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An investigation of underground monitoring and communication system based on radio waves attenuation using ZigBee

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ABSTRACT

In the challenging environment and changing topology of a mine, reliable and effective communication is a high-stake issue along with the objectives of safe and efficient mining operations. Automation by remote and automatic systems have improved workplace health and safety for employees, cost-effectiveness, management of technical problems, energy saving, real-time response to events. In response to these challenges, wireless sensor networks (WSNs) have been widely employed in underground monitoring and communication systems for the purpose of environmental monitoring, positioning of workers and equipment, operational monitoring and communication system. Considering the capabilities of WSNs, ZigBee network is adapted. In this study, common WSNs are evaluated for application in underground mines and demonstrated why ZigBee network performance is suitable for such environments. ZigBee radio waves attenuation is investigated to evaluate stable communication range between ZigBee nodes at straight and curved tunnels in a real mine scenario. Moreover, experimental measurements of ZigBee radio waves attenuation are validated by simulation results. Based on the analysis of the experimental and simulation results, the effective factors on the radio waves attenuation in the junctions, curvatures and fields near and far from the source are assessed. Finally, stable wireless communication ranges between developed ZigBee nodes in the underground Angas Zinc Mine is concluded 100 m and 70 m for straight and curved tunnels, respectively. The development of ZigBee network application compared to other WSNs in underground mines is also approved.

1. Introduction

The increase in demand for mineral products continues to drive the global expansion of the mining sector. Recently, new technologies have focused on deeper mines as near-surface ore is depleted. Also, underground mining is a risky operation because of typical workplace characteristics. Many research papers have been dedicated to clarifying factors which cause humans casualties and injuries, recurring hazards and unexpected costs in underground mines (Saleh and Cummings, 2011; Khanzode et al., 2011; Molina et al., 2011). Typical hazards associated with the underground mining include poor lighting conditions, narrow space, rock falls, poor ventilation, wet conditions, communication constraints and structural complexity. To improve safety and management efficiency in underground mining, some studies have focused on operational problems such as fleet management including dispatching, routing and scheduling (Gamache et al., 2005) and geotechnical considerations for example; ground movement and tunnel collapse (Li et al., 2010; Ghorbani et al., 2012). As a result, it is necessary to enhance future safety and operational management through using new technologies based on monitoring and communication systems to ameliorate unpredictable work hazards.

Wireless sensor networks (WSNs) have been utilised in underground mines as an alternative to enhance safety and productivity and reduce operational costs (Chehri et al., 2009; Bhattacharjee et al., 2012). The underground WSNs consist of a few to several hundred nodes between a surface gateway and specified sensor nodes in the underground levels. Each node can connect to one or more nodes in order to transmit data. The common WSNs for monitoring and communication system in underground mining are mainly comprised of Bluetooth technology, ultra-wideband (UWB) technology, Wi–Fi technology and ZigBee technology.

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Table 1
Comparison of common underground WSNs.

Parameters	Bluetooth	UWB	Wi–Fi	ZigBee
Communication distance (m)	10	<10	50–100	50–500
Frequency range (GHz)	2.4	3.1–10.6	2.4 or 5	2.4
Data rate (Mbps)	1	100–500	11	250×10^{-3}
Network capacity (nodes)	7	10–500	32	65,536
Power consumption (mW)	1–100	30	500–1000	20–40
Complexity	High	Medium–high	High	Low

For the investigation of applicable and reliable wireless system, the main features of underground WSNs are illustrated in Table 1 (Kawamura et al., 2013; Bandyopadhyay et al., 2009; Jinyun et al., 2009; Bluetooth, 2013). As shown in Table 1, Bluetooth has limited applicability because of its very short communication distance between nodes (i.e. high number of needed nodes in tunnels) and its low network capacity. However, UWB meets a suitable data rate, network capacity and low power consumption node but the communication distance restriction may cause congestion of nodes in tunnels. Thus, traffic routing would be a crucial problem in a UWB system.

Wi–Fi is a common wireless technology utilised in underground mines. It has adequate communication distance and high communication speed. Some negative aspects of this network are high power consumption nodes, the need of infrastructure access points for clusters, continuous power supply and access point connections for cabling. Additionally, there is no multi-hop network topology between Wi–Fi nodes, even though; data is able to be transmitted between nodes and access point.

ZigBee is a new wireless technology which includes more benefits compared to other WSNs for monitoring and communication systems in underground mines. It has suitable communication distances between nodes, substantial capacity of nodes within a network, low energy consumption sensor nodes and low complexity, as shown in Table 1. Also, ZigBee technology has very cost-effective nodes, network installation and maintenance compared with other underground WSNs. It does not require any access point or central node to transmit data between clusters. Although ZigBee network has very low data rate (250 kbps) for image, voice and video communication, it is capable in providing networking applications for data transmission between nodes (node to node relays) with high performance based on many wireless hops.

