ZigBee-Based Remote Environmental Monitoring for Smart Industrial Mining

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ABSTRACT
Wireless sensor networks (WSNs) consist of large number of small and low-cost devices equipped with sensing and communication facilities to monitor the environment. The collected data are transmitted to one or more base stations which can attach to other networks and/or databases. WSNs show particular promises in applications that involve complex, human-made systems such as underground mines, factory and industrial installation. In this paper, smart sensor network architecture for temperature and fire monitoring in underground mine is evaluated. Based on application requirements and site surveys, we develop a general architecture for this class of industrial applications. The architecture is based on multiple complementary wireless communications access networks between the environment and external environment, by using IEEE802.15/ZigBee, IEEE 802.11 and the Internet.

Keywords
Keywords Wireless sensor networks; smart space; underground mine; industrial mining; data collection, monitoring.

1. INTRODUCTION
The mining industry is now a major player in Canada's economy contributing nearly 5% of the country's gross domestic product, and employed over than 300,000 workers in mineral extraction, smelting and manufacturing [1]. With new mineral deposits being discovered regularly, the economic potential of the Canadian mining industry is enormous. The ambitious development plan in Northern Quebec (i.e, Plan Nord) is one of these examples. However, before the full benefit of this industry certain criteria must be met. The SAFETY has long been a controversial issue in the mining business especially with underground mining. Underground mines environment is often wet and dark; working in these conditions are considered as a dirty and dangerous job. In spite of strong safety standards used in mines today, there are still more than 10,000 miners killed every year around the world [2]. In most cases, the mine's accidents are exacerbated by the lack of relevant and sufficient information.

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The hazards involved in underground mines necessitate a continuous risk monitoring. However, the size, the complex topology, and the dynamic nature of mines make this task more difficult. The advances in technology over recent years have opened a lot of opportunities in the field of industrial monitoring. A ubiquitous system for remote data monitoring could be crucial task to ensure safe working conditions or to detect hazards as soon as they arise. The main parameters that allow to the miner to determine the underground mine's safety level may include: temperature, fire detection, toxic gas detection, oxygen concentration, etc. If these parameters are remotely monitored, actions could be taken to prevent the dangerous situation. This "continuous" data monitoring is mandatory for risk assessment and for effective safety management. Therefore, the mining activities need a continuous data stream from surface to underground and vice versa [3]. A wireless sensor network (WSN) is a self-organized wireless network composed of a large number of sensor nodes wirelessly interconnected that interact with the physical world [4], [5]. The increasing study of WSNs aims to enable computers to better serve people by automatically monitoring and interacting with physical environments [6], [7], [8]. Generally speaking, the employments of wireless technologies in industrial and automation environments are attractive for many reasons. Compared to the wired systems, WSNs provide a huge advantage since they do not require expensive wiring cable to connect sensors to a base station [7]. The advantages of such system include low installation cost. This allows for easy sensor installation even in hard locations, easy expansion. Hence, the information could be collected with more monitoring points. In addition, the WSNs have also great flexibility (ability to add or move sensors). Furthermore, the system is generally easy to manage and maintain, since many of these networks are self-configuring. While this technology offers unprecedented flexibility and adaptability; implementing WSNs in practice is not without its difficulties. The process of deploying WSNs presents a set of challenges. The performance experienced by users depends on a number of factors: the environment, the placement of the node, the transmitter and receiver equipment, network coverage, network topology, radio propagation, the set of established links and their PHY parameters (data rate and transmit power), the operational protocols (MAC, routing,..), etc. The development of each deployment designs is strongly dependent on the individual application [5]. Therefore, evaluating the characteristic of the system in a real environment is crucial. The aim of this work is to take another step towards a smart mine. A Zigbee-based (called ZiMuMs) remote information monitoring for confined space architecture is proposed. We evaluate the performance of the ZiMuMs by building a robust wireless links and by testing its feasibility with several experimentations. We integrated six Silicon Laboratories commercial sensors to the system platform. By using these sensors, we are able to measure six temperatures at different locations. The measured temperatures are important for fire detection or for maintaining a healthful environment for the workers. The rest of this paper is organized as follows. Section 2 discusses related works. Section 3 gives an overview about ZigBee technology. Section 3 introduces environment. Section 4 presents design details of the proposed systems. Section 5 presents the performance evaluation through experimental results. Section 6 concludes this paper.

