A Distributed Location Algorithm for Underground Miners Based on Rescue Robot and Coal-Mining Wireless Sensor Networks

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***Abstract*—Rescue robot places an important role when any severe disaster in underground coal mine happens. To locate and keep a track of miners working in a well becomes an impossible completed mission once the well communication infrastructure is all destroyed due to the disasters such as fire damp explosion. Wireless sensor networks, together with underground mine rescue robot provide a potential solution for the challenges in terms of many unique advantages of the wireless sensor networks like random deployments of nodes and network self-organized multi-hops. In this paper, a new coal-mining wireless sensor network (C-WSN) is developed. We propose a distributed system architecture and an improved location algorithm for rescue robot based on radio signal strength indicator (RSSI). The experimental results are analyzed. Finally, we draw conclusion and address the future work.**

***Keywords*—location,rescue robot, wireless sensor networks**

I. INTRODUCTION

The safety of underground mine is an important global issue. Among potential hazards in mines are methane, a naturally occurring gas that can ignite and explode, and carbon monoxide, a toxic gas that can occur as a byproduct from combustion. The underground-operation is with great fatalness, in case the accident happened, rescue action is difficult to be operated for the complicated structure and severe condition underground. Continuous and remote monitoring of miners and environmental factors such as temperature, carbon monoxide level and methane level in underground mines could also help prevent accidents. Developing inspecting and rescue coal mine robot, to implement environment monitoring before disaster occurring and realize the rescue when disaster happened, is an important application area for robot.

Sandia's Intelligent Systems and Robotics Center (ISRC) of America developed an underground mine robot called “RATLER”, which can successfully enter the mine and complete the task of mine atmosphere sampling [1]. "Simbot" is a small robotic device that invented by University of South Florida of United States, which can alert rescuers to the presence of dangerous gases in the event of a mine collapse[2]. Australian mining researchers have created a miniature rescue robot for mine disasters which can crawl down a small hole drilled from the surface into the mine and then crawl through rubble and mud using its sensors to find trapped miners and to sniff the air for toxic or flammable gases.

When underground mine accidents occur, location of rescue robot and two way communications between robot and the miners could enhance rescue efforts. But in underground mine environment, global positioning system (GPS) and cellular network localization technology could not be used because the deployments of base stations are so difficult. The hard-wired systems especially wired communication technologies currently used are not reliable in emergency situations. Wireless sensor networks appear more and more advantages in underground mine applications for their self-organized and reliable mesh network characters.

To realize a WSN localization system for rescue robot becomes possible now. Deng ZD et al. realize localization and dynamic tracking using wireless-networked sensors and multi-agent technology [3]. For high accuracy sensor location, measuring time-of-arrival (TOA) and angle-of-arrival (AOA) are preferred. Ranging via TOA has been implemented with a combination of RF and ultrasound [4]. Location estimation using RSSI has been researched and simulated for wireless sensor networks in [5]-[7] and demonstrated in [8][9]. But there is no implement about miner location in underground mine with RSSI method for its harsh environment.

The remainder of the paper is organized as follows. In Section 2, we give distributed system architecture and a location model. In Section 3, the location algorithm is implemented. We then analyze our experiment results in Section 4. Finally, we conclude our paper.

II. DISTRIBUTED SYSTEM ARCHITECTURE AND C-WSN LOCATION MODEL

A. Distributed system architecture

To realize environment monitoring before disaster occurs and realize the rescue when disaster happened, a ZigBee coal mine wireless sensor network（C-WSN） is deployed at underground mining face. ZigBee is a self-organized wireless personal area network (WPAN) protocol based on IEEE802.15.4 MAC and physical layer [16]. It appears more advantages than ultra-wide band radio and very low frequency through-the-earth in mine applications.

In C-WSN, different types of sensor nodes including methane nodes, oxygen nodes, carbon monoxide nodes and smoke nodes are deployed. They join the C-WSN as ZigBee end device type, acquire the environment information and transmit sensing data to ZigBee gateway node at fixed time cycle. Once the data go beyond the threshold value, emergency responding will be set up. To localize the underground working miner, a ZigBee location node is installed on each miner's hat. Miner location node realized the coordinate calculating through the cooperation with the reference nodes in C-WSN, including rescue robot once mine disaster happened. As shown in Figure 1, sensor data and coordinate location information are sent to ZigBee coordinator, which can be regard as gateway of C-WSN, through multi-hop method. The node which performs transmission and reference coordinate function is called reference node. It is ZigBee router device type. C-WSN gateway connects to a fiber modem which can transform the gateway data transparently and access to the internet through a switch or hub. All information data are processed and displayed in monitoring center with several distributed servers including socket server, database server, manager server and view client.

