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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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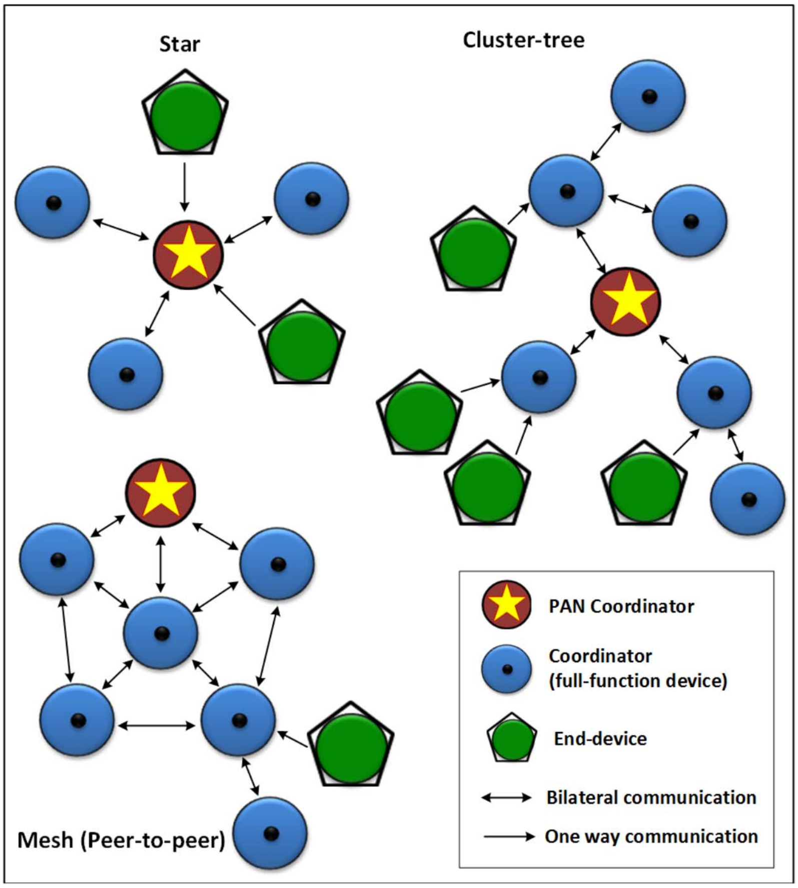


Fig. 1. Network architecture of the ZigBee topologies.

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)