2. RELATED WORKS

In underground application, the uses of wireless sensor networks are still in their early stage of development. Only a few studies have been published in the last couple of years [9], [10], [11], [12]. The authors in [9] developed an energy efficient senor placement (EESP) strategy for tunnel wireless sensor networks. Their objective is to minimize the average energy consumption of nodes and prolong the network lifetime. The authors in [10] presented the design of an early warning system in a "Bord & Pillar" coal mine. Based on theoretical models, Roy et al. used WSN-based system to detect the exact fire location. Based on a single semiconductor (sc) of gas and temperature sensors for temperature; Reimann et al. developed a system for fire detection in coal mines [11]. In [12], the authors have investigated on the use of wireless sensor network for mine safety monitoring. The reliability for both the point-to-point communication and multi-hop communication has been studied. The main characteristic of the networks such as the throughput, the received data rate, latency have been evaluated. However, compared to theoretical studies, the experimental tests of WSNs are largely underdeveloped. The application of these efficient networks for the mining industry is still rare. This may be changed with the appearance on the market of various hardware sensor nodes; therefore, various real applications have been done recently. An interesting work was presented by Pitro et al [13], the main idea of this work was the experimental evaluation of many WSN devices for tunnel monitoring. Li and Liu proposed a monitoring system called (SASA). The design objectives of SASA include: 1) the ability to rapidly detect the collapse area and report to the sink node; and 2) the ability to maintain the system integrity when the sensor network structure is altered [14]. To better evaluate the scalability and reliability of their systems, the authors conducted a large-scale trace-driven simulation based on real data collected from the experiments [15]-[19].

3. ZIGBEE TECHNOLOGY

IEEE 802.15.4/ZigBee defines together a whole protocol stack for a new low rate wireless network standard designed for automation and control network. The standard is aiming to be a low-cost and low-power solution for systems consisting of unsupervised groups of devices in houses, factories, and offices. It is expected to be used in applications for building automation, security systems, remote control, remote meter reading, and computer peripherals [12]. However, ZigBee has the potential to serve other application fields as well. The standard low-power solution and network organization abilities make it interesting for the use in industrial monitoring. Some of these abilities are the reliability, launching time, network organization, and power consumption. A comparative study of WLAN, Bluetooth, and ZigBee for sensor networks has been done in many works. The results show that ZigBee has promising specifications when it comes to power consumption and launching time, which will be crucial for sensor networks.

3.1 Normal or Body Text

3.1 ZigBee Specifications The ZigBee standard uses the IEEE 802.15.4 standard as radio layer: MAC and Physical (PHY). Three radio bands are defined: • Global: ISM 2.4 GHz band with 16 channels and a data rate of 250kb/s • USA and Australia: 915 MHz band with 10 channels and a data rate of 40kb/s

• Europe: 868 MHz band with single channel and a data rate of 20kb/s. The defined channels are numbered 0 (868 MHz), 1 to 10 (915 MHz), and 11 to 16 (2450 MHz). Due to the protocol overhead, the actual data rates will be lower than the above mentioned. The maximum defined length for an IEEE 802.15.4 packet is 127 bytes including the header and the 16-bit checksum (CRC). The data payload is up to 104 bytes. Figure 1 shows the ZigBee protocol stack and the relations between IEEE 802.15.4 and the ZigBee Alliance in terms of the protocol.