Recently, ZigBee has been used in the field of mine safety for a range of applications mostly in underground coal mines as automatic meter reading systems, security systems and remote controls with supporting other WSNs (Hongjiang and Shuangyou, 2008; Chehri et al., 2011). In this study, a monitoring and communication system for underground mines based on ZigBee network performance without supporting other WSNs is proposed. Use of central (sink) nodes or access points is eliminated because of high power consumption and cable damage risk. In fact, ZigBee is selected for its powerful networking capability through ad-hoc and multi-hop topology, its considerable network capacity and cost-effectiveness. Based on this system, data from sensors (fixed nodes) and workers and vehicles (mobile nodes) locations in underground mine could be transferred to a surface gateway for monitoring and bilateral communication. Wireless network coverage for long distance is mandatory considering the spatial positions between the surface gateway and ZigBee nodes in underground mines. Therefore, investigations to prove the proposed system as a reliable and secure network are delineated as below:

- Stable communication range for packet delivery.
- Network throughput and latency (delay) data.
- Accuracy of the position of mobile nodes.

Based on expanded knowledge of underground WSNs, the research has focused on the stable communication range between ZigBee nodes.

The procedure of the specified WSN selection in underground mines is illustrated in Fig. 1. To investigate the stable communication range between ZigBee nodes, first the theory of radio waves propagation models to simulate experimental measurements in the tunnel is described. Then, the methodology of experimental measurements and simulations on radio waves attenuation are provided. Finally, discussion, comparison of the results and conclusion are presented according to Fig. 1.

2. Radio waves propagation models in tunnels

Radio waves propagation in underground mine environments is described based on tunnel channel models. There are different models to evaluate effective factors on the wave's attenuation of the tunnel environment. Practically, received power is predicted from the attenuation model by knowing the transmitter power level. For example, the radio waves propagation near the walls or floor of the tunnel can be simulated by the two-ray (two-slope) model where free-space model (Friis equation) is preferred for simulation in the hollow space of the tunnel. Moreover, the radio waves propagation is modelled with Rice distribution for line-of-sight (LOS) between the transmitter and receiver nodes in straight tunnel, and the Rayleigh distribution model is considered for non-line-of-sight (NLOS) passing over tunnel curvature (Lamminmaki and Lempiainen, 1998; Boutin et al., 2008). Fig. 2 illustrates typically practical measurements for attenuation trend and a theoretical model in a tunnel channel at the frequency of 2.4 GHz [after 17].

In this study, multimode waveguide model is investigated to simulate both near and far regions from the source by summing the power of rays received from reflections on the tunnel walls and the source. The excitation plane is used in the geometrical optics (GO) model of Shooting and Bouncing Ray (SBR) method to analyse different field distributions and attenuation coefficients (Zhi and Akyildiz, 2010). Based on this method, rays are first traced from the source then reflected rays from tunnel walls are calculated. According to this technique, Maxwell's equations and eigenfunctions, the received signal power (P_r) at the coordinate (x, y, z) would be obtained by Eq. (1):

$$P_r(x,y,z) = P_t G_t G_r \left(\frac{1}{E_0} \Sigma_{m,n} C_{m,n} \cdot E^{eign}_{m,n}(x,y) \cdot e^{-(\alpha_{mn}+j\beta_{mn})\cdot z} \right)^2 \tag{1}$$

P_t is the transmitter power; G_t and G_r are the antenna gains of the transmitter and the receiver, respectively. m and n indicate the field of all significant modes. $C_{m,n}$, $E^{eign}_{m,n}$, α_{mn} and β_{mn} are the mode intensity in the excitation plane, eigenfunctions, the attenuation coefficient and the phase-shift coefficient, as given by Eqs. (2)–(5):

$$C_{m,n} = \frac{E_0 \pi}{ab\sqrt{1 - \left(\frac{m\pi}{2ak}\right)^2 - \left(\frac{n\pi}{2bk}\right)^2}} \sin\left(\frac{m\pi}{2a}x_0 + \varphi_x\right) \cdot \cos\left(\frac{n\pi}{2b}y_0 + \varphi_y\right) \tag{2}$$

$$E^{eign}_{m,n}(x,y) \cong \sin\left(\frac{m\pi}{2a}x_0 + \varphi_x\right) \cdot \cos\left(\frac{n\pi}{2b}y_0 + \varphi_y\right) \tag{3}$$

$$\alpha_{mn} = \frac{1}{a}\left(\frac{m\pi}{2ak}\right)^2 Re \frac{\overline{k_v}}{\sqrt{\overline{k_v} - 1}} + \frac{1}{b}\left(\frac{n\pi}{2bk}\right)^2 Re \frac{1}{\sqrt{\overline{k_v} - 1}} \tag{4}$$

$$\beta_{mn} = \sqrt{k^2 - \left(\frac{m\pi}{2ak}\right)^2 - \left(\frac{n\pi}{2bk}\right)^2} \tag{5}$$