Optimisation of Energy Consumption Balance in Multi-Hop Topology Wireless Sensor Networks for Environmental Monitoring Systems along Railway Tracks

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Abstract— The implementation of IoT requires careful planning so that the system can function optimally. This study describes the planning of WSN development as a network in an IoT system with a long, straight topology, such as that found on railway tracks. The planning includes the use of appropriate technology with minimal power consumption. Three simulation scenarios were conducted using LPSAN, LPWAN, and a combination of both to compare their performance on a straight-line topology. The profile of each technology in LPSAN and LPWAN in terms of their performance in transmitting sensor data in the IoT system will be determined. The network lifetime performance is also determined to demonstrate the energy efficiency of each technology. Thus, the most optimal scenario in terms of configuration and topology in a straight-line network will be selected. From the experiments conducted, it is concluded that multihop topology is generally recommended for use in straight-line networks compared to star topology, except in conditions where nodes are very close to the gateway.

Index Terms— IoT, WSN, LPSAN, LPWAN, Straight-line topology..

1. Introduction

Technological advances and digitalisation are currently in high demand. Digitalisation has successfully demonstrated its role as an enabler that can assist humans in solving problems. The use of IoT aims to collect digital data from the field, which can then assist humans in making the right decisions based on the processed data that has been collected.

This is no exception in the transportation industry, which has needs related to safe, smooth and fast transportation. This is especially true for high-speed rail, which is a reliable mode of transportation. In its efforts to support the safety and smooth operation of high-speed trains, it is necessary to monitor the surrounding area for potential safety risks, such as land subsidence, external disturbances, and internal rail system disturbances. Therefore, a rail environment monitoring system is used through field inspections to ensure that the conditions around the rails are safe for use in accordance with high-speed train operational standards.

The Internet of Things can be utilised as part of the rail area monitoring system to provide data on the conditions around the rails. It is equipped with various sensors to record the conditions of the area around the rails. The data collected through the sensors can then be used to monitor and control the rail environment to ensure the safety and security of high-speed trains.

In its implementation, adequate device and network infrastructure is required so that the monitoring and surveillance system can run optimally. Railway monitoring infrastructure is basically divided into two [1]:

a. Ground-based system
   Monitoring systems are usually installed near the rails and the coverage monitored varies from a few metres to tens of kilometres depending on the coverage of the sensors used. They usually use cables or fibre optics to connect nodes to controllers or servers.
b. On-board installation
   In this system, the monitoring system is installed on the train body and generally uses WSN. This system typically uses short-range wireless or long-range wireless technology. This system usually focuses more on monitoring the technical condition of the carriages/trains and rarely monitors the tracks or rails themselves.

One example of a scalable IoT infrastructure implementation is the use of wireless sensor networks (WSNs), where WSN nodes are installed along railway tracks. In general applications, WSNs are deployed in square or circular areas. For narrow areas, WSNs are deployed in a star topology. For larger areas, a clustering topology is recommended. Even 3D WSN configurations are recommended for multi-storey building SHM and UWSN applications. A special feature of WSN design for HSR monitoring systems is the fact that HSR tracks are narrow but very long. The arrangement between nodes must then be taken into account for straight and long network topologies in railway areas. Nodes in an IoT system can function as clients/subscribers or as masters, or both simultaneously.

Several studies related to WSN topology in various forms have been conducted by researchers.