3.2 ZigBee network system

The ZigBee network system consists of different components. The most basic is the device. A Device can either be a Full Function Device (FFD) called also the coordinator or a Reduced Function Device (RFD) represented by the end device (figure 2). A network has to have at least one FFD acting as the Personal Area Network (PAN) coordinator. The coordinator can be connected to a PC or PDA. A FFD can operate in three different modes: a PAN coordinator, a coordinator or a device. RFDs on the other hand are intended for very simple tasks and can only act as an end device. A FFD can communicate with other FFDs or RFDs, whereas a RFD can only communicate with a FFD.

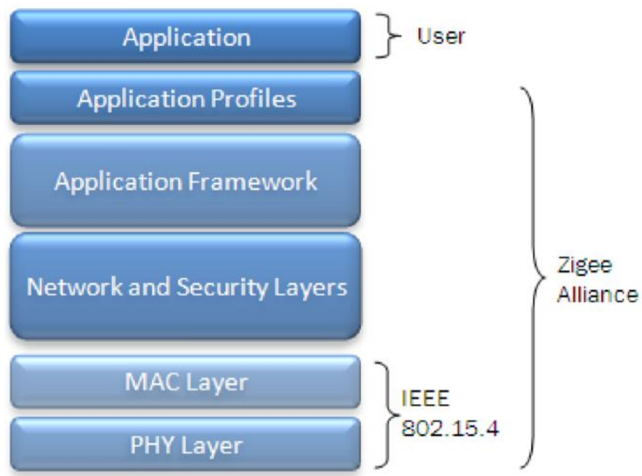

Fig. 1. ZigBee protocol stacks.

Today, most available hardware is implemented as FFDs, which is also the case for the hardware used for experiments presented later. RFDs are intended to be even simpler, more inexpensive and more power efficient and meant for low complexity sensor applications. Each ZigBee network can have a network coordinator. The coordinator starts the network, takes care of the structure and controls the procedure of assigning devices to and from the network. Every device that does not belong to a network has to go through a network association procedure. This includes that the device starts by sending an authentication request. The coordinator will answer this request within a predefined time. If a device intends to rejoin a network, it has to start the same procedure. An equivalent procedure is defined for the process of leaving a network. The device then issues a disassociation request [8].

3.3 ZigBee Protocol

In addition to the Physical (PHY) and the Medium Access Control (MAC) defined by the IEEE 802.15.4, the ZigBee Protocol Stack consists of the Network Layer (NWK), the Application Support Sub-Layer (APS), and the ZigBee Device Object (ZDO).

Medium Access Control layer controls the access to the shared radio channel. The layer generates and recognizes the addresses in addition to verifying the frame check sequences. The MAC layer also handles the transmissions of frame in the non-beacon mode. When the beacon-mode is enabled, there is an optional superframe structure, Figure 3 that can be used to guarantee access to the channel if required.

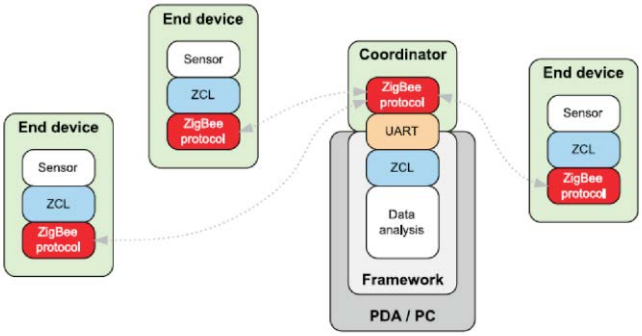

Fig. 2. Different devices of ZigBee technology.

This superframe is initiated by the beacon received by coordinator and followed by 16 equal time slots. The first nine slots can be used by any device, and the following seven slots are Guaranteed Time Slot (GTS), which can be reserved and be allocated to individual devices by request.