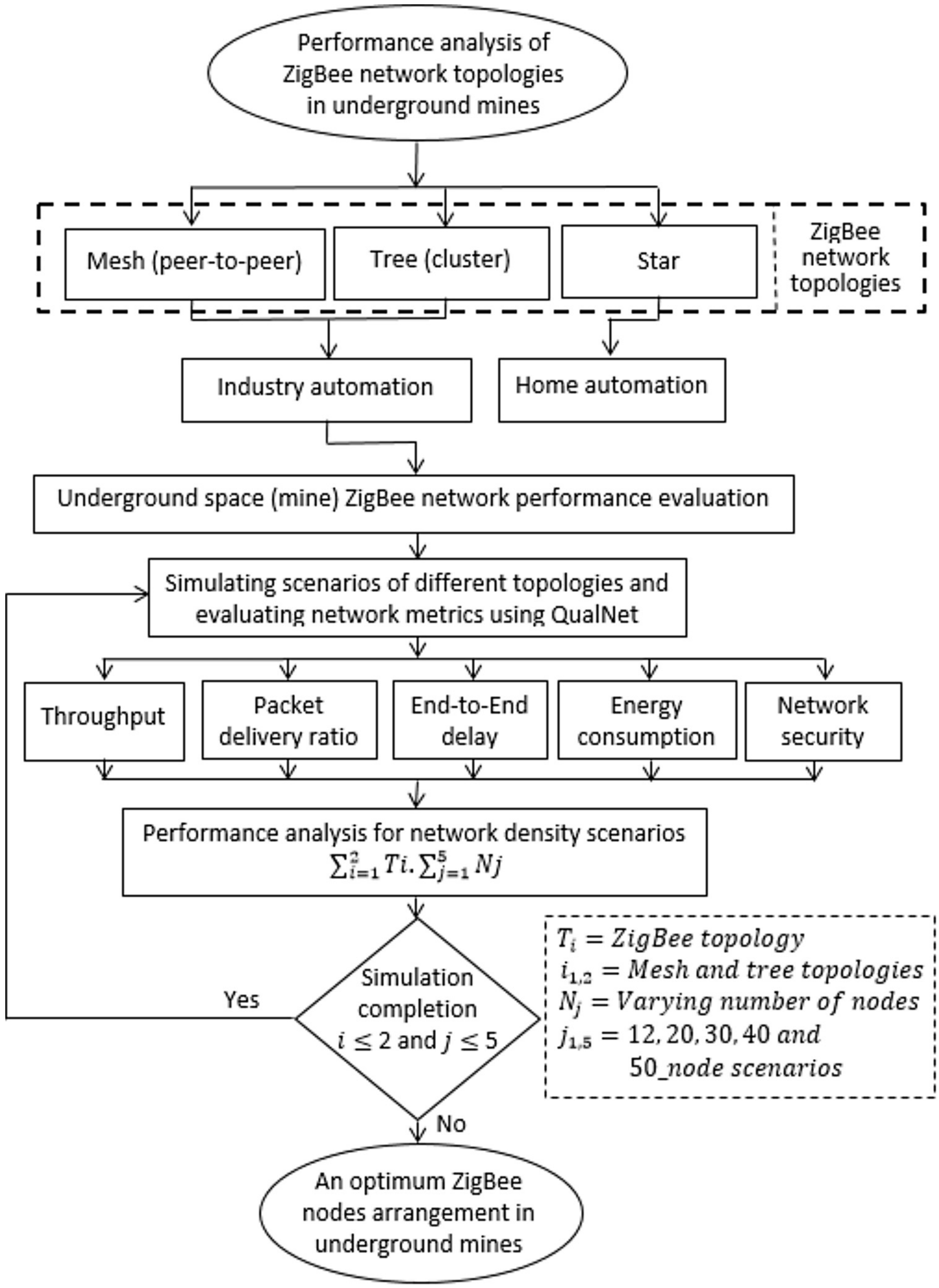


Fig. 2. Procedure of optimum arrangement of ZigBee nodes for underground mines.

(QoS) metrics such as throughput, packet delivery ratio, end-to-end delay, energy consumption and network security.

However, even though there are some performance evaluations of ZigBee networks in underground mines (Chehri et al., 2011, 2013; Bo et al., 2012), the simulation of node positioning comparing different topologies in such environments is hardly investigated. In this work ZigBee nodes arrangement considering the mesh and cluster-tree topologies in underground spaces is investigated based on the analysis of QoS metrics and a secure packet delivery.

3. ZigBee network performance metrics

ZigBee network topologies for the analysis study of optimal nodes arrangement including the mesh (Peer-to-Peer) and cluster-tree which is challenged in industry applications are evaluated. Typically, the performance of network topologies is assessed on the basis of metrics that mainly consist of throughput, packet delivery ratio, end-to-end delay and energy consumption. In particular any topology involved with higher throughput and packet delivery ratio, and lower end-to-end delay and energy consumption is more adequate for ZigBee applications. In these concepts, a packet is defined as a formatted unit of data carried along a communication channel, and each packet carries the information that will help it get to its destination. In the following, we define the basic metrics:

Throughput: It is defined as the ability of data packets successfully sent from source node to destination node in the unit time. In our study, the throughput (bits per second) is generated by the ZigBee application within scenario simulation times and is calculated as Eq. (1):

$$T = \frac{Tps \times 8}{Tlps - Tfps} \tag{1}$$

where the total packet sent, the time last packet sent and the time first

Table 1
Simulation parameters and node configurations.

Parameter	Details
Node placement	Stationary
Number of nodes	12, 20, 30, 40 and 50
Network topology	Mesh and Cluster-tree
Area of simulation	1000 m * 1000 m
Channel frequency and data rate	2.4 GHz and 250 kbps
Physical and MAC models	802.15.4 radio
Energy model	MicaZ
Battery model	Simple linear, 1200 mAh
Transmission Power	3 dBm
Antenna model	Omnidirectional
Modulation scheme	O-QPSK
Routing protocol	AODV
Path loss model	Two Ray model
Traffic	ZigBee application
No. of items and Payload Size	100 and 127 bytes
Simulation time	10 mins

packet sent are denoted as Tps, Tlps and Tfps, respectively.

Packet delivery ratio: The ratio between the packet number received at the destination node and the packet number sent by the source node is defined as packet delivery ratio (PDR).

End-to-End delay: Delay or latency through wireless networks is time taken by the packets to propagate from the source to the destination. The end-to-end packet delay is comprised of the summation of route discovery (source-processing delay), queuing (network delay), propagation and transfer time (destination delay). The end-to-end delay is one of the most critical and fundamental issues for WSNs. Many applications of sensor networks require an end-to-end delay guarantee for time sensitive data.