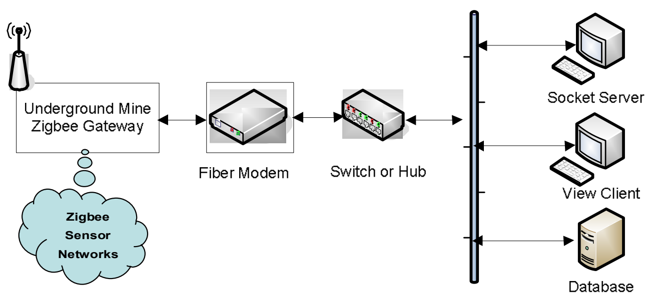

Figure 1 Distributed system architecture

Once underground mine explosion happens, all electric power system and C-WSN would be destroyed. We proposed that part of sensor nodes are still in working with backup battery and some miners are trapped and alive. It is still dangerous for rescuer to enter underground mine because the possibility of second time explosion. At this time, rescue robot can perform the job and execute the following tasks:

As a spread device, spreads the router nodes to rebuild or repair the destroyed C-WSN.

As a C-WSN mobile router node, finds the trapped miners and sensor nodes with broadcast communication, communicates with them and transmits the coordinate and sensor information to up pit monitoring center.

To perform the previous task, a robust, dynamic C-WSN and a distributed location algorithm are required. Figure 2 is a sketch map of rescue job for robot. Once the disaster happened, rescue robot would enter underground mine and spread the router node near the mining face, broadcast the rescue information. The nodes on trapped miner's hat will scan the new ZigBee network. If the nodes can rejoin the network, they will start location program again and report the coordinate to router node or rescue robot.

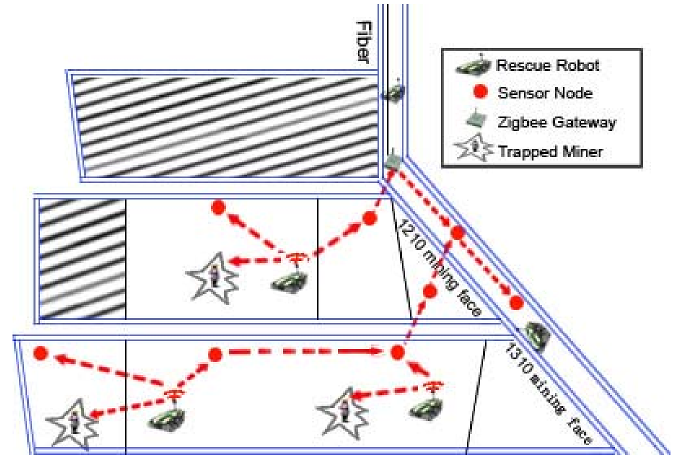

Figure 2 Sketch map of carrying out rescue job using multiple robots

B. *C-WSN location model*

In the C-WSN system, to realize the location algorithm, CC 2431 chip is adopted. Each node on miner's hat is a hardware implement of CC2431.The CC2431 is a true system-on-chip (SOC) for wireless sensor networking ZigBee/IEEE 802.15.4 solutions of Texas Instruments (TI). The chip includes a location engine that can be used to receive signals from reference nodes and estimate own position. To determine the distance from the RSSI values, TI applies a free space path loss model shown in Figure 3 and (1) [15].

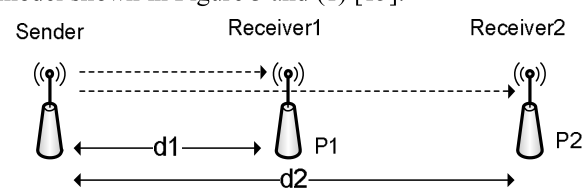

Figure 3 Free space path loss model

$$\frac{P_1}{P_2} = \left(\frac{d_1}{d_2}\right)^n \tag{1}$$

where

$P1$ = power at distance $d1$ [W],

$P2$ = power at distance $d2$ [W],

$d1$ = distance to the sender [m],

$d2$ = distance to the sender [m],

n = path loss coefficient.