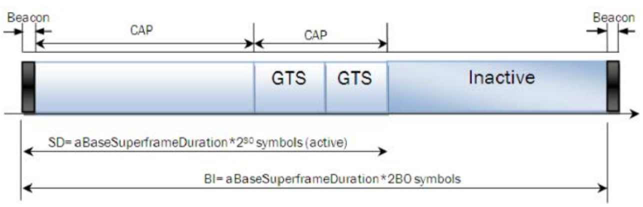

Fig. 3. Superframe structure in beacon mode.

4. ZIGBEE-BASED REMOTE INFORMATION MONITORING

WNs allow to the user to collect the information with more monitoring points, providing awareness, safety, or enabling agile and flexible monitoring and control systems. These networks connect critical processes or assets with the systems, or the experts can interpret the data and/or take immediate action. At the end of the day, the operational teams with more visibility of processes can prevent shutdowns and increase efficiencies while reducing the total cost of data acquisition In order to introduce radio-based technologies to the industrial automation systems, the automation domain specific requirements have to be fulfilled. These requirements include guarantees for the real-time (RT) behavior, functional safety, and security. The wireless sensing/control industry has traditionally relied on star networks, but the advent of inexpensive and low power microcontrollers has enabled the use of network routing protocols in low cost and battery powered nodes. Our proposal design attempts to integrate several solutions to provide a scalable and interoperability monitoring solution for smart mine.

The system that we proposed in this paper consists of six sensor nodes connected to a local LAN through a gateway. Our system provides context-aware services, especially the temperature measurement to a supervisor in home or building through interaction between the sensor and the gateway.

4.1 Hardware and Software description

The 2.4 GHz ZigBee development kit contains all necessary files to write, to compile and to debug an IEEE 802.15.4/ ZigBee -based application. The development environment includes an IDE, evaluation C compiler, software libraries. The software library includes the 802.15.4 MAC and PHY layers. The Silicon Laboratories Integrated Development Environment (IDE) serves as the primary programming and debugging tool. The IDE includes an evaluation version of the Keil C compiler, assembler, and linker. The kit also includes an adapter for programming and debugging from the IDE environment. The software library includes the 802.15.4 MAC and ZigBee Network layers. A Network Application Programming Interface (API) contains all necessary network primitives to manage and access a ZigBee network from a user defined application. In addition, the 2.4 GHz ZigBee Development Kit includes six target boards (nodes). These boards are all identical and may be used for demonstration or development. Each board features a Silicon Laboratories C8051F121 microcontroller and a Chipcon CC2420 2.4 GHz 802.15.4 transceiver. The CC2420 operates in 2.4 GHz ISM band with an effective data rate of 250 kbps, a much higher rate than older radios. In the 2.4 GHz band, it has 16 channels with each channel occupying a 3 MHz bandwidth with a center frequency separation of 5 MHz for adjacent channels. CC2420 uses an encoding scheme that encodes 32 chips for a symbol of 4 bits. This encoded data is then OQPSK modulated. The support components include a USB interface, JTAG programming interface, a variety of pushbuttons and LED's, and a voltage regulator. The system characteristics of GHz 802.15.4 transceiver are summarized in Table I. Furthermore, the controller on the 802.15.4 Development board is the Silicon Labs C8051F121 Precision Mixed Signal MCU with following features:

- 100 MIPS 8051 CPU. 128 kB Flash memory.
- 8448 bytes RAM. 12-bit 100 ksps SAR ADC
- 8-bit 500 ksps SAR ADC
- Two 12-bit DACs, Two analog comparators
- Voltage reference, Temperature sensor
- Five 16-bit timers, 6-channel PCA
- 48 digital I/O pins, 16 x 16 MAC

The 2.4 GHz Development Kit contains a variety of preconfigured networks for demonstration purposes. The neighbor table manager provided standard interconnections between the Full-Function Device (FFD) and the Reduced Function Device (RFD) terminal nodes.