The average end-to-end delay of ZigBee applications for different scenarios is computed based on the Eqs. (2) and (3):

$$AD = \frac{Tt}{Npr} \tag{2}$$

where the average end-to-end delay, the total of transmission delay of all received packets and the number of packets received are denoted as AD, Tt and Npr, respectively.

$$Tdp = Tpr - Tpt \tag{3}$$

where the transmission delay of a packet, the time packet received at destination node and the time packet transmitted at source node are denoted as Tdp, Tpr and Tpt, respectively.

Energy consumption: Energy efficiency is another critical aspect in the QoS of WSNs, because nodes are powered by batteries and require time and costs in recharging once they deployed. Energy consumption of a node in any network depends on four modes: transmit (TX), receive (RX), idle, and sleep modes. A node is listening nearby nodes in the idle mode, thus it wastes an amount of energy only for searching through the network. When nodes are in the sleep period the energy consumption decreases because there are no packets being sent or received. When nodes are required to send data, they become reactivated and forward the data to the next nodes within the range. This causes a greater energy consume in the transmit mode.

In the simulation, the total energy consumed in milliwatt-hour (mWh = 1/1000 Wh) is calculated from Eq. (4):

$$\text{Tec} = T + R + I + S \tag{4}$$

where the total energy consumed (in mWh), the transmission mode (in mWh), the reception mode (in mWh), the idle mode (in mWh) and the sleep mode (in mWh) are denoted as Tec, T, R, I, S, respectively.

4. Underground ZigBee network simulation setup and design

In this study, two ZigBee topologies under protocol IEEE 802.15.4 for varying traffic loads are evaluated to find optimum nodes arrangement using QualNet®7.3. QualNet is one of the network simulators that mimic the behaviour of a real network. A network simulation is a cost-effective method for developing the early stages of network centric systems. QualNet allows us to evaluate the basic behaviour of WSNs and test combinations of network features that are likely to work. It also provides a comprehensive environment simulation for ZigBee PHY layer and MAC layer to analyse performance, operation and management of discussed network topologies. Scalability is one of the key features of the selected simulator that enables for creating a virtual network in underground environments so as to model large networks with adequate reliability.

An underground mine with a vertical shaft and connected horizontal tunnels is modelled for mesh (peer-to-peer) and cluster-tree network evaluations. The network models have a surfaced PAN Coordinator and 12, 20, 30, 40 and 50-node located in the shaft and tunnels. The nodes are selected as a coordinator (router) and an end device depending on the required use in the network topology. These scenarios are to simulate a real underground mine, covering an area of 1000 m length and 1000 m depth. The remaining simulation parameters are listed in Table 1.

In the scenarios, the MicaZ model (QualNet7.3, 2014) for the radio interface is employed. All the nodes in the scenarios are battery-operated devices, and we use a simple linear battery model for the comparison of the scenarios. Therefore energy is consumed by those interfaces according to the energy specification of MicaZ model shown in Table 2.

Only one PAN co-ordinator is considered as a final sink server to communicate with other source nodes for data processing and delivery in this multi-hop system. In other words, a wireless network between the surface PAN coordinator and the underground sensor are created. The PAN Coordinator and other sensor nodes including the full function and end devices remain stationary.

The transmission of ZigBee signal in an underground mine tunnel is influenced by a variety of factors such as the corner, walls surface, damper, geometer, and the slop. It is supposed that a dense layout of nodes is required to ease network communication through the tunnel while the use of more nodes, in particular full-function devices, caused in lower packet delivery (Bo et al., 2012). Considering this and performed experiments for the secure communication distance of the developed devices, the scenarios are designed with the different densities for the mesh and cluster-tree topologies to analyse the simulations result. The simulation for these scenarios including the network size of 12, 20, 30, 40 and 50-node is given in Table 3.

In the simulation, the methodology for the mesh topology is designed based on the peer-to-peer data transmission with one PAN coordinator. A ZigBee node can communicate with other nodes through the network as long as they are in the range. This topology allows multi-hops data transferring from the source node to the PAN coordinator and vice versa. Such a networking can be ad hoc, self-organizing and self-healing with employing more coordinator nodes (full-function devices). In the tree topology, child nodes can only transfer data to their parent (coordinator) and this is the parent node which has bilateral communication with PAN coordinator. This makes clusters including mostly the end-devices (also could be full-function devices) as source nodes connected to the full-function devices. Therefore, more full-function

Table 2
Specifications of MicaZ energy model.

