A Practical Evaluation of ZigBee Sensor Networks for Temperature Measurement

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Abstract. Wireless Sensor Networks (WSNs) offer numerous advantages over traditional networks, such as elimination of costly wires, enhanced monitoring precision and larger area coverage. This paper presents the design and implementation of a mine temperature monitoring based on sensor networks. For the proposed monitoring schema, we evaluated the performance and the interoperability of sensor network with various network such as IEEE 802.11g (WiFi), IEEE 802.11s (wireless mesh network) and Internet. So the ambient temperature of a mine gallery can be measured and displayed in real time no matter where we are. In addition we describe some initial results of link characteristics. We discuss on the sensor wireless link performance in terms of the received signal strength.

Keywords: sensor networks, zigbee, underground mines.

1 Introduction

A wireless sensor network (WSN) in its simplest form can be defined as a network of low-size, low-complex and locally powered sensor nodes that can sense the environment and communicate the information gathered from the monitored field through wireless links. The data is forwarded via multiple hops relaying to a central node (or sink) that can use it locally, or is connected to other networks through a gateway. The claim of wireless sensor network proponents is that this technological vision will facilitate many existing application areas and bring in to existence entirely new ones [1], [2].

Detection of world's physical parameters makes sensors most suitable technology for monitoring. Sensors though are not just limited to environment sensing. Any application involving sensing of physical parameters like sound, humidity, pressure, temperature, etc, might use sensor network.

Considering the importance of this technology, a deployment of WSN in mining industry can be considered as original application. For example, an operator could remotely supervise different physical phenomena in the mine from his computer and thus provide safe air/oxygen for the miners underground by monitoring the level of methane and other noxious gases, dust and particulates from sources such as diesel

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vehicles. He could also monitor the temperature, detect any anomaly, or locate workers and objects in the galleries of the mine in real time. These applications can be seen as a first step toward the concept of *"smart mine"*.

Usually, we verify performance of any network by using simulations or experiments. In simulations, we cannot control precise packet timing, radio range transmission, an unlimited memory and processing resources, and real PHY/MAC layer events. In fact, not all simulation results are equal to the real experiments. In real experiments, we have complex environment settings and resource sharing problems.

In this paper, we discuss the challenges and requirements of developing efficient WSN for temperature monitoring for mining industry. For this reason, we have set up a testbed at CANMET[1] that provides a heterogeneous platform to support realistic environmental data measurement application.

The remainder of this document is organized as follows. Section 2 provides a review and motivation of using wireless sensor network in mining industry. Then, in Section 3, we will present the characteristics of the commercial sensor used in our experiments. Section 4, describes the measurements, and gives the results and the most important challenges. Finally, we will conclude with Section 5.

2 Motivation for Using WSN

Underground mining is a hazardous industrial activity. The harsh physical environment and distinct topology that make mining dangerous act as a hindrance or constraint to the very techniques and technologies that could improve safety and productivity.

Working conditions in underground mining are associated with a considerable number of health risk factors, such as a high physical workload, fire and radiation exposure, high temperature and humidity conditions and exposure to dust and gas phase hazardous substances.

Generally, the motivation for using wireless sensors in mining industry is twofold: economy and safety. From a system operation perspective, wireless sensors give an opportunity to safely and cost efficiently increase measurement coverage of the network, including locations where wiring is impossible. In fact, this emerging technology, unconstrained by expensive wiring, has the potential to provide operating efficiencies. These efficiencies are made possible through reduced installation costs, lower operating costs, installation flexibility, and scalability.

Wireless sensor networks allow faster deployment and installation of various types of sensors because many of these networks provide self-diagnosing, self-configuring self-organizing and self-healing capabilities to the sensor nodes. Some of them also allow flexible extension of the network.

Another advantage of wireless sensors is their mobility. These sensors can be placed in transporting vehicles to monitor the environment. They also can be attached on rotating equipment, such as a shaft to measure critical parameters.

However, despite all its advantages the deployment of wireless sensors in underground mines is still at the beginning stage. Three majors application scenarios of wireless sensor networks can be identified [3].

[1] Canadian Center for Minerals and Energy Technology (CANMET) experimental mine.

