$ and $\varepsilon_{amp} = 100pJ/bit/m^2$. Detection frequency is $0.1s$. Considering the multi-path attenuation in coal mine, the path loss exponent α set to 4.

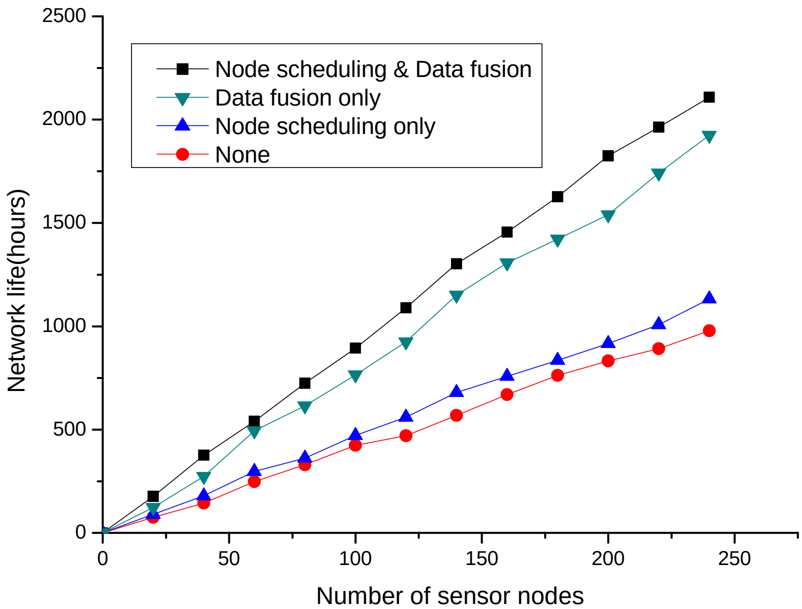

Figure 5. Network life of NCWSN with different N

Figure 5 shows network life of NCWSN with different number of nodes N, where $K = 8$. It is distinctly that node scheduling and data fusion have great energy efficiency under different N. The network life is twice of former network.

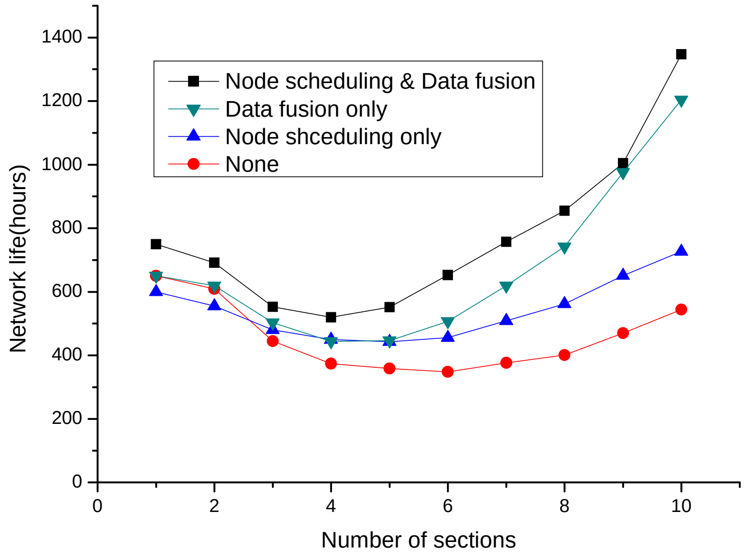

Figure 6. Network life of NCWSN with different K

Figure 6 shows network life of NCWSN with different number of sections K , where $N = 100$. It is clearly that node scheduling and data fusion have great energy efficiency under different K . The network life is prolonged evidently.

4.2. Network capability

Because of the chain-type and node scheduling, the number of sections K is the most important factor to NCWSN capability. Therefore, in our experiments, we consider that each section has only one node, the latency of NCWSN with different K is investigated by simulating with OPNET [10]. Interrelated parameters are as follow, MAC protocol set to IEEE 802.15.4 MAC without ACK mechanism; Transmission band set to 2.4GHz; Data rate set to Auto Calculate.