Mode	Radio mode	Power @ 3 V (mW)
Active	TX	48.0
Active	RX	56.5
Active	Idle	10.79
Sleep	Sleep	1.50

Table 3
Simulation scenarios of ZigBee topologies with different network size.

Topology	Network size (nodes)
Mesh	12
	20
	30
	40
	50
Cluster-tree	12
	20
	30
	40
	50

devices are required to set up the mesh topology while the cluster-tree topology comprises a great number of end-devices through the network, find Fig. 2. For both topologies the PAN coordinator first initializes the network then other nodes within the range are turned on and automatically connected to the network.

Screenshots from the QualNet simulator on 12-node scenarios of the mesh and cluster-tree topologies are illustrated in Fig. 3. In these topologies, full-function devices act as routers to transfer (or relay) data for the nearby source nodes and as a sensor node to also sense the surrounding environment. An end-device only senses and sends to nearby nodes. The nodes in the scenarios are arranged diagonally. This arrangement allows a better signal distribution through the network as well as proving a very cost-effective alternative considering the results of previous underground experiments (Moridi et al., 2014). ZigBee applications defined in the software are used to evaluate traffic loads between nodes pair with the capability of sending 100 packets, each packet size having 512 bytes which are active during simulation time.

5. Results and analysis

The simulation results can be evaluated through various performance metrics in both the mesh and cluster-tree topologies. By using similar traffic loads, an optimum ZigBee node arrangement is found for different underground mines. As mentioned above, the results are analysed based on the performance network metrics of throughput, packet delivery ratio, end-to-end delay and energy consumption (see Section 2 for the definitions).

5.1. Throughput

The throughputs between nodes in 12-node scenarios are illustrated in Fig. 4. The throughput between source node (SN) and destination node (DN) of (2,1), (3,2), (4,3), (5,3) in either the mesh or cluster-tree topology is a maximum of 4137 bits/s. It shows a significant reductions in throughput in the cluster-tree topology compared to the mesh topology for other communications between SNs and DNs. This is due to simultaneous increase in receiving packets at the destination nodes (Yasin et al., 2013). WSNs based on the IEEE 802.15.4 standard commonly act as displays from sharp throughput drops at higher loads.

The comparison of changes in the number of nodes at the scenarios of 12, 20, 30, 40, and 50-node with the average throughputs are illustrated in Fig. 5. The figure shows that average throughputs of 3866 and 2079 bits/s for the 12-node scenarios are moderately reduced, as the number of nodes increases, with a minimum of 2918 and 1178 bits/s for the 50-node scenarios of mesh and cluster-tree topologies, respectively. It is also observed that there is an acceptable throughput within the network for both topologies, however, the mesh topology performs a better throughput from SNs to DNs due to its path finding techniques. Based on the Eq. (1) and Fig. 4, it can also be proved that the cluster-tree topology compared to the mesh topology has a lower throughput because of losing signals and reducing total packets sent. This becomes even worse by in increasing the number of nodes within the network.

A drop of throughputs after 12-node scenarios among the mesh topology has occurred because of rising congestion of packets delivery in full function devices (coordinators) and because of an increase in the choices of links to nearby nodes and thus paths through the network.

5.2. Packet delivery ratio

The packet delivery ratios (PDRs) are computed based on a percentage denotes a ratio between total packets received by DNs and total packets sent from SNs. The PDRs results for the varying numbers of nodes of the mesh and cluster-tree topologies are illustrated in Fig. 6. The PDR in the mesh topology changes slightly from 81.8% for the 12-node scenario to 77.2% for the 50-node scenario, but it drops considerably in the cluster-tree topology from 64.5% for the 12-node scenario to 23.4% for the 50-node scenario. A higher PDR value shows a better performance within the network. Therefore, a visual comparison of the results indicates that the mesh topology has a higher network performance at the same traffic loads for the ZigBee applications. The reason is that the cluster-tree topology scenarios have the disadvantage of the collisions due to the numerous transmissions at the DNs and the reduction of the packet number received.