2.1 Environmental Data Measurement

In this scenario, the nodes are located at fixed position in the mine. Some node may be equipped with a sensor, while others are routing the data. The important parameters that could be measured in underground mines are: temperature, oxygen concentration, humidity.

The global network is characterized by a great number of nodes which collects and measures in a continual way of the data towards a central unit.

The management of the networks is treated in the high level of the networks. A sensor management protocols determine which nodes are needed to provide data (sensing mode selection) and which are needed to ensure a connected topology and the data routing (topology control). This last aims to rotate active nodes; therefore the energy drain of performing routing task is distributed evenly among all the nodes in the networks [4]. Other configuration process can be used to find the upper bound of attainable lifetime using sensor management algorithms that determine sensing, routing and data fusing roles for each sensor in the networks [5].

The data are periodically transmitted from child node to the parent node. For much of scenarios the typical periods of measurements are about few minutes because the supervised parameters of environment, like the temperature, the intensity of the light, do not change rather quickly to require measurements with very close intervals [6].

2.2 Security Monitoring

For this type of application, the nodes are placed at fixed locations in order to supervise continuously some parameters. The goal is to detect possible anomalies like fires, gas explosions, premature explosions of charges, toxic gases (carbon monoxides, carbon dioxide), or even a roof failure using microseismic and rock deformation sensors.

2.3 Localization

Monitoring the precise location of mobile assets in underground mines is valuable information not only for safety but also as an enabler of business process optimization such as ventilation-on-demand, automated logging of LHD mucking cycles, or traffic light control in ramps. Since GPS does not work underground, an alternative method of mobile asset tracking must be implemented.

Localization and tracking of moving objects is an essential capability for a sensor network. For this kind of application, we suppose that any agent (such as a miner or a vehicle) entering in underground mine can accurately located. We assume that a large number of anchors (sensor node with known location) are deployed in underground mines. The agent is equipped with small sensor, this sensor can estimate it distance from these anchors (ToA), and then use the positioning algorithm (triangulation) to determine its own position. This location can be sending over the networks and collected by central node to indicate the position of this agent. Therefore, wireless sensor networks can provide an ideal solution to track and locate the miners. It can be considered as an end-to-end rescue communication network for miners during an incident [7].

3 Wireless Sensor Networks Testbed

When choosing deployment of WSN in underground mine, it should be necessary to make a compromise between conflicting requirements. The priority is to insure a robust global network with battery-operated nodes. Therefore, the network was developed with the following goals in mind. Firstly, the node must be able to communicate with other notes via a highly reliable radio module compatible with the IEEE 802.15.4 standard. Secondly, the network should be robust to monitor temperature for long time.

We deployed a wireless sensor network in April 2009. The network contains all elements of the architecture (will be described in the next subsection). To withstand the temperature conditions, dust, and the strong humidity present in underground mines, we designed environmental protective packaging that minimally obstructs sensing functionality. The selected motes by their design are fairly robust mechanically, with the battery case firmly integrated with the main processing and sensor boards.

Wireless communication is achieved with a transceiver compliant with the IEEE 802.15.4/ZigBee™ standard. ZigBee™ is a global standard for wireless network technology that addresses remote monitoring, environmental data measurements and control applications. ZigBee™ is an open specification that enables low power consumption, low cost and low data rate for short-range wireless connections between various electronic devices.

In this section, an overview on the hardware implementation and the software protocol are given. First, a customized wireless communication test platform for evaluating wireless networking protocols is presented. A detailed description of capabilities and limitations of the test platform is discussed. The testbed consists of the following components:

- Hardware Description;
- Software Description;
- Network Architecture;
- Networks Topology;
- Node Deployment;
- WSN to Internet communication.

3.1 Hardware Description

The Silicon Laboratories 2.4 GHz 802.15.4 Development Board (DB) provides a hardware platform for the development of 802.15.4/ ZigBee™ networks. The DB includes a Silicon Labs 8051-based MCU, a Chipcon CC2420 RF Transceiver, a JTAG (Joint Test Action Group or IEEE 1149.1 standard) connector for in-circuit programming, an assortment of programmable buttons and LEDs and a USB interface for connecting to the host computer.