We can rewrite (1) in logarithmic notation to yield the following.

$$P_2[\mathrm{dBm}] = P_1[\mathrm{dBm}] + 10n(\log_{10}(d_1) - \log_{10}(d_2)) \tag{2}$$

TI defines the radio frequency model parameter A to be the absolute power value in dBm, received at a distance of one meter from the sender. By applying this fact to (2), we can reduce the equation as shown in (3) and (4), where P2 is the measured RSSI value at distance d from the sensor.

$$P_2[\mathrm{dBm}] = P_1[\mathrm{dBm}] + 10n(\log_{10}(d_1) - \log_{10}(d_2))$$

(RSSI) (-A) (0)

(3)

$$\mathrm{RSSI} = -(A + 10n(\log_{10}(d)) \quad (4)$$

where

d = distance to the sender [m],

n = path loss coefficient,

A = absolute value of power at one meter distance to the sender [dBm].

III. IMPLEMENT OF DISTRIBUTED LOCATION ALGORITHM

Our distributed location algorithm includes three parts of programs: reference node program, including static reference and mobile robot node, miner node program and gateway node program. Static reference node provide the original coordinate information to location node and complete the function of ZigBee router, such as routing package, finding children nodes and reporting to coordinator. Miner node realizes the location calculating with location engine. Gateway node is the coordinator of ZigBee network, which can be can regarded as the header of C-WSN. It manages the whole PAN and provides the interface to graphics user.

A. Algorithm on reference node

Figure 3 shows the program flow for reference node. As we know, TI Z-Statck supports multiple tasks running on chips. All nodes must join the ZigBee network after initialization. For all reference nodes, especially static reference nodes, a mesh network task must be loaded. All self-organized networks protocols, such as routing algorithm, network topology maintenance, data transmitting etc, are executed in this task. To support the distributed location algorithm, all reference nodes must response to the broadcast package of location node and send their coordinate and RSSI information to location node.

In order to decrease the influence of fast fading noise and improve the performance of the RSSI method, the averaging solution is used with reference node. As shown in (5), the averaging over time is implemented.

$$\overrightarrow{\mathrm{RSSI}} = \frac{1}{n}\sum_{i=0}^{n} \mathrm{RSSI}_i \quad (5)$$

Once the mine disaster happens, C-WSN will be destroyed. For rescue robot node, a network repairing and orphan node searching task must be loaded. In this task, rescue robot node will broadcast searching package in a fixed time cycle. The orphan node, which has lost the network state, will rejoin the C-WSN through rescue robot and send their data to gateway again.

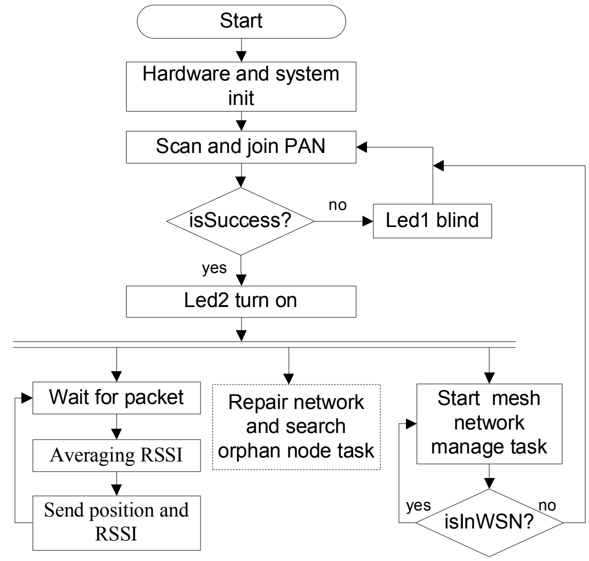

Figure 3 Flow chart for reference node

B. Algorithm on location node

Location node is installed on miner's hat. To perform the location function, the node must join the C-WSN firstly and also run a mesh network managing task. The location process includes four phases: broadcast location request, collect data, calculate position in location engine, and send the coordinate information to destination. Figure 4 shows the program flow for location node.