The proposed monitoring system has the ability to interconnect with various solutions. The presented network has a one coordinator node and set of nodes. The coordinator node has to take care about consistency of wireless network topology. In this schema, the nodes communicate with the central node, which is connected with a laptop on site.

4.2 Subsequent Pages

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Table 1. System Performance Summary

Parameters System Specification	Parameters System Specification
Standard Basis	IEEE Std. 802.15.4™
Frequency (MHz)	2400 - 2483.5 GHz
RF Bandwidth (KHz)	1200 KHz
Nb of channel	16
RF Channel Spacing	3 MHz 250 kbit/s
Data Rate Burst	QPSK
Modulation Type	DSSS
Spreading Technique	15-chip m-sequence
PN Code	0 dBm (to 50 Ω)
Tx Output Power	-98 dBm
Rx Sensitivity	17.4 mA
Typical Supply Current	

The laptop is connected to IEEE 802.11 g wireless local area networks (LAN) trough access point (AP). The LAN is connected to Internet through a gateway. Gateways play the role of communication between WSNs, LAN and Internet access. At the end, the node transmits the data into data server located in monitoring room using wireless communication network, and dynamically release the information on internet.

5. MEASUREMENT SETUP AND RESULTS

Intensive measurements were carried out in underground galleries of a former gold mine at CANMET in Val-d'Or, Qc, Canada. The measurements were conducted at level 70 m in the mine. In the first part, we describe the radio frequency link characteristics from the test-bed received signal level and secondly we analyze the collected temperature data.

5.1 Measurement setup

In the first measurement campaign, the central node remained at a fixed position whereas the salve node was moved at different locations. The measurements were taken for both static and moving node (Fig. 4).

Fig. 4. Gallery mine (Canada's CANMET Mining and Mineral Sciences Laboratories).

Four sets of experiments are designed to evaluate the various performance behaviors of IEEE 802.15.4, including the effects of the distance separation between the controller and the end device. The experiments were run in a one-hop star topology. The distance between the coordinator and the device start from 1 meter to 115 m. This process helps us to determine where and at which distance we are able to place the node while the link performance remaining good. We used the LQI to evaluate this performance. Based on this set-up measurement, we have deployed the six monitoring nodes.

5.2 Link-Quality Metric (LQI)

The link quality indicator (LQI) is an indication of the quality of the data packets received by the receiver. The received signal strength Indicator (RSSI) can be used as a measure of the signal quality. The RSSI is a measure of the total energy of the received signal. The ratio of the desired signal energy to the total in-band noise energy (SNR) is another way to judge the signal quality. As a general rule, higher SNR translates to lower chance of error in the packet. Therefore, a signal with high SNR is considered a high-quality signal. The link quality can also be judged using both the signal energy and the signal-to-noise ratio.

In IEEE 802.15.4 standard, the LQI measurement is defined as a characterization of the strength and/or quality reception of a packet. The value of the LQI is calculated at physical layer. The LQI measurement is performed for each received packet, and the result is reported to the MAC sub-layer as an integer number for 0 to 250. The minimum and maximum LQI values are associated with the lowest and the highest signal qualities detectable by the receiver and the values of LQI is always varies between these two limits. LQI can be formulated as:

$$\mathrm{LQI} = \frac{\text{Received Msg Power}}{\text{Interference Power} + \text{Noise}}$$

Where, the Receive Msg Power shows the value of signal strength of received signal. Interference power gives the value of interference of coming signal to other signal on the same radio and noise power is a value of noise in that environment. By such values the definition of LQI can be summarized as: LQI is a ratio of received signal strength to sum of interference power and noise power.

A relationship graph between distance and their corresponding values of LQI is shown in Figure 5. The maximum value of LQI observed is around 250 at distance of 95 m. Then it is gradually decreasing as the separation keeps on increasing. The results conclude that small sized frames of ZigBee take relatively more time at extreme distances and remain almost constant at feasible distances. Furthermore, this critical point coincides with a slight curvature of the underground gallery.