Figure 1. (a) shows a block diagram of the DB. The DB card has been developed with a minimal number of components. This is due in part to the low power-consumption requirement and in part to the need to keep the mote size and manufacturing costs to a minimum. The core of the platform is a Silicon Labs C8051F121 (MCU) ultra-low power microcontroller. The device is quite powerful

with an 8051 CPU (100 MIPS). This microcontroller can typically operate at clock frequencies up to 8 MHz with 128 kB of flash memory and 8448 bytes of RAM.

Wireless communication is provided by the Chipcon CC2420 radio transceiver. This circuit combines low power and efficient operation with support for IEEE 802.15.4. It operates in the 2.4 GHz Industrial-Scientific-Medical (ISM) unlicensed radio frequency band, with 16 channels. It uses an automatic PCA (Parallel Channel Adapter) and address filtering. The consumption of CC240 is estimated at 19.7 mA for Rx and 17.4 mA for Tx.

Automatic acknowledgment transmission is used, and a CRC criterion (Cyclic Redundancy Check) is employed to decide whether a packet was received correctly or not. The radio module is connected via an SMA connector to an omnidirectional antenna.

The DB has a total of eleven LEDs. The LEDs are used to show the state of the mote (after reset, sending a message, etc.) and two of them are used for power status indicators. An internal temperature sensor is included in the board with a measuring range of (-40 C to +85 C). The DB is powered with a 9 V battery. Some basic parameters are summarized in Table 1.

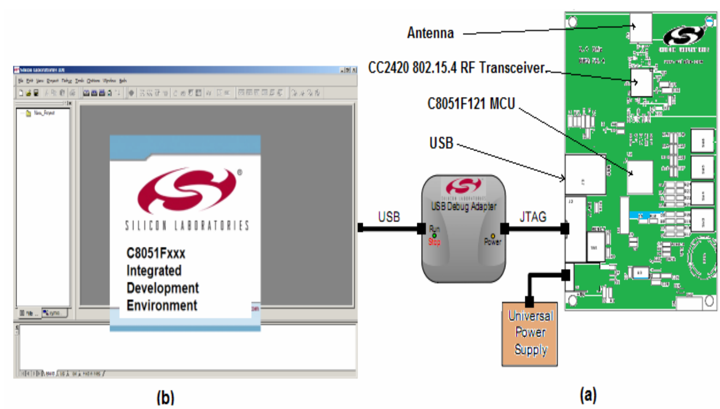

Fig. 1. The Silicon Laboratories 2.4GHz 802.15.4 mote (a) Development Board, (b) software interface

3.2 Software Description

The 2.4 GHz ZigBee^{TM} development kit contains all necessary files to write, compile, download, and debug a simple IEEE 802.15.4/ ZigBee^{TM} -based application. The development environment includes an IDE, evaluation C compiler, software libraries, and a several code example. The software library includes the 802.15.4 MAC and PHY layers.

The ZigBee^{TM} demonstration provides a quick and convenient graphical PC-based application. The kit also includes an adapter for programming and debugging from the IDE environment as shown in Figure 1 (b).

A Network Application Programming Interface (API) contains all necessary network primitives to build a 802.15.4 network from a user-defined application. A software example illustrates the MAC API. This example builds an ad-hoc 802.15.4 network using the included MAC API software library.

Table 1. System Performance Summary

Parameter	***System Specifications***
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
Data Rate Burst	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 (Tx)	19.7 mA
Typical Supply Current (Rx normal, frame reception)	

3.3 Networks Topology

The geographical nature of a mine galley (narrow and elongated corridors) has a direct impact on the design of sensor network applications. In its simplest form, a sensor network is single-hop, allowing every sensor node to communicate directly with every other node.

