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Procedia Engineering 26 (2011) 2406 – 2414

Procedia Engineering

www.elsevier.com/locate/procedia

First International Symposium on Mine Safety Science and Engineering

# ZigBee-based positioning system for coal miners

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**Abstract**

China's present communication systems in coal mine can not effectively provide the information such as dynamic distribution of coal miners in work and production environment. Hence, rescue efforts are hard to be carried out in case of coal mine accident. To deal with this problem, the paper at first introduces the characteristics, structure and network construction method of ZigBee protocol. Then, by using the ZigBee technology based on IEEE802.15.4 criteria, the wireless communication network and the structure of ZigBee communication module for coal mine are studied and designed. At last, multilateration positioning algorithm is employed to realize the positioning of coal miners. Coal miner positioning system enters into computer management system via network, laying important actual significance to the production safety and emergent resuce of coal mine.



Selection and/or peer-review under responsibility of China Academy of Safety Science and Technology, China University of Mining and Technology(Beijing), McGill University and University of Wollongong.

*Keywords*: ZigBee; wireless sensor network; personnel positioning; multilaeration positioning algorithm

## 1. Introduction

Most of the coal mines in China are confronted with complicated geological structure, as a result, in the process of their production, they are threatened by natural calamities such as coal and gas outburst, flood, fire, coal dust explosion and roof caving. Frequent coal mine accidents seriously endanger the life safety of coal miners. Therefore, it is of important actual significance to further enhance safety management in coal mine enterprises.

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doi:10.1016/j.proeng.2011.11.2452

A common problem puzzled by coal mine enterprises is the failure of the ground management to timely know the distribution of the coal miners, and thus the difficulty to exactly locate the frontline workers. Some coal mine enterprises at home and abroad use bluetooth, RFID, PHS and other technologies to realize the mobile communications and personnel positioning in coal mine. However, these technologies have defects in positioning precision, effective transmission distance, reliability and power consumption and so forth. ZigBee-based coal miner positioning can effectively eliminate these defects, improve positioning precision, realize monitoring and dispatching of the coal miners at work and enhance the safety management capability of coal mines.

## 2. Overview of ZigBee protocol

In December 2000, Institute of Electrical and Electronics Engineers (IEEE) established IEEE802.15.4 subcommittee, who set out to develop ZigBee technology. In August 2001, USA's HONEYWELL and other companies sponsored and founded ZigBee Union. From then on, ZigBee technology has been confirmed as the criteria of IEEE802.15.4. In December 2004, ZigBee Union presented Version 1.0 of ZigBee technical norm. Compared with Wi-Fi, bluetooth, X-ray and RFID, ZigBee technology has its peculiar features [1,2]:

(1)A variety of operating frequency ranges. ZigBee uses such frequency ranges as 2.4GHz, 868MHz and 915MHz, all free of charge.

(2)Low speed. Only data transfer rate of 20Kbps-250 Kbps.

(3)Low cost. ZigBee protocol is simple, so its cost is significantly reduced, and ZigBee protocol is free of patent royalty.

(4)Short time delay. Time delay of device search is 30ms, time delay for dormant activation 15ms, and time delay for active device channel access 15ms.

(5)Low power consumption. The power consumption for receiving and sending messages is very low. Moreover, dormant mode can be used, and work cycle is short.

(6)The network capacity is large. One ZigBee network can accommodate 254 slave devices and one master device. ZigBee network can accommodate 65,000 devices at the most[1].

(7)Small effective scope. Its effective coverage scope is 10m-75m.

(8)High security level. Its encryption algorithm is AES-128. Meanwhile, its security attributes can be determined flexibly.

(9)High reliability. It adopts collision avoidance mechanism, thus effectively avoiding the competition and conflict in sending data.

