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Performance analysis of ZigBee network topologies for underground space monitoring and communication systems

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ABSTRACT

The advancement in tunnelling and underground space technologies and the need for large scale monitoring and communication systems for safe and efficient operations has triggered the era of wireless sensor networks (WSNs). The progress of WSNs have been associated with the innovation of sensor nodes with the more significant features of smaller size, more cost-effectiveness, lower latency and powerful antenna coverage. The sensor nodes arrangement in dense industrial WSNs is one of the crucial issues for a better quality of service and a reliable message transmission through the network. In this study, we investigate various sensor node arrangements of ZigBee networks for underground space monitoring and communication systems. The performance of ZigBee topologies are analysed in 12, 20, 30, 40 and 50-node scenarios for stationary node deployment in underground environments. The metrics used for the performance evaluation include throughput, packet delivery ratio (PDR), end-to-end delay, energy consumption and packet delivery security. The results evaluation confirms the mesh topology is prioritised in WSNs design considering higher throughput, packet delivery ratio and network security, while the cluster-tree topology is preferred in case of lower end-to-end delay and lower energy consumption. The analyses show that the mesh topology creates a more reliable monitoring and communication network with an adequate quality of service in underground spaces and tunnels. Therefore, greater end-to-end delay and energy consumption could not be major concerns for the mesh topology in underground mine applications based on the acceptable data latency and using mine power.

1. Introduction

Wireless sensor networks (WSNs) have recently been proposed for underground mine monitoring and communication to enhance safety and productivity and so as to reduce operational costs (Chehri et al., 2009; Bhattacharjee et al., 2012). Typically, 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. In particular, the placement of the sensing nodes plays a very important role to allow for efficient transmission as well as providing maximum security through the network. It is inevitable for underground WSNs to perform at a high level of network efficiency with lower energy-consumption and the most cost-effective establishment and maintenance. Despite the progress of WSNs technologies, they still rely on infrastructure such as so-called sinks to transfer data from underground sensors to the management server at the surface (Bennett et al., 2010).

According to the experiments of developed ZigBee nodes on the radio propagation in underground environments (Moridi et al., 2015), the study focuses on the reliability of multi-hop data transmission between nodes in underground mines. ZigBee is standardized based on IEEE 802.15.4 protocol. This protocol has developed to realize the physical and multiple access control (MAC) layers for a low rate-wireless personal area network (LR-WPAN). In the following, PAN is technically defined as a LR-WPAN in an ad-hoc and self-organising network designed to serve a variety of applications especially in WSNs. ZigBee, based on IEEE 802.15.4 standard (Chandane et al., 2012), is comprised of PAN Coordinator, coordinator (full-function device) and end-device.

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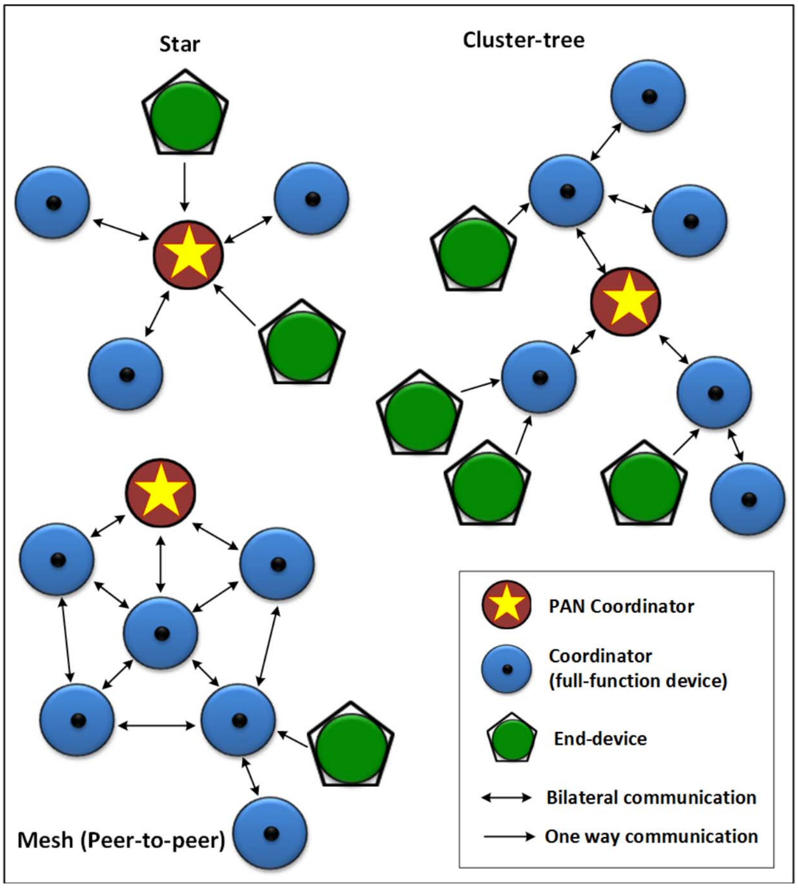

Fig. 1. Network architecture of the ZigBee topologies.

A ZigBee PAN Coordinator forms the only root of the network. First, it creates the network, and then waits for automatic joining connections of other nodes. It enables all nodes to communicate within the network and stores data. Due to a limited communication range, intermediate coordinator nodes (full-function devices) are involved to transfer data between sensor nodes (the actual end-device) and the PAN Coordinator through multi-hop routing. Fig. 1 illustrates the network architecture of different ZigBee topologies. A full-function device can sense the environment, as well as communicate with the other nodes. An end-device is only capable of sensing and sending data to the PAN Coordinator or nearest coordinator node. The PAN Coordinator is usually AC powered, while routers and end-devices are typically battery powered.

ZigBee based on the IEEE 802.15.4 standard has three main types of network topology for data transmission (the star, the cluster-tree and the peer-to-peer mesh) as illustrated in Fig. 1. As seen, end-device nodes may be more beneficial in the cluster-tree topologies considering energy saving during sleep times, while more full-function devices have to be employed in mesh topologies as they need to relay the data of nearby nodes.

A key factor to evaluate the efficiency of the WSNs performance is the routing protocol. The protocol provides routes for each node (Subramanya et al., 2011). Routing is the process of selecting paths within a network to send data from one node to the nearby nodes.

This study aims to evaluate ZigBee network performance and security in underground mines based on the link quality indication (LQI) for each received signal or packet using QualNet® 7.3[1](2014). For this purpose, we investigated an optimal arrangement of ZigBee nodes by creating various scenarios of mesh and cluster-tree configurations, and LQI-related metrics evaluation in mine tunnels. In the scenarios, all nodes including the Pan Coordinator, the full-function devices and the end-devices are assumed to remain stationary. Our procedure and methodology of an optimal arrangement of ZigBee nodes in underground mines is illustrated in Fig. 2. As star topology mostly suit for the home automation, we focus on the mesh and cluster-tree topologies in underground spaces to analyse the simulations based on the network performance metrics of throughput, packet delivery ratio, end-to-end delay, energy consumption and packet delivery security.

2. Related work

ZigBee network performance in the perspective of nodes positioning design has theoretically been developed by numerous research solutions (Singh et al., 2008; Guinard et al., 2011; Tian et al., 2012; Chatterjee et al., 2013) and proposed algorithms (Medhat et al., 2012; Yingxi et al., 2012; Huang et al., 2012). These solutions and algorithms improved the results and network performance of the WSNs. Since real tests within industry environments are faced with performance difficulty as well as being costly and time consuming, simulation is a common way to study new and optimising routing protocols and topologies. The routing protocols simulation is analysed for the improvement of ZigBee network performance and applications to select optimal paths to transfer data to the destination (Zen et al., 2008; Subramanya et al., 2011; Narmada and Sudhakara Rao, 2011; Sharma and Kumar, 2012; Roberts et al., 2013). Routing evaluation is an important task in ad-hoc networks that do not rely on a pre-existing infrastructure where the nodes are mobile through the environment. Other studies simulated different topologies to optimise ZigBee network performance for industrial systems using stationary nodes (Ullo et al., 2010; Chandane et al., 2012; Yasin et al., 2013; LAVRIC et al., 2013; Khan et al., 2013; Moridi et al., 2015). Reliable and cost-effective networks of ZigBee topologies require an analysis of quality of services

[1] QualNet®: http://web.scalable-networks.com/content/qualnet (last accessed 7 September 2015)