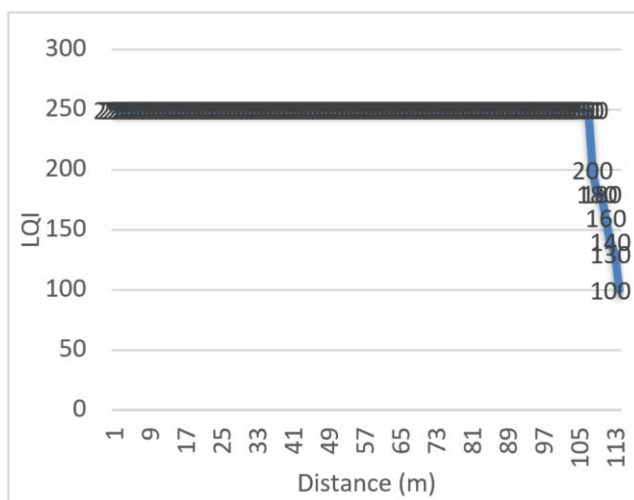

Fig. 5. The received LQI vs. distance.

5.3 Temperature measurement

The trial was started at approximately 9:00 and finished at approximately 15:00. In this scenario, the six nodes were located at fixed positions. The temperature values measured by six wireless sensor nodes are shown in Figure 6. Local temperature values were strongly influenced by the node location. Node E was near ventilation system. Thus, the temperature stayed lower compared to other nodes. In addition, this figure shows that the temperature in all locations differed by at least 5 C and stayed stable from 9:00 to 15:00. An example of measured temperature of node B is given in Figure 6.

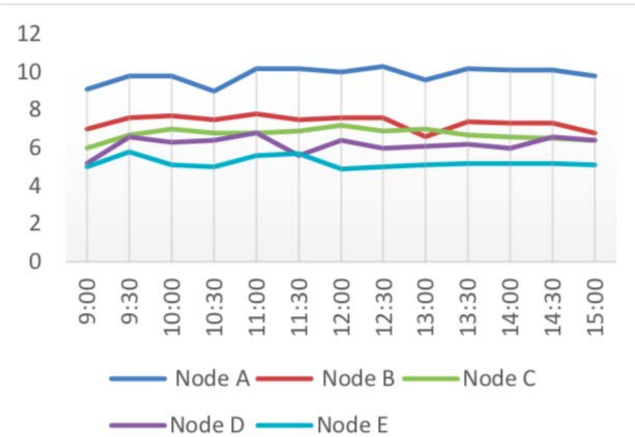

Fig. 6. The measured temperature.

5.4 Power Consumption

is a low-power wireless specification that uses a PHY and media access control (MAC) based on IEEE 802.15.4. The ZigBee standard is designed for applications that need to transmit small amounts of data while being battery powered so the architecture of the protocols and the hardware is optimized for low power consumption of the end devices. This is a great advantage when it comes to using ZigBee devices in sensor networks. The battery lifetime requirement is essential in order to avoid the necessity of frequent battery changes. Using a ZigBee device with conservative power consumption is both adequate and desirable. The implementation of network topologies has also a great impact on the power consumption. By enabling beacons, the network can allow RFDs to go into sleep-mode and wake up on beacons from the network coordinator at predefined time slots.

6. CONCLUSION

In this paper we described Zigbee-Based remote information monitoring for smart space. The developed system is low-power and robust, with possibilities of remote control and maintenance, thus appropriate for various environmental monitoring applications. This architecture based on multiple complementary wireless solutions, through IEEE 808.15.4/ZigBee, IEEE 802.11 and Internet. The system is not only capable of providing real-time temperature monitoring and alarm in case of a fire (when the reported temperature increases dramatically), but also able to provide the exact fire location and spreading direction by continuously gathering, analyzing, and storing real time information. The overall system is expected to also help to reduce the cost installation of the current systems.

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