A study to determine the performance of the 6 LoWPAN protocol on WSN networks reviewed QoS parameters on grid and random topologies. The Cooja simulator was used to simulate the performance of the 6 LoWPAN protocol, and Wireshark was used to analyse the output. The highest throughput, lowest delay and lowest jitter were achieved by the grid topology. The use of grid topology for the 6 LoWPAN protocol is better than random topology [2]. Research on selecting the most efficient wireless system based on data rate, network range, energy consumption, etc. Comparing the performance of Bluetooth, Zigbee, and WiFi wireless systems through various topologies. Bluetooth is suitable for wearables (BSN), Zigbee is suitable for industrial automation and WSN, while WiFi is suitable for stand-alone and mobile devices [3]. Designing a WSN-based train monitoring prototype using WSN with nRF24L01 modules as nodes arranged in a star topology to determine the position of the train and estimate its arrival time [4]. Applied research for environmental condition detection has also been conducted. A landslide detection system based on microcontrollers and WSN has been built using accelerometer sensors, gyroscopes, etc. to detect ground movement, using LoRa as the communication medium and point-to-point LoRa connections with a maximum distance of 350 metres [5]. Other researchers have built a simple, low-cost, and efficient landslide monitoring system. This system uses WSN as a communication medium, namely Xbee pro, and is arranged in a star topology, using compressed sensing to save data transmission and power, thereby enabling more efficient data transmission by reducing data transmission through Compressed Sensing (CS) [6]. Another study was able to build a landslide detection system using 20 WSN nodes and 50 sensors, using a crossbow micaz network that divides nodes into: lower level (wireless node), middle level (cluster head) and higher level (sink node). WSN is the most efficient technology for building this system. The system is capable of producing real-time data and providing warnings related to landslides [7].

Another study also developed an IoT system to monitor the temperature, humidity and electricity of buildings using a combination of Zigbee and LoRa WSNs. Zigbee and LoRa can be used in a single IoT system, with Zigbee for low-range communication and LoRa for long-range communication. This combination has been proven to improve energy efficiency [8].

Research exploring and evaluating the performance of the Fibonacci Adaptive Tuning (AFT) protocol on different topologies. Using the Cooja simulator to evaluate AFT performance on elliptical, grid, random, and linear topologies. Simulation results show that the AFT protocol consistently achieves increased resource energy savings and outperforms traditional counterparts by varying percentages for overall network lifetime under different topologies [9].

The performance of IoT networks has been measured by comparing the lifetime of devices using wireless network technologies such as: IEEE 802.15.4/e, BLE, IEEE 802.11 powersaving mode, IEEE 802.11ah, LoRa and SIGFOX. The research was conducted using an analyser that calculates energy consumption for specific protocols based on the power required under certain conditions (Sleep, Idle, Tx, and Rx) and the duration of each condition. BLE showed the best lifetime performance within its capacity range, followed by LoRa, which performed well for ultra-low traffic [10].

Although there have been many previous studies, further investigation is still needed on how to design a linear topology WSN for optimal railway monitoring. The purpose of this study is to identify the performance of LPSAN and LPWAN in order to design a WSN topology that suits the needs of the railway monitoring system. This study will analyse and compare WSN technologies in terms of their performance in a linear topology based on the parameter of energy efficiency. The benefit of this study is that it can serve as a reference for designing WSNs with similar conditions, such as designing WSNs for other long areas, such as conveyor belts, motorways, and other areas.

2. Research Method

The energy consumption model in WSN commonly used in many papers is the model proposed in [11], which consists of three parts, namely:

1. To send an l-bit message at a distance d, the radio system at a node requires energy

$$E_{tx}(l,d) = \begin{cases} lE_{elec} + l\epsilon_{fs}d^2 & for\ d \le d_0 \\ lE_{elec} + l\epsilon_{mp}d^4 & for\ d > d_0 \end{cases} \quad (1)$$

2. To receive the message, it takes as much energy

$$E_{rx}(l) = lE_{elec} \quad (2)$$

3. The energy to perform data aggregation is equal to W_{DA}

For the implementation of IoT in a railway environment, WSN nodes are arranged in a long line. Since the data sent by each node is relatively small, it would be logically inefficient for each node to have a direct internet connection and be connected to a server. A commonly used strategy is to install one sink node for each group of sensor nodes, which acts as a link between the sensor nodes and the internet network. This network topology is illustrated in Figure 1. The figure shows that a group of nodes (in this case, 200 sensor nodes) sends data to the sink node, which acts as a gateway to the internet network or server. We refer to this model as a star topology network model.