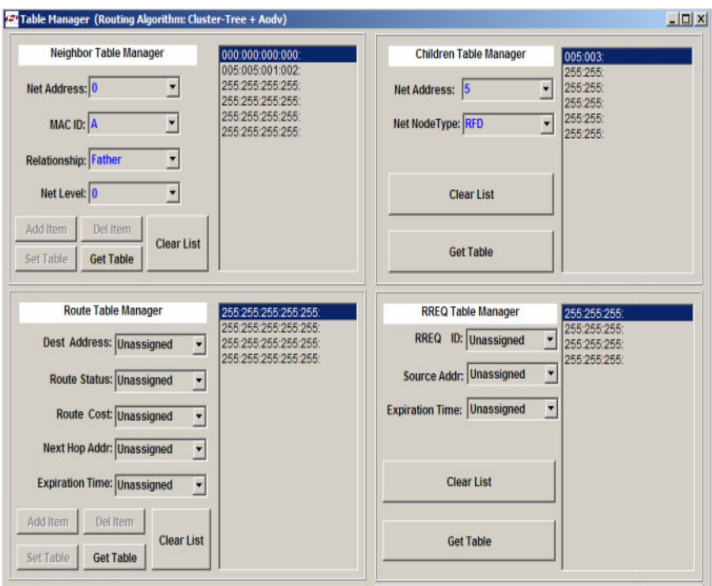

Fig. 2. The neighbor table manager

The Silicon Laboratories 2.4 GHz development kit contains several preconfigured network topologies. These topologies are predefined and downloaded first to each node via a USB connector. For our measurements, cluster tree, star and linear topologies were separately adopted.

For example, Figure 2 contains the blacklist table for central node of the cluster tree topology. Node A is the designated master (central node) in this topology. Other nodes are Full-Function Device (FFD) routing nodes or Reduced Function Device (RFD) terminal nodes, depending on the network topology selected.

3.4 Network Architecture

Wireless sensor network is used to transfer the sensor data frames from the sensor unit over a radio interface to the central node. If a radio link can be established between these modules for peer-to-peer communication, the radio modules put each sensor data frame into a radio message, send the message over the radio link, and extract the sensor data frame from the received radio message. Figure 3 shows that the sensor data are transmitted directly from the sensor node to the central node, which then transmits them to the base station.

The network organizes itself and is self-healing, i.e. network nodes automatically establish and maintain connectivity among them.

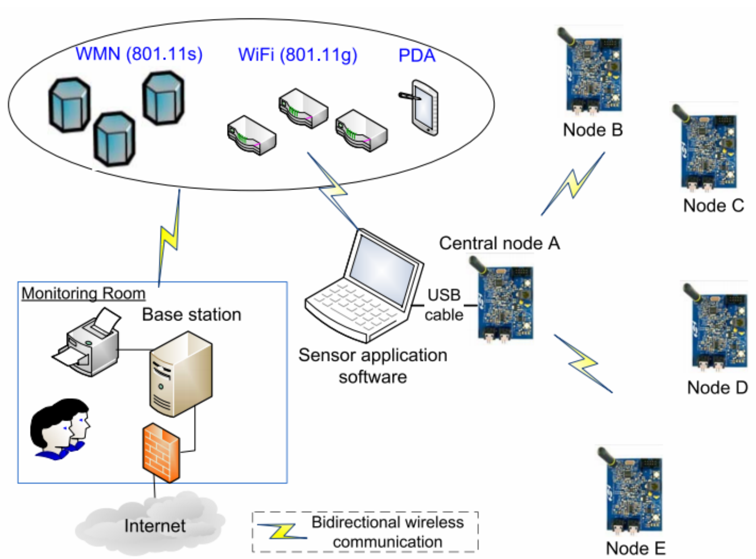

Fig. 3. Block diagram of the heterogeneous wireless network's deployment

3.5 Node Deployment

The deployment of sensor nodes in the physical environment may take several forms [8]. In the case of an underground mine, the deployment may be random (unexplored part of mine), at deliberately chosen spots on the top of the gallery or at a fixed position on the gallery walls. In manual deployment, the sensors are manually placed and the data are routed through predetermined path. The deployment operation may be a one-time activity, where the installation and the use of a sensor network are strictly separate activities. However, deployment may also be a continuous process, with more nodes being deployed at any time during the use of the network, for example, to replace failed nodes or to improve coverage of the network.

3.6 WSN to Internet Communication

For practical deployment, a sensor network only concerned with itself is insufficient. The network rather has to be able to interact with other information devices, for example, a miner equipped with a PDA moving will be able to read the temperature sensors even this node is located in different mine galley. To this end, the WSN first of all has to be able to exchange data with such a mobile device. This schema can be generalized to other important security parameter (carbon monoxides, or smoke concentration, for example).