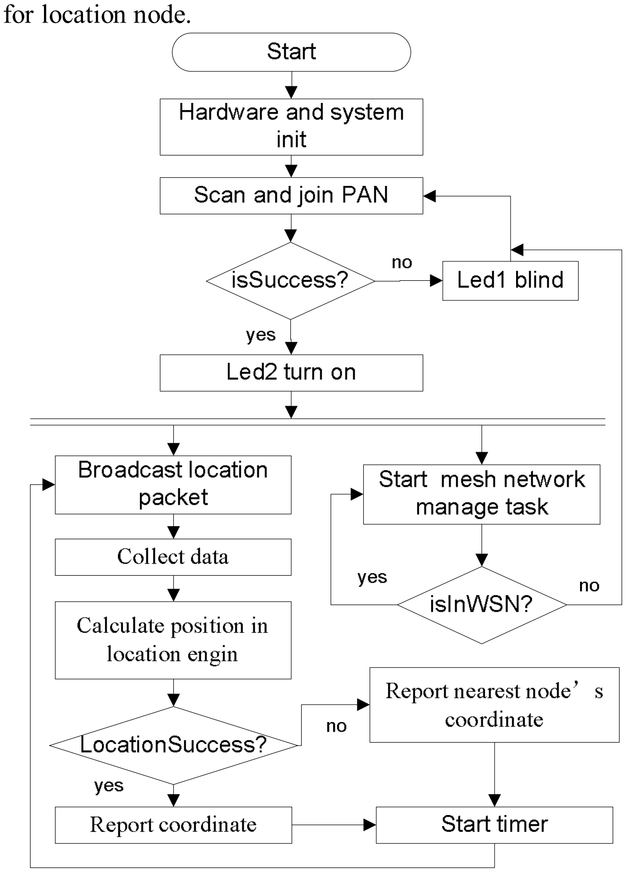

Figure 4 Flow chart for location node

In first phase, location node broadcast a one-hop location request package to C-WSN on a fixed time cycle. All reference nodes which received package calculate the RSSI between itself and location node. After an averaging, reference node sends the RSSI and its coordinate information to location node. In collecting data phase, location node compares the RSSI value from all data and selects the stronger nodes. The numbers of reference node can be determined in software. In our program, we select the minimum value 3 and maximal value 8. In third phase, location node sends the RSSI value and reference node's coordinate to location engine, and executes the calculating process. At last, location node sends the calculation result to the destination. If the numbers of reference nodes are less than 3, location node will select the strongest RSSI reference node, and report this reference node's coordinate to destination. The destination will know that location node is near to this reference node.

C. Algorithm on gateway node

Gateway node is the coordinator of C-WSN. It creates a PAN at first and manages the whole network. Also, it is the connector between C-WSN and the graphic user interface. As a coordinator, the gateway must execute the task which ZigBee specification requires, such as choosing certain key network parameters and maintaining the devices on the network, assigning a short address to the devices. So our gateway program includes three tasks: manages the C-WSN; reports the C-WSN data to user interface; transmits the user command to C-WSN node by broadcast or unicast method. Figure 5 shows the main program flow of gateway node.

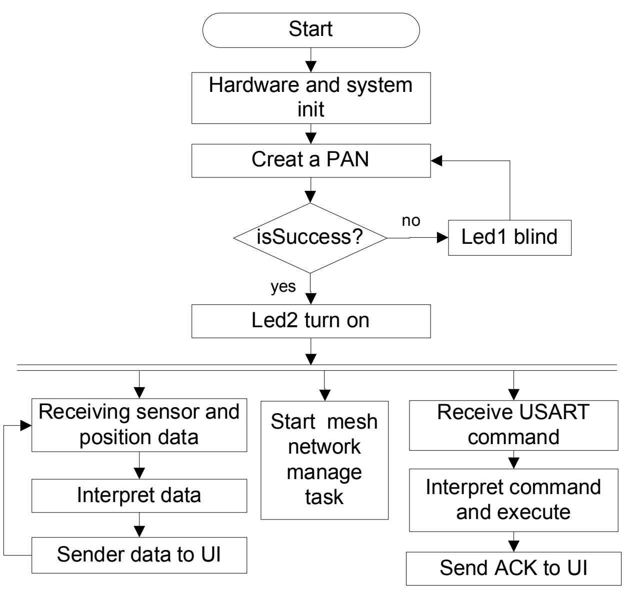

Figure 5 Flow chart for gateway node

IV. EXPERIMENTAL RESULTS

Our experiments are carried out in an indoor environment because the requirements of mine products authentication and authorization, including authentication of waterproof and explosive-proof are in proceeding. We deployed a ZigBee Wireless sensor network with 20 nodes including reference nodes and location nodes. Sensor nodes sample the data every five second. Location node sends its coordinate data every two seconds. The running of network is stable.

Figure 6 is the graphic user interface of location unit. On the map, brown dot is reference node and white-blue dot is mobile location node.