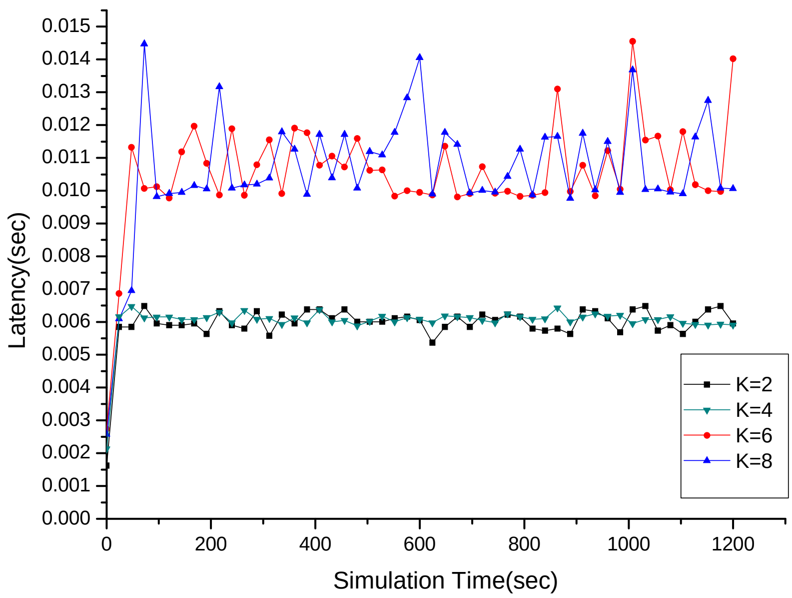

Figure 7. Latency of NCWSN with different K

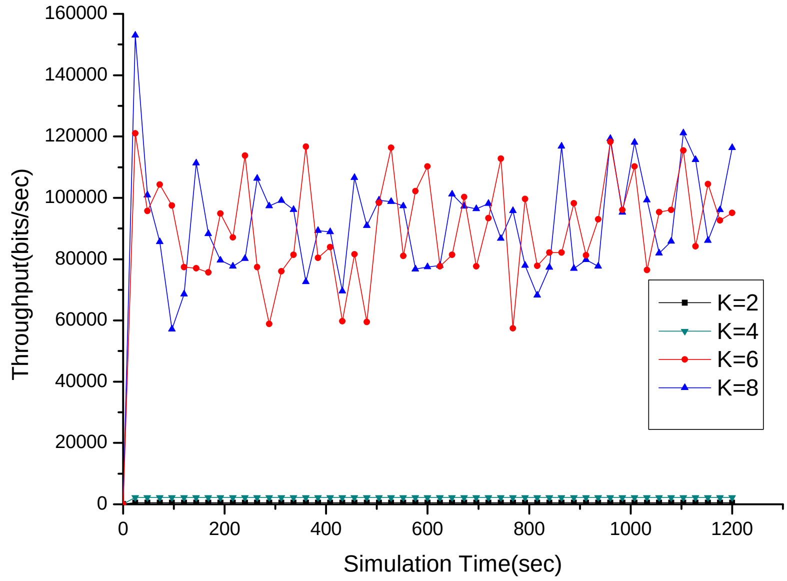

Figure 8. Throughput of NCWSN with different K

Figure 7 and figure 8 show the latency and the throughput of NCWSN with different K. Generally, with the increasing K, the latency and the throughput of NCWSN are increased. Take $K=5$ as threshold, when K is small, the latency is more stable, and the throughput is a constant. However, when K is large, the latency become uncertain, and the throughput is also unstable.

4.3. Conclusions of NCWSN performances

From the results of energy efficiency and network capability, we can conduct several conclusions as follow.

(1) Energy efficiency is improved to double by adopting node scheduling and data fusion.

(2) It is important to keep the balance among energy cost, network capability and detection precision by choosing appropriate number of sections. When K is small, energy cost and network capability are excellence, but detection precision is poor; When K is medium, detection precision and network capability are good, but energy cost is mediocrity; When K is large, energy cost and detection precision are excellence, but is network capability poor.

5. Conclusions

In this paper, an energy-efficient chain-type wireless sensor network is proposed. For gas monitoring in coal mine, two methods are adopted in gas monitoring NCWSN which are node scheduling and data fusion. From the simulation result, It is shows that energy efficiency is improved to double by adopting node scheduling and data fusion. In addition, it is important to keep the balance among energy cost, network capability and detection precision by choosing appropriate number of sections.

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