Therefore, for the proposed WSN monitoring system, we evaluated the performance and interoperability of sensor network with various network such as 802.11g (WiFi) and IEEE 802.11s (wireless mesh network). In this schema, the nodes communicate with the central node, which is connected with a laptop on site. This last one has the capability of communicating wirelessly with other computers located in a monitoring room via IEEE 802.11 networks (or wireless mesh network). The number of access points of both WiFi and wireless mesh network are sufficient to ensure a total coverage of mine gallery. The system is connected to Internet through a gateway. Gateways play the role of communication between WSNs and Internet access. We use a single board computer with public IP address as gateway in a WSN. So the ambient temperature of a mine gallery can be measured and displayed in real time no matter where we are. The global schema of WSN mine gallery temperature monitoring is shown in Figure 3.

Fig. 4. Gallery mine (CANMET)

4 Measurement Setup and Results

4.1 Measurement Setup

The measurements were carried out in an underground gallery of the MMSL-CANMET laboratory mine located 540 km north of Montreal, QC, Canada. We have performed the measurements at the 70 m level. Figure 4 show an example the node placement in the mine gallery for LOS (line-of-sight).

In this measurement campaign, the central node remained at a fixed position whereas the salve node was moved at different locations in mine gallery. The measurements were taken for both static and moving node.

4.2 Link Characteristics

In this section, we describe some preliminary results of measured link characteristics from the testbed. Specifically, we discuss some statistics of the wireless link performance in terms of delay, received signal loss, link quality indicator and throughput.

4.2.1 Received Signal Strength

Figure 5 plots the received signal strength versus the distance. One can observe two regions of path loss. In the first region (1 to 40 m), signal attenuation is about 40 dB between 1 m and 40 m, which is significant considering that the transmitter and the receiver, in this case, are in line-of-sight. However, the second region (from 40 m to 105 m) is characterized by small signal attenuation. This small attenuation is due to

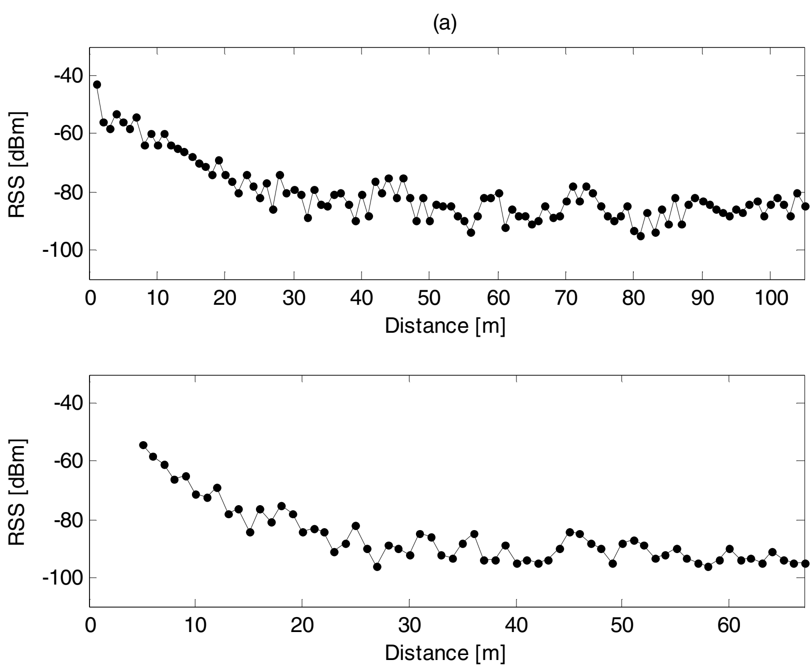

Fig. 5. The received signal of a node vs. distance (a) LOS, (b) NLOS

the topology of the gallery. In fact, this region of the gallery is represented as a narrow corridor in which the multipath adds; therefore the signal can travel a long distance with a small attenuation. This is known as the "waveguide propagation phenomenon".