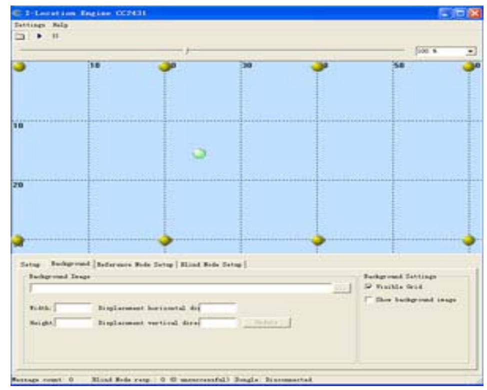

Figure 6 Graphic user interface for location unit

The RSSI value and location range are two important factors for our location system. In order to conquer the difficulty which hash underground mine environment brings to us, we improve the location range with 200 meters while TI reference implement is 63.5 meters [16]. To do this, we increase a power amplifying circuit on node hardware which is called Cicada 2.5 at first. Then we implement a range mapping in software. The RSSI value is typically in the range -40 dBm to -90 dBm for TI reference design while Cicada2.5 is in-10 dBm to -90 dBm. Table1 shows the RSSI value contrast between TI node and cicada2.5.

TABLE I. RSSI CONTRAST BETWEEN TI NODE AND CICADA2.5

RSSI(dBm) / Range(meter)	TI Node	Cicada2.5
1	-45	-10
30	-63	-33
65	-90	-55
100	--	-73
200	--	-90

Location precision is another import parameter for a location system. Figure 7 shows the error for TI node. The blue dot shows that a location node calculates its own position in same environment with different experiments. We can calculate the biggest difference for *X* is 5.5 meters (24.5-19). The biggest difference for *Y* is 3 meters (29.5-26.5). Figure 8 shows the result of our experiments. The red dot is the real position of a location node while blue dot is computing result location. We write down the (*X*, *Y*) coordinate each time and show it in the map. The biggest *X* value location error is in the coordinate (15, 0) and coordinate (19, 0). Its difference is 4 meters. The biggest Y value location error is in the coordinate (15, 10) and coordinate (18.4, 12.5). Its difference is 2.5

meters. The result shows that the averaging solution in location algorithm improves the location precision.

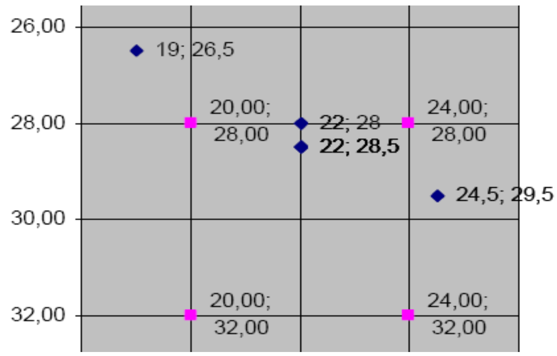

Figure7 Location error for TI node

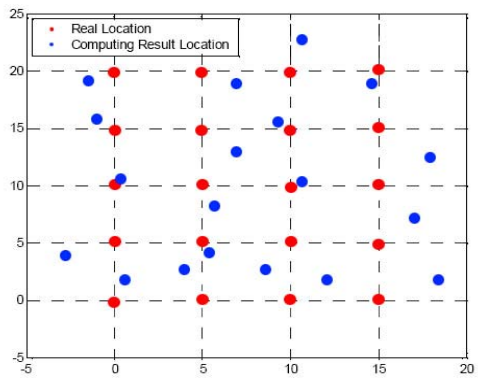

Figure 8 Location error for Cicada 2.5 node

V. CONCLUSION

A distributed location algorithm for rescue robot based on coal mine wireless sensor networks is presented. To locate an underground miner for rescue robot, a coal mine ZigBee wireless sensor network is deployed. We propose a distributed system architecture and an improved location algorithm for rescue robot based on receive signal strength indicator (RSSI) including programs on miner nodes, robot node, static reference nodes, and gateway node. The results of our experiments are analyzed.

Also, we still have some issues to resolve because the harsh underground mines environment. The method of calculating the distance using the measured RSSI value and the free space path loss model, causes some problems. For example none line of sight and diversity of the parameter N's value problems cannot be solved now [10]. Some novel location methods are proposed in papers [11]-[14]. We plan to add more types of sensors such as accelerometer, laser sensor etc. to our system and use multiple sensor fusion and filter methods to improve the location algorithm. The advantage of our system is that we have deployed a mesh and robust ZigBee wireless sensor networks for underground mine.

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