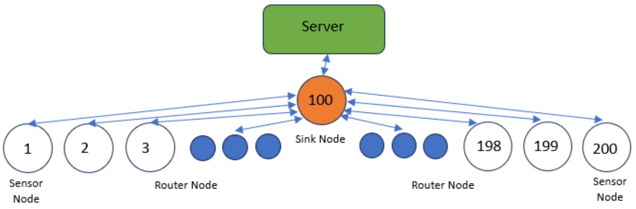

Fig. 1. WSN network with a star topology model.

Referring to the energy model in (1), where Etx is a quadratic function or power of 4 of the distance, nodes that are far from the sink will consume more energy than those that are close. This condition will result in nodes that are far from the sink running out of energy first. An alternative solution to the above problem is the multi-hop network model illustrated in Figure 2. With multi-hop, the transmission distance is relatively close and evenly distributed between nodes, so there is no problem of differences in energy consumption due to differences in distance.

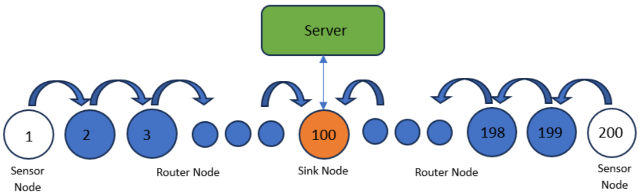

Fig. 2. Multi-hop WSN model of a railway.

However, the multi-hop communication topology model has an imbalance in data load between nodes that are far from the BS and those that are closer. Hops that are closer to the BS relay more data, thus requiring greater energy consumption. This paper investigates a comparison of the energy consumption performance of the two topology models in various parameter variations. To compare the energy consumption performance of the two models, it is necessary to formulate an energy consumption model for both topologies.

2.1. Formulation of Energy Consumption in Star Topology

Referring to the energy model in equation (1), all nodes in the star topology consume energy only for data transmission purposes. Sensor nodes do not receive data and do not perform data aggregation. Assuming that the distance between nodes is equal (dx), the distance from node n to the sink is:

$$E_n(d_n) = lE_{elec} + lE_{mp}d_n^4 = lE_{fs} + l(n_{dx})^4 \quad \text{if} \quad n_{dx} > d_0 \tag{3}$$

$$E_n(d_n) = lE_{elec} + lE_{efs}d_n^2 = lE_{fs} + l(n_{dx})^2 \quad \text{if} \quad n_{dx} < d_0 \tag{4}$$

2.2 Energy Consumption Formulation for Multi-hop Topology

For multi-hop topology, each node sends data to the next node and receives data from the previous node, except for the end node which does not relay data. Thus, the energy consumption formula is:

$$E_n = E_{rxn} + E_{txn} = lE_{elec} + lE_{elec} + l(n-1)E_{fs}d_x^2$$

$$E_n = 2lE_{elec} + l(n-1)E_{fs}d_x^2 \tag{5}$$

Based on formulations (4) and (5), a numerical analysis was performed with specific parameter values and constants to produce a comparison of the energy consumption of each topology.

3. Results and Discussion

To determine the performance of each topology, a numerical analysis was performed using specific parameter values commonly used in previous analyses, as shown in Table 1.

Table 1
Test Parameters.

Parameter	*Symbol*	*Value*
Farthest *node* distance	dN	500 m
Number of *nodes* per side	N	100
Distance between *nodes*	$d_i - d_1$	50 m
Electronic energy	E_{elec}	50 nJ
Multipath energy	E_{mp}	0.013 µJ
Free space energy	E_{fs}	10 µJ
Data length	l	1 bit

With these parameters and using equation (4), the energy consumption per node for the star topology is shown in Figure 3.

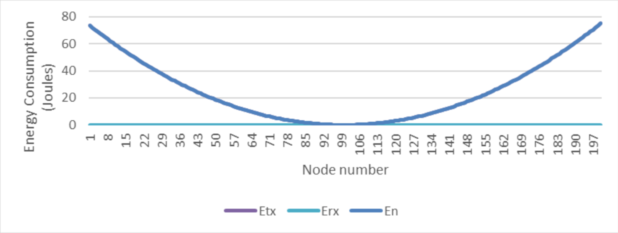

Fig. 3. Energy consumption of each node with star topology.