4.3 Temperature Measurement

The ultimate goal of wireless sensor network research is to enable novel applications that change the way we interact with the world around us. Wireless sensor networks allow information to be collected with more monitoring points, providing awareness for the environmental conditions (for fire detection for example) that affect overall uptime, safety, or compliance in mining environments and enabling agile and flexible monitoring and control systems.

In the literature, several works deal with WSNs for temperature monitoring [9], [10]. As an illustrative example, we have used the nodes to monitor the ambient temperature of the mine gallery. Note that the nodes could easily be adapted to monitor other types of temperatures (the temperature of a machine).

To test how the entire system deal with the gathering of data from multiple sensor networks five nodes were used during measurement. The first wireless sensor network (A) involved a base-station (connected to laptop) and four slave node placed in different positions. The trial was started at approximately 9:00 and finished at approximately 15:00.

The data is shown in Figure 6. This figure shows that the temperature in both locations differed by at least 2 °C. The transfer of data across the Wi-Fi and mesh network was largely perfect.

4.4 Some Challenges

Real applications of WSN are being explored and some of them are yet to come. While the potential of sensor networks in underground mine is only beginning to be realized, several challenges still remain.

One of theme is the complex nature of wave propagation in underground mine. This is due to scattering and rough surfaces diffraction in mine tunnel. So, the RF link budget should include a safety margin of several dBs to ensure reliable communications between nodes. Also, in underground mine environment, a daisy chain of nodes installed along a tunnel must with stand the failure of a node. One effective way add to redundancy is to ensure each node in the chain is in range of at least two other nodes on each side. Networks topology designs should also take into consideration potential attenuation caused by rubble if ever part of mine tunnel collapses.

Here we expose some limiting challenges for using WSN in underground mine applications:

- Power consumption always an issue.
- Topology change due to human activity (system should scale well on a large number of topologies).
- It is necessarily to take into account the characteristics of the mine, like gallery size and shape, and the desired coverage.
- Radio connectivity varies over time and is very sensitive to position.
- Temperature measurements can be affected by changes in surrounding conditions (ventilation system for example).

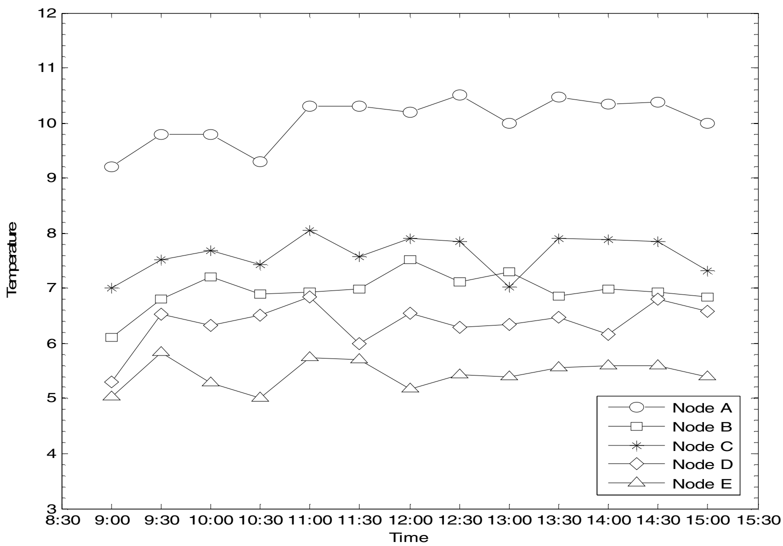

Fig. 6. Temperature data recorded simultaneously from five sensor node

5 Conclusion

Wireless sensor networks became a key technology and are used in more and more industrial and environmental applications. In this paper we have evaluated a WSN testbed to conduct an integrated monitoring system. We have tried to demonstrate that the proposed architecture can be used to measure the temperature of underground mine gallery in real-time. This scenario can be easily generalized to others environmental parameters (toxic gas detection, humidity, etc).

Challenges remain in conducting experiments with larger number of sensor nodes in more complicated scenarios. We highlight all the problems identified at this initial phase, which will influence the final deployment of the complete WSN. This work is being developed in the context of an ongoing project on underground mines environmental monitoring using WSNs.

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