### *2.1. Structure of ZigBee protocol*

A complete ZigBee protocol consists of physical layer (PHY), MAC layer, data link layer, network layer and application layer. The application layer is composed of application sub-layer (APS), application framework (AF), ZigBee device object (ZDO) and present application object. The schematic of ZigBee protocol is shown in Fig.1. PHY offers PHY data service and PHY management service, comprising 2.4GHz PHY, 868 MHz and 915MHz PHY. The two PHYs have the same data packet format, their only differences are operating frequency, transfer rate and modulation technology, and so forth. 2.4GHz PHY adopts high order modulation technology with transfer rate of 250Kbps; 868MHz has transfer rate of 20Kbps, and 915MHz of 40Kbps. PHY uses direct sequence spread spectrum (DSSS), which defines the interface between physical wireless channel and MAC layer. MAC layer can support multiple LLC norms, and provide MAC layer data service and MAC layer management service. The frame of MAC layer consists of frame header, load and frame end, which facilitates reliable data transfer in multi-noise wireless channel. The network layer is located between the MAC layer and application layer of

IEEE802.15.4, which provides data service and management service. The network layer has powerful functions: it can set up a new network; admit new members to the network; allocate addresses to the devices in the network; make all the devices in the network to be in synchronization; provice paths for the data to safety arrive to the target node[3].

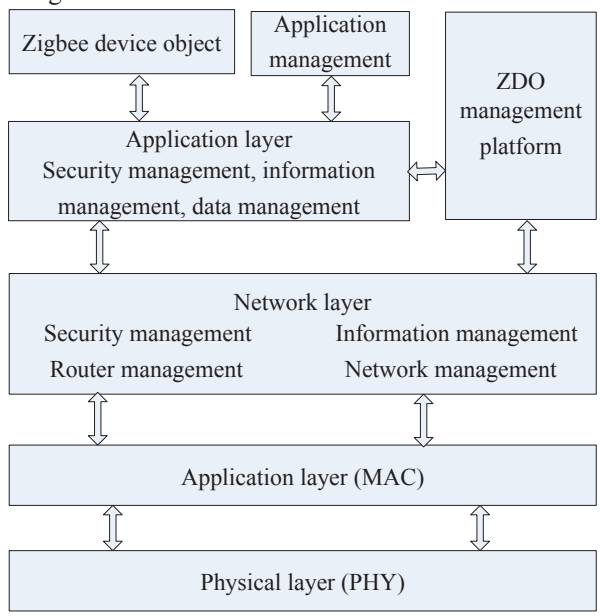


Fig.1 Structure of ZigBee protocol stack

*2.2. Network construction method of ZigBee protocol*

Based on the components, ZigBee divides nodes into physical devices in two types: full function device (FFD) and reduced function device (RFD). FFD can act as network coordinator to construct network. It has sufficient storage space to store routing messages and powerful processing capability[4]. RFD can not serve as coordinator. It has small memory and low power consumption. The network topological structure of ZigBee, based on the two devices, is diversified, having star structure, tree structure and net structure, as shown in Fig.2.

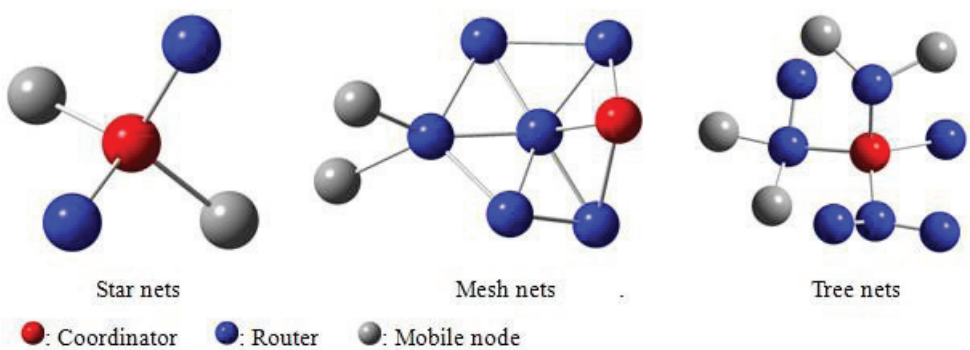


Fig.2 Topological structure of ZigBee network

Star type structure is the simplest, consisting of one coordinator and a lot terminate nodes, and having no router. The messages of device terminate node are transmitted via the coordinator. For tree

structure, the coordinator is responsible to set up network and set initial parameters. The router adopts graded routing. The tree structure can make the nodes in the network in synchronization, has longer service life and is easy to paralyze. In the net structure, the coordinator is also responsbile to set up network and set initial parameters. The router does not produce beacon. Network of such structure is not easy to paralyze, but the nodes in the network are hard to be in synchronization.

## 3. Construction of ZigBee network in coal mine

### *3.1. Design of ZigBee network in coal mine*

By means of reasonable node layout and appropriate positioning algorithm, ZigBee wireless communication network in coal mine can avoid the influences of a variety of factors, such as wall reflection, changes in environment factors like mine temperature and humidity, secondary radiation of coal seam roof, size of laneway cross section and piezoelectric effect[5], and thus realize multiple functions such as dynamic positioning of mine personnel, search of information on personnel path, attendance of mine personnel, SOS and alarming in forbidden zone.

The operating principle of ZigBee coal miner positioning system: via industrial Ethernet, ZigBee wireless network transmits in real time the data gathered to the master computer in the ground monitoring center. After performing analysis and processing, the master computer reflects the dynamic distribution of the coal miners at work on the master interface of the computer, realizing the real time positioning of the coal miners. The wireless network consists of three layers: the router sets up internal network and allocates internal network for the master switch being the first layer network; the master switch then constructs the second layer network, and allocates small segment address to the sub-switches being the second layer network; the sub-switch then allocates smaller address to the devices being the third layer network, namely, ZigBee wireless network, as shown in Fig.3.

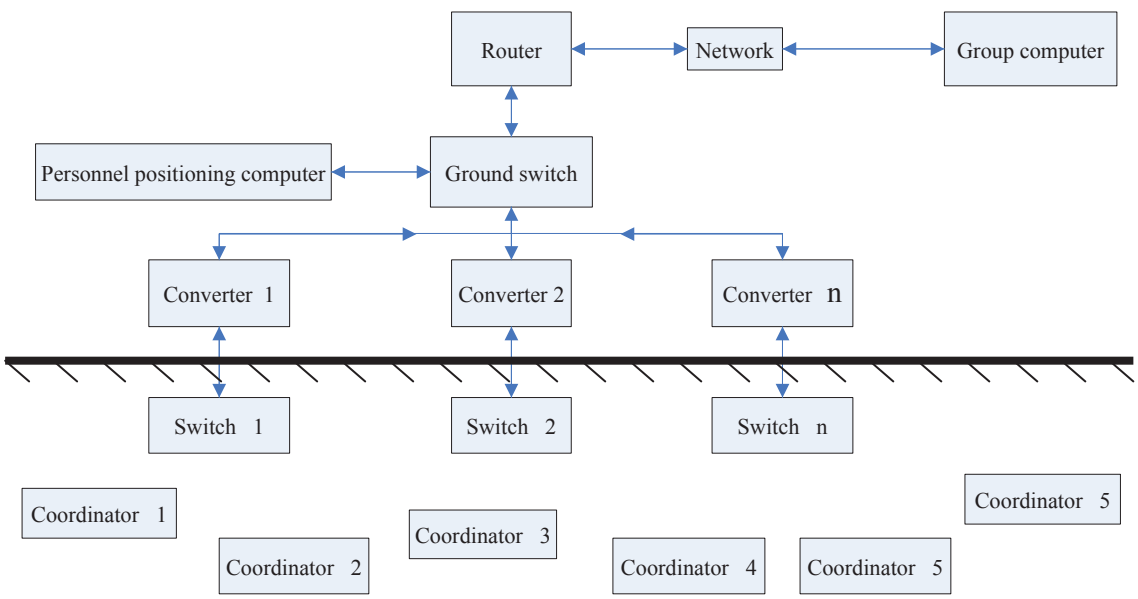


Fig.3 Schematic of coal mine network structure

ZigBee wireless network in coal mine mainly is designed in net structure. On the both sides of the laneway, a coordinator is secured every 70m, and at the turn of the laneway, an additional coordinator is

secured, so as to guarantee uninterrupted transmission of messages. On the work face, due to complicated environment and more data to be gathered, a coordinator is secured every 30m. The personnal information card of coal miners at work is placed in the mine lamp cap, to ensure adequate electric capacity and normal operation of the card.

### *3.2. Design of ZigBee wireless module*

Wireless sensor network consists of coordinator, router and terminal device. The coordinator and router are made up of FFD nodes, secured on the laneway walls, briefly called secured nodes. The terminal device is composed of RFD, carried by the coal miners, briefly called mobile nodes. ZigBee coordinator is control center, having three main functions: collecting the data of each node sensor; simply processing the data; maintaining communicatoin with external network. When the coordinator malfunctions, other FFDs can also function as the coordinator.

The circuit board on the secured node is designed with interface circuit module, processor, radio frequency module, swithc communication module and wireless module, and so on. The interface circuit module of the secured node is responsible for providing the energy source of all nodes. The processor consists of two CC2420 pieces: one CC2420 is responsible for controlling the other CC2420, and receiving and encoding data, and storing them into the memory; the other CC2420 is responsible for data exchange with the switch. The circuit board on the mobile node is designed with power module, processor, sensor module, radio frequency module, wireless module, and so on[6]. The processor on the mobile node is responsible for coordinating with all modules for their work, sending instructions to the sensor to gather data; sending instructions to the radio frequency module to realize radio frequency communications[7]. The structural frameworks of secured node and mobile node are shown in Fig.4.

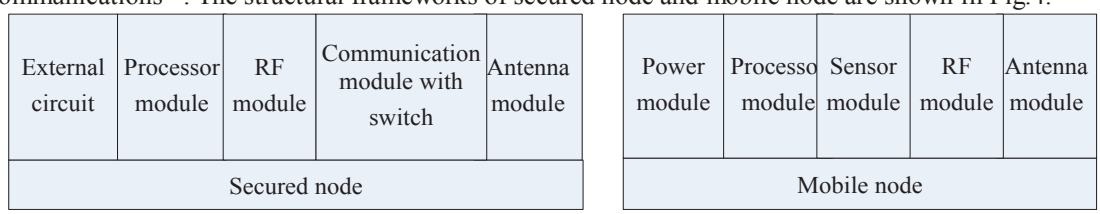


Fig.4 The block box of ZigBee wireless module

### *3.3. Design of software for ZigBee networking running*

ZigBee network in coal mine consists of coordinator, router and mobile node. Their work status determines the operation of the whole network. The coordinator is the first device for the wireless communication network in coal mine. At first, a network is set up, then, channel scanning is made for the PHY, to find all channels available; ID is assigned to the channel. As a result, monitoring status is realized. The coordinator is also responsible for communication with the switch of the second layer network, to realize real time transmission of data. Its work is realizable by the following program:

```
Public Class Form1
    Public Declare Function GetTickCount Lib "kernel32" () As Short
    Public Sub DelayTime(ByVal DelayMsTime As Short) 'quantatitive delay program
        Dim TimeDelay As Short
        TimeDelay = GetTickCount
        Do
            System.Windows.Forms.Application.DoEvents()
        Loop Until GetTickCount - TimeDelay > DelayMsTime
```

```
        End Sub
        Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As System.EventArgs)
Handles initialization.Click
            Initialization.Visible = False
            TextBox1.Visible = True
            TextBox1.Text = "set up network"
            DelayTime(500)
            TextBox1.Text = "scan channels, select ID"
            DelayTime(500)
            TextBox1.Text = "receive wireless signals and data"
            DelayTime(500)
            TextBox1.Text = "assign an address to the node"
            DelayTime(500)
            TextBox1.Text = "send message to the rescue center"
        End Sub
        Private Sub 1_Load(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles
MyBase.Load
        End Sub
    End Class
```

After the coordinator has set up the network, router node can find the network, and participate in router selection. At work, it adopts dormant mode, can at any time link and leave from the network, and can gather data from the mobile node and transmit promptly the data to the coordinator. The mobile node is carried by the coal miners at work, which converts their geographic locations and other message into data and transmit the data to the router node.

## 4. Realization of coal miner positioning algorithm

### *4.1. Existing positioning algorithms*

The existing positioning algorithms are roughly divided into three categories: triangle measuring method, scene fingerprint method and adjacent method.

(1) Triangle measuring method

The principle of such positioning algorithm: based on the geometric and algebric nature of triangle,the location of the object is ascertained by computation[8]. Such measuring method is extensively used. According to the differences in the measured object, it can be divided into: based on signal intensity (RSSI), with low measuring precision; based on time of arrival of signals (TOA), with very high positioning precision, but demanding more on the hardware; based on time difference (TDOA), the precision of which can reach centimeter level, but the hardware cost of which is high; based on angle of arrival (AOA), which has extremely high positioning precision, needs special hardware facilities, and is not easy to be used; mixed positioning algorithm, namely, combine the four methods, give to full play the advantages of each algorithm to improve positioning precision.

(2) Scene fingerprint method

Scene fingerprint method acquires the user location through scene features. Implementation is made in two stages: the first stage, offline learning state; the second stage, actual measuring stage[8]. Information is measured in real time, and appropriate matching algorithm is adopted to determine the matching degree between the information and each information recording fingerprint, thus to judge the actual location of the user. At present, the commonly used positioning systems by scene fingerprint method include three types: indoor fingerprint positioning system, reception signal intensity fingerprint positioning system, multipath angle component power fingerprint positioning system. The precision of

scene fingerprint positioning technique mainly depends on the size of measured mesh and network density. As long as the location of sufficient small granuality is available, higher positioning precision and accuracy can be obtained.

(3) Adjacent method

Positioning by adjacent method can only determine to which location the moving object adjoins, or in which zone he is, but can not ascertain its exact location. Commonly used methods for realization of positioning by adjacent method include: detective physical contact, wireless community access point monitoring and automatic identity (ID) certification[9].

### *4.2. Positioning principle of multilateration positioning algorithm*

The positioning algorithm adopted in the paper is a multilateration positioning algorithm obtained by improving the trilateration positioning algorithm. The principle of the trilateration positioning algorithm is: for the distance between a known mobile node and three secured nodes in two-dimensional space, their focus coordinate can be solved by the radius of the three secured nodes and the circle center coordinate, and the coordinate is just the coordinate of the mobile node. However, the wireless network in coal mine is no longer a two-dimensional space, the distance measured by the node always has error, making the three circles in no way intersect in one point. As such, it is hard to exactly position the coal miners at work. Multilateration positioning algorithm evolved from triangle positioning algorithm, which more exactly estimates the location of the mobile node by adding the number of secured nodes, uses the principle of the least square method to compute the gap between actual coordinate and estimated one, thus works out the coordinate of the mobile node.

Assume the coordinate of the mobile node is $(a,b)$, and the coordinates of $n$ mobile nodes involve in the computation. Their coordinates are $(a_1,b_1)(a_2,b_2)(a_3,b_3)\cdots,(a_n,b_n)$, respectively. The distance between the mobile node and these secured nodes is $d_1,d_2,d_3\cdots,d_n$, respectively, expressed by formula (1):

$$\begin{aligned} d_1 &= \sqrt{(a_1-a)^2+(b_1-b)^2} \\ d_2 &= \sqrt{(a_2-a)^2+(b_2-b)^2} \\ d_3 &= \sqrt{(a_3-a)^2+(b_3-b)^2} \\ d_n &= \sqrt{(a_n-a)^2+(b_n-b)^2} \end{aligned} \tag{1}$$

Formula (1) is a nonlinear equation set. The coordinate of the mobile node to be solved $(a,b)$ can be expressed by its approximate location $(\Delta a,\Delta b)$ and the offset of the two nodes $(\Delta a,\Delta b)$. Using Taylor's series, unfold by centering $(\Delta a,\Delta b)$, then the coordinate of the mobile node can be expressed by formula (2):

$$\begin{aligned} a &= a_0+\Delta a \\ b &= b_0+\Delta b \end{aligned} \tag{2}$$

The distance of the mobile node and the distance of approximate location are expressed by formula(3):

$$g_i(a,b) = d_i = \sqrt{(a_i - a)^2 + (b_i - b)^2}$$
$$g_i(a,b) = d_i = \sqrt{(a_i - a_0)^2 + (b_i - b_0)^2} \quad (3)$$
$$i = 1,2,3...,n$$

Formula (3) is unfolded by Taylor's series, formula (4) is obtained:

$$g_i(a,b) = g_i(a_0 + \Delta a, b_0 + \Delta b)$$
$$= g_i(a_0,b_0) - \frac{a_i - a_0}{\sqrt{(a_i - a_0)^2 + (b_i - b_0)^2}}\Delta a - \frac{b_i - b_0}{\sqrt{(a_i - a_0)^2 + (b_i - b_0)^2}}\Delta b \quad (4)$$

Suppose $c_{a_i} = \frac{a_i - a_0}{\sqrt{(a_i - a_0)^2 + (b_i - b_0)^2}}, c_{b_i} = \frac{b_i - b_0}{\sqrt{(a_i - a_0)^2 + (b_i - b_0)^2}}$, formula (4) is rewritten as formula (5):

$$\Delta d_i = d_i - d_{0i} = c_{a_i}\Delta a - c_{b_i}\Delta b \quad (5)$$

Substituting formula (5) into formula (1) gives formula (6):

$$\begin{aligned} \Delta d_1 &= c_{a_1}\Delta a - c_{b_1}\Delta b \\ \Delta d_2 &= c_{a_2}\Delta a - c_{b_2}\Delta b \\ \Delta d_3 &= c_{a_3}\Delta a - c_{b_3}\Delta b \\ \Delta d_n &= c_{a_n}\Delta a - c_{b_n}\Delta b \end{aligned} \quad (6)$$

By the equation $f_i(\Delta a, \Delta b) = \sum_{i=1}^{n}\left[\Delta d_i - \left(c_{a_i}\Delta a + c_{b_i}\Delta b\right)\right]$, use the least square method to solve formula (6) to obtain $\Delta a$ and $\Delta b$. In this way, perform continuous iteration, till the ideal location precision of the mobile node is obtained.

### *4.3. Positioning results and analysis*

Compared with the trilateration positioning method, the coordinate of the mobile node computed by the multilateration positioning algorithm is much improved, but to have ideal positioning precision, the following two aspects should be noteworthy:

First, RSSI easily fluctuates under the influence of the environment of coal mine. Therefore, deviation appears in the distance estimation. In order to avoid such circustance, in choosing RSSI value, the RSSI of the most occurrence probability substitutes for average RSSI value. In so doing, positioning precision will be improved, and computation quantity is significantly increased.

Second, in positioning the mobile node by the multilateration measuring method, the key is to choose the approximate location. Initial location should be chosen based on the trilateration positioning, as this can reduce computation quantity and improve positioning precision.

## 5. Conclusions

(1) The paper designs ZigBee-based three-layered network structure and ZigBee wireless network communication system for coal mine, which can effectively overcome the interference of coal mine complicated terrain with communications. It covers the blind zone, and transmits the data gathered in coal mine in real time to the ground command center and group management center, facilitating to enhance the coal mine's safety management level.

(2) ZigBee network node is a new system integration technology. The paper designs the network nodes that can in real time monitor the environment parameters and various kinds of data in coal mine, and designs the software system for the node running, which can improve the working efficiency and service life of ZigBee nodes.

(3) The positioning algorithm for coal miners designed in the paper can realize the exact positioning of operators. The method of improving positioning precision is proposed. It facilitates the attendance of coal miners by the ground management center, knowing in real time the dynamic positioning of coal miners at work. In case of emergency, rescue efforts can be effectively carried out, and alarm be given to the coal mine operators in the forbidden zone.

## Acknowledgements

This research is supported by China National Key Basic Research Development Project Program (2011CB201202), National Natural Science Foundation of China (50874110), New Century Excellent Talents Program from the Ministry of Education of China (NCET-07-0799), the Fok Ying-Tong Education Foundation for Young Teachers in the Higher Education Institutions of China (111053). The authors would like to express their gratitude to these foundations.

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