From Figure 3, it can be seen that the distance of the node to the gateway greatly contributes to the energy consumption of each node. This is understandable because nodes with a star topology do not require energy to receive data, so all the energy is used for sending data. Referring to the energy model in (1), the energy consumption for transmission is directly proportional to the square of the distance and the length of the data. However, since the data length sent is the same for all nodes, energy is only affected by distance. This is evident from the quadratic shape of the graph as distance increases.

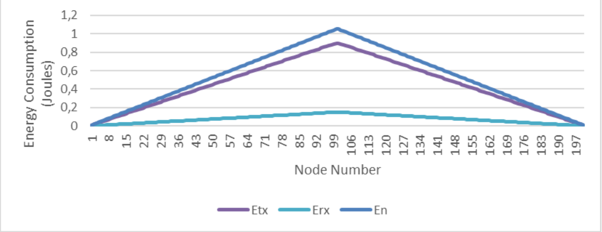

Fig. 4. Energy consumption of each node with a multi-hop topology.

From Figure 4, it can be seen that nodes far from the gateway consume little energy, which increases linearly as nodes get closer to the gateway. This condition applies to both Tx and Rx energy. This can be analysed as follows:

1. The transmission distance for all nodes is the same, namely the distance between nodes. The increase in energy is influenced by the amount of data sent. This occurs because the data sent by a node is an accumulation of data from the previous node and

the node itself. The closer to the gateway, the more nodes the data must be forwarded to.

2. A similar situation occurs with Rx energy, which is only influenced by the amount of data, as modelled in equation (2).
3. Total energy increases as it approaches the gateway because both energy components increase.

From the analysis of the two topologies, a contrasting phenomenon occurs, where in the star topology, the energy decreases as the distance to the gateway decreases, while in the multihop topology, the energy increases as the distance decreases. A comparative analysis of the two topologies is shown in Figure 5. The figure shows that, in most cases, the increase in energy due to data accumulation is still much smaller than the increase in energy caused by the increase in distance. The effect of data accumulation will begin to be more significant than the effect of distance when the node is 15 hops away from the gateway, as shown in Figure 6.

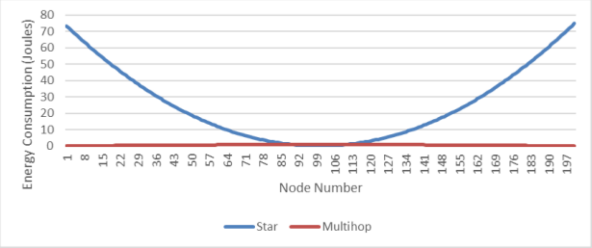

Fig. 5. Comparison of energy consumption between topologies.

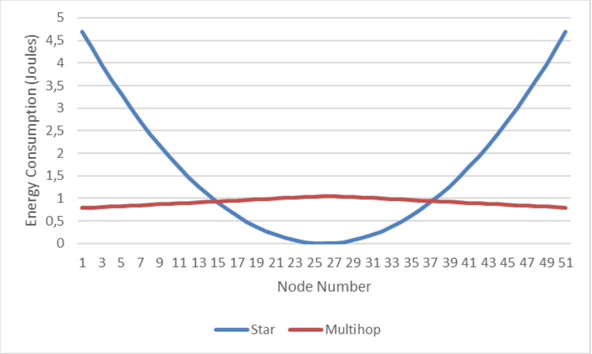

Fig. 6. Comparison of energy consumption between topologies on nodes around the gateway.

4. Conclusion

Of the two topologies offered, there is a contrasting change in energy consumption. In general, the multihop topology provides greater savings in energy consumption performance. The star topology is better at saving energy consumption when the distance between nodes is around 15 hops or closer to the gateway. Under these conditions, the multihop topology is more recommended for implementing a straight-line network pattern. Further investigation is required, including the influence of hop distance, data size variations, and so on. Real-world testing in the field using nodes with specific WSN protocols needs to be conducted to validate the results of the numerical analysis.

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