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# Preliminary studies of an energy efficient BLE wireless network for underground positioning systems

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# PRELIMINARY STUDIES OF AN ENERGY EFFICIENT BLE WIRELESS NETWORK FOR UNDERGROUND POSITIONING SYSTEMS

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*ABSTRACT* Positioning is a safety measure and a disaster management method used in the mining industry. Therefore, a positioning system is vital to ensure safety and reduce the risks to life of the workers at mine sites. The major challenge with existing positioning systems located in underground mines is the sending the collected positioning data to the positioning server through the energy-constrained, stationary wireless network nodes. This research is the first to identify the power challenge in sending positioning data in underground mines. By exploiting the mining environment, the authors of this paper propose to use Bluetooth Low Energy (BLE) communications and a cluster-based miner detection system that reduces the frequency of positioning data transmission to the positioning server, hence the burden on the energy-constrained stationary nodes.

Furthermore, the proposed architecture minimises the frequency of scanning, which is the highest power-consuming radio state in the BLE wireless protocol. This paper concludes through empirical evaluation that the most power-efficient BLE neighbour discovery configuration for SRNs of the proposed cluster-based data transmission wireless network is to use a 50% duty cycled 10ms scan interval. Moreover, in our future work, we expect to evaluate the power and latency performances of a BLE Stationary Reference Node (SRN) and a mobile Cluster Head node (CH) using an Omnett++ simulation model

## INTRODUCTION

The mining industry uses positioning systems to locate the miners and vehicles during emergencies in underground mines. This helps in emergency situations, especially as the locations of miners and mine vehicles are known. A mining contractor was critically injured and died due to a loaded fall in Moranbah North Mine. It was the most recent mining accident reported in Australia (Maddison, 2022). Similarly, many accidents are reported annually, confirming the importance of positioning systems for the mining industry.

In an underground positioning system, a wireless network deployed along the mine tunnel is used to carry the collected data to a positioning server. The network nodes collect data about the position of the miners and vehicles and transports this data to the positioning server in a control room at the surface level for calibration and computation (Ikeda et al., 2021, Ünsal et al., 2016). In an underground mine, the network nodes are battery-powered and there is limited access to continuous electric power (Ünsal et al., 2016). The distance between the control room and the locations of miners and vehicles can be several kilometres due to the length of the tunnels (Li et al., 2019). A few research studies have focused on wireless data transmission networks in underground mines. Branch et al. (2020), investigated the scalability, reliability, and performance of the physical layer of LoRa networks in underground mines for data transmission. However, despite LoRa being a low-power system, the research does not fully address the power challenges when designing communication systems for underground mines with battery powered network nodes.

According to Huang et al. (2010), when using an underground localisation system based on ZigBee radio technology and WebGIS, the network can last a maximum of six months. Access to underground mines is restricted because of the risky nature of their operations. Therefore, the battery replacement labour cost is higher than in usual working environments. As a result, specially trained staff are needed

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for maintenance of equipment and battery replacement. That makes replacing batteries every six months uneconomical.

Generally, in underground mines, the miners work in shifts. Furthermore, they move and work in groups. Working in shifts allows the equipment “on the miners” such as cap lamps and radios to be charged at the end of the shifts. Thus, the energy constraints are in the wearables in contrast to traditional systems where the stationary scanning devices are supplied with electric power (Saylam et al., 2021).

This research proposes using a cluster-based wireless network architecture to decrease power consumption and increase the communication system uptime. The authors of this paper show that it is possible to use Bluetooth Low Energy (BLE) wireless technology and clustering to minimise power consumption of the communication system.

The remainder of the paper is organized as follows. The sections System Design presents the proposed cluster-based wireless network architecture. The following sections then describe how BLE experimental measurements were used to find the power consumption of different BLE link layer configurations and the most power-efficient discovery configuration for the stationary reference nodes of the wireless network. Subsequent sections describe the experimental setup and results. The final section shows the viability of the proposed system and presents suggestions for future work.