5.3. End-to-End delay

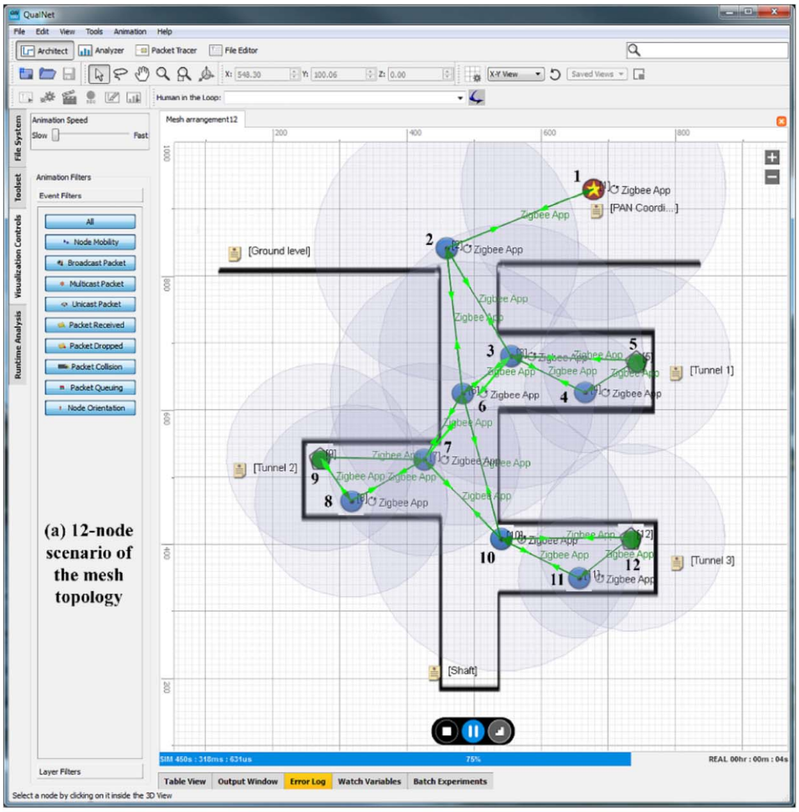
The average end-to-end delays at each destination node for 12-node scenarios are illustrated in Fig. 7. In these bar charts, the node IDs are those as specified in Fig. 3. The charts show that end-to-end delays occur at nine destination nodes in the mesh topology, while it reduces to seven destination nodes in the cluster-tree topology with the same traffic load. It therefore causes a greater data latency through the mesh topology as a result of the increase in the number of hops, which results in greater queuing time, channel access delays and transmission delays. The end-to-end delay is considerably risen for the mesh topology scenarios with increasing the number of the DNs (hops) through the network. Consequently, the cluster-tree topology supports a more reliable network in the case of data latency compared to the mesh topology.

As seen in Fig. 7, there is no delay for node IDs 5, 9 and 12 in the 12-node scenario of the mesh topology, while it also does not occur for node IDs of 4, 5, 8, 9 and 12 in the 12-node scenario of the cluster-tree topology. In fact, the amount of the total delay is reduced with the increasing number of end-devices through the network.

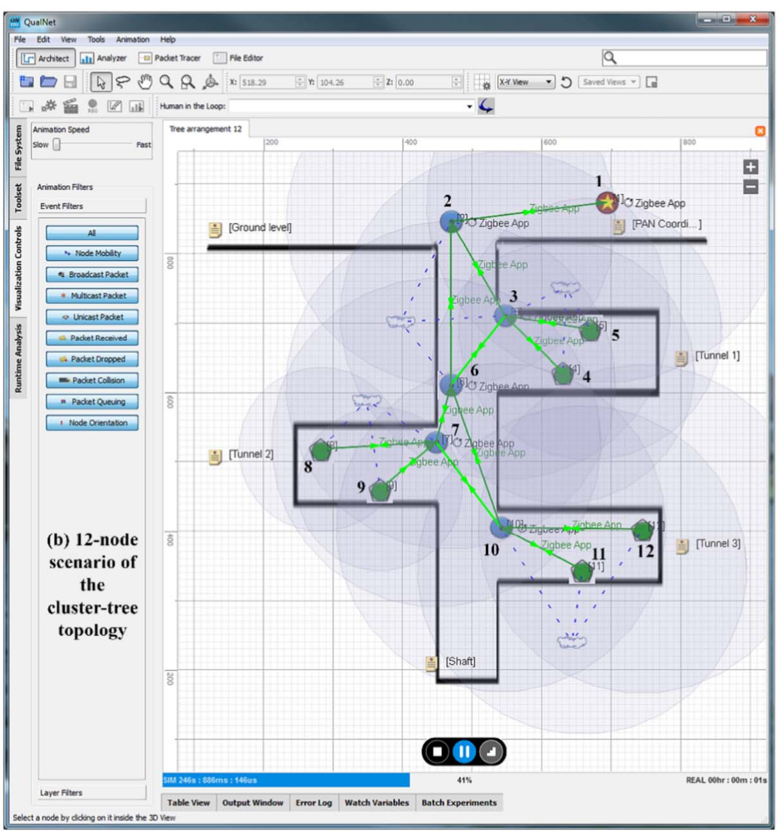
The tendency of total end-to-end delay of the mesh and cluster-tree network topologies versus varying number of nodes is illustrated in Fig. 8. The curves clearly show that the tendency of end-to-end delay is enhanced with increasing node density in the networks. According to the mesh topology architecture, the rise in the number of full-function nodes, which are providing multi-hop routes, results in significant data latency in the network. From the graph in Fig. 8 is observed that the total end-to-end delays for 12-node scenarios are 9s and 6s, whereas these reach to 32s and 13s for 50-node scenarios in the topologies of the mesh and cluster-tree, respectively.

5.4. Energy consumption

The next step is evaluating the efficiency of the network by measuring the energy consumption. Fig. 9 illustrates the total energy consumption for the mesh and cluster-tree topologies of ZigBee network versus varying number of nodes. The trends of the curves in the graph show an increase in energy consumed for more dense networks. It is also observed that the total energy consumed of 18.4 mWh for 12-node scenario increases to 99.44 mWh for 50-node scenario in the mesh topology, and it climbs from 15.7 mWh for 12-node scenario to 64.2 mWh for 50-node scenario in the cluster-tree topology. Thus, the cluster-tree topology is more energy efficient than the mesh topology. This is due to



(a) 12-node scenario of the mesh topology



(b) 12-node scenario of the mesh topology

Fig. 3. Arrangement view of ZigBee nodes in an underground mine. (a) Mesh topology, (b) Cluster-tree topology.

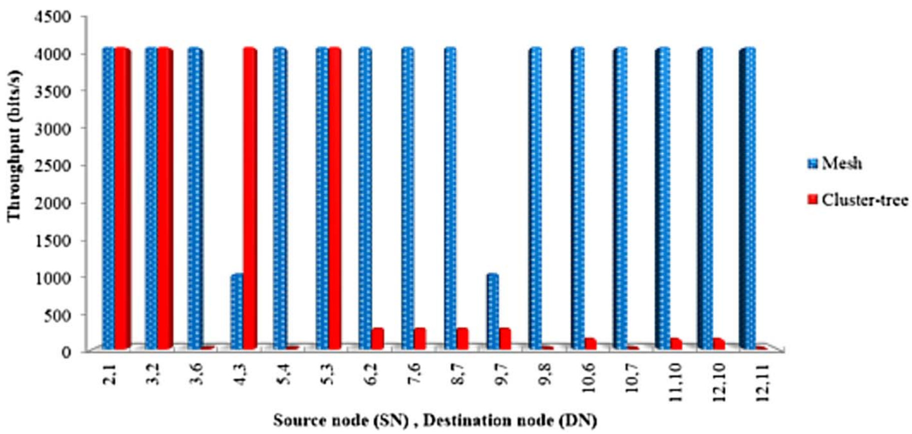


Fig. 4. Throughput versus 12-node scenarios of the mesh and cluster-tree topologies.

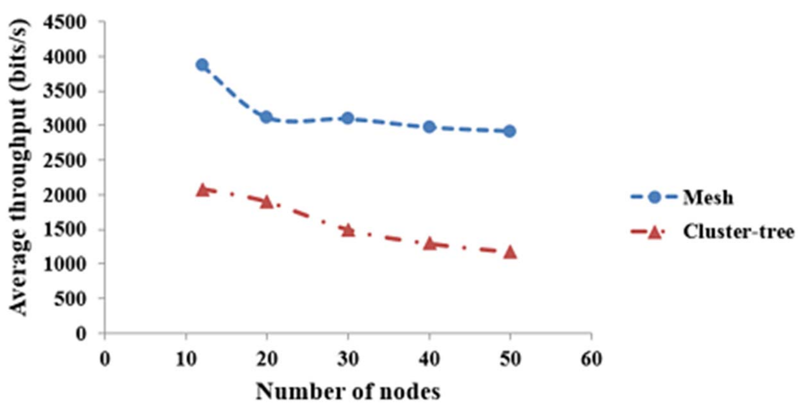


Fig. 5. Average throughputs versus varying nodes numbers for the mesh and cluster-tree topologies.

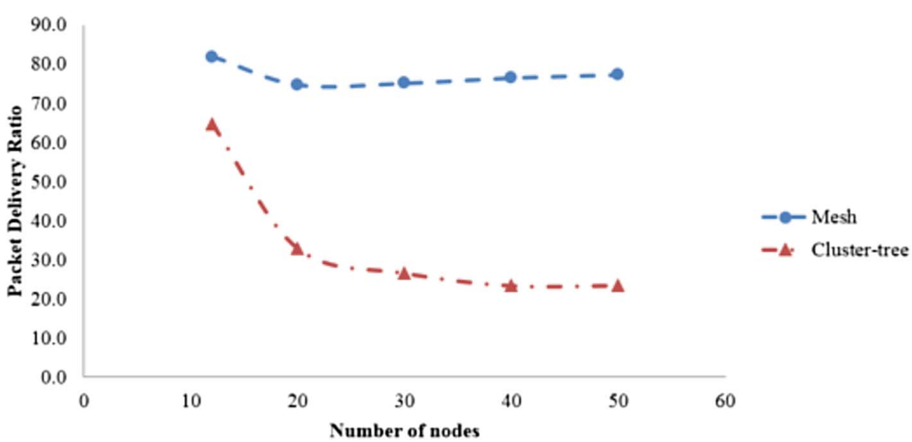


Fig. 6. Packet delivery ratios versus varying nodes numbers for the mesh and cluster-tree topologies.

the fact that more end-devices remaining in sleep mode in the cluster-tree topology. On the other hand, a considerable number of full-function destination nodes are more engaged in the mesh topology, which causes higher energy overall consumption. First, such destination nodes have to be largely in idle mode in order to communicate with nearby nodes. Secondly, the number of nodes predicted to receive data (receive mode) within a network of the mesh topology is more necessary than those in the cluster-tree topology.

5.5. Packet delivery security

In a network with mesh (peer-to-peer) topology, all the devices that participate in relaying the messages are usually full-function devices because end-devices cannot be as a router and support bilateral communication. The PAN Coordinator might often be mains powered, while the devices will most likely be battery powered. Multiple hop communication of the mesh topology with a variety of routing alternative between nodes provides a higher network security for data delivery within the network. Underground mine applications such as environment attributes monitoring and bilateral communication under emergency condition are beneficial from a higher security of such network topology.

6. Discussion

The performance investigations of different ZigBee topologies in underground spaces (mines) are summarised in Table 4. The simulation results show that the mesh (peer-to-peer) topology provides more reliable networking for the arrangement of ZigBee nodes in underground mine tunnels. This network topology has higher throughput, packet

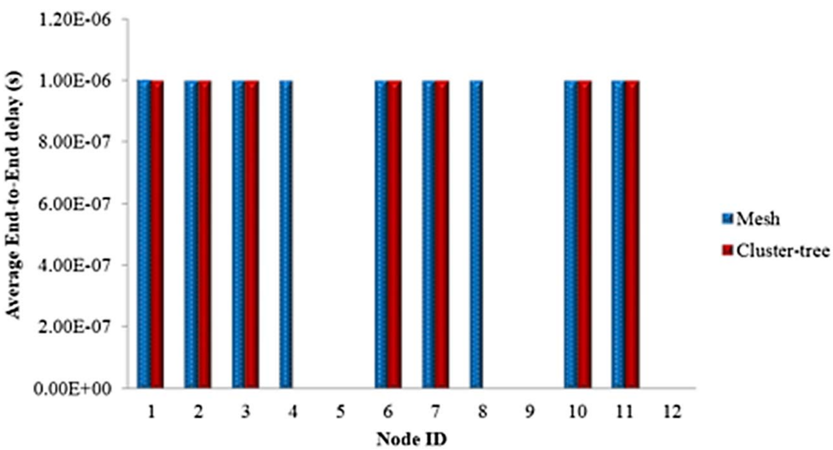


Fig. 7. Average end-to-end delays at each destination node for the mesh and cluster-tree topologies.

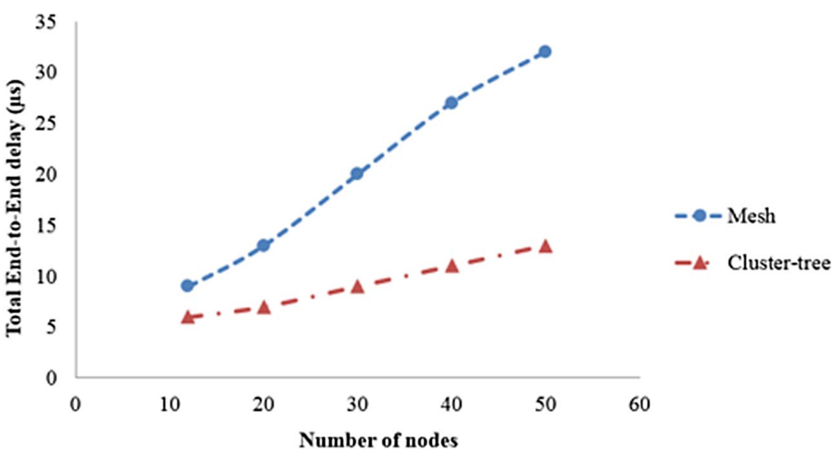


Fig. 8. End-to-End delays versus varying nodes numbers for the mesh and cluster-tree topologies.

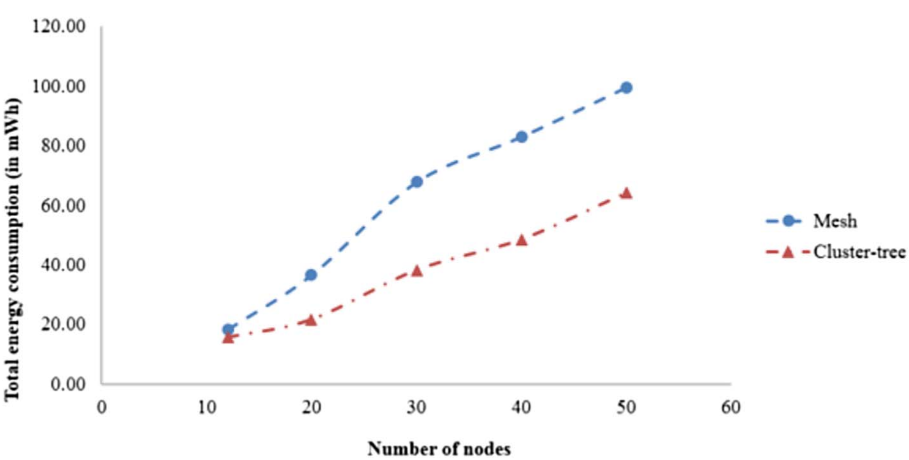


Fig. 9. Energy consumption versus varying nodes numbers for the mesh and cluster-tree topologies.

delivery ratio and network security. Although the cluster-tree topology is involved with lower end-to-end delay and energy consumption through the network, such benefits do not play significant roles for underground ZigBee network communication. As seen in Fig. 8, the delay time of packet deliveries from the source nodes to the destination nodes for 12, 20, 30, 40 and 50-node scenarios in the mesh topology are 3, 6, 11, 16, 19 µs longer than the similar scenarios with the same conditions created with the cluster-tree topology, respectively. For actual underground operations, such a small increase in the end-to-end delay of the mesh topology would not be significant. In addition, the greater energy consumed through the network will not be as bad a negative aspect for the mesh topologies, as ZigBee nodes that are currently in development will be able to switch between battery power and mine power.

7. Conclusion

The selection of an appropriate network topology is crucial for the nodes arrangement of the industrial wireless sensor networks (WSNs). In this study, the performance of different network topologies for ZigBee-based WSNs was analysed for underground mine applications. Then scenarios of the ZigBee mesh and cluster-tree topologies under the IEEE 802.15.4 standard are investigated in the light of most important network metrics. Throughput, packet delivery ratio, end-to-end delay, and energy consumption are evaluated during simulations for the scenarios with varying nodes number.

Table 4
Comparison of the simulation results of ZigBee topologies reliability in underground spaces

Metric	The reliability of ZigBee network topologies	
	Mesh	Cluster-tree
Throughput	✓	✗
Packet delivery ratio	✓	✗
End-to-end delay	✗	✓
Energy consumption	✗	✓
Network security	✓	✗

✓ is a better choice compared with ✗

In many sensitive industrial applications, the arrangement of wireless sensor nodes mostly depends on achieving higher throughput, packet delivery ratio and network security as well as lower latency data and energy consumption. While the cluster-tree topology meets advantages of lower latency data and energy consumption, the benefits of the mesh topology are higher throughput, packet delivery ratio and network security, which are the most significant features for the underground ZigBee node arrangements. The larger data latency and the slight increase in energy consumption through the network are no major concerns for underground mine projects, as the delay increases by only a few µs and future ZigBee nodes will be able to switch power between battery and mine power. Thus, it is concluded that the mesh topology enables ZigBee nodes to create an underground space wireless network that is more secure and delivers a higher quality of service than cluster-tree topology networks.

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