## SYSTEM DESIGN

An Underground Positioning System (UPS) consists of three subsystems: the communication system, detection system and decision-making system. The communication system is a stationary wireless network deployed along the mine tunnel. It consists of battery-powered Stationary Reference Nodes (SRNs) and Relay Nodes (RNs). The SRNs detect the presence of miners and vehicles. This is done using battery-powered mobile tags worn by the miners, which determine the locations of the miners relative to the SRNs and send the information to the SRNs. The SRN collects the positioning data and forwards it to the positioning server at the control centre or where necessary, it forwards the positioning data to RNs that simply relay the communications between an SRN and the control centre. The rest of this section provides a detailed explanation of the wireless network architecture and wireless technology.

### Wireless Network Architecture

Wireless networks can be categorised as centrally coordinated networks (Infrastructure mode) and Ad-hoc networks which provide connectivity between devices. In centrally coordinated networks, each end node is connected to an Access Point (AP). In other words, the end nodes are connected via an AP. In an ad-hoc architecture, the end nodes can communicate with each other directly. The nodes organise themselves and form routes to the destination node (Raza et al., 2016).

A wireless network deployed in an underground mine tunnel represents an ad-hoc network where SRNs are stationary nodes. The tags worn by the miners are mobile end nodes. In other words, the wireless network architecture in a UPS is a partially mobile ad-hoc network, where the end nodes are mobile and the intermediate nodes are stationary. This is schematically shown in **Figure 1**.

### Energy Efficient Cluster Architecture

In the above wireless network architecture, wireless tags send messages to SRNs when their position changes. Thus, it is possible for the SRNs to sleep until a message is received. Sleep/wake-up schemes have been used for energy-efficient routing, data reduction, battery repletion and radio optimisation in wireless sensor networks (Rault et al., 2014). This research uses the optimal selection of the sleep/wake-up interval and clustering approaches to minimise the power consumption of the UPS. According to Rault et al. (2014) clustering is an energy-efficient design for energy-efficient routing. In networks that use clustering, the nodes send the data to one node known as the Cluster Head (CH). The CH is responsible for managing the cluster and transferring the data to the next node, in this case, to an SRN or an RN. The SRN discovers the CH and forwards the received data to the positioning server directly or via the RNs.

It is possible to use clustering and sleep/wake-up architecture for designing an energy efficient communication system. The miners enter the mines in groups and work in the mine site in these groups. The CH can be elected among the tags. The CH node collects the data of member tags and forwards it to the SRN only when a new tag joins the cluster or when a tag moves out of the cluster. In the cluster architecture, the CH is locally monitoring its members. Therefore, by using a local cluster monitor, it is possible to minimise the use of the energy-constrained SRNs and increase the communication system's uptime.

If clustering is not used when data of individual tags are sent to the SRN, only a sleep/wake-up method will be used. It will lead to increased delays in reporting positioning data to the positioning server, increasing the probability of not detecting the packets broadcasted by the tags. This decreases reliability and also increases power consumption, as many packets will be broadcasted and will be detected by the SRN. In the proposed system, the authors optimise power consumption vs latency trade-off using a cluster architecture and communicating the positioning data only, when necessary, as depicted in **Figure 1**.

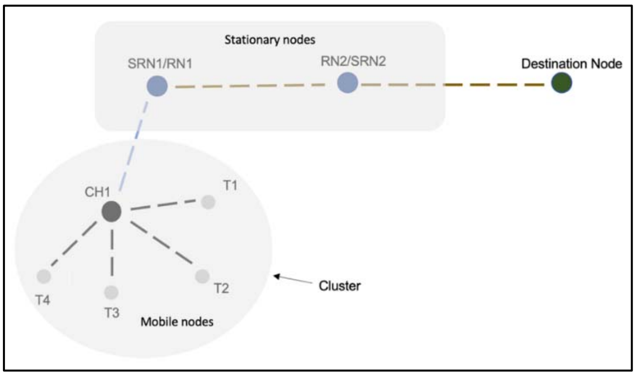

**Figure 1: The mobile and stationary nodes of the cluster-based Ad-hoc wireless network architecture**

## Wireless Technologies

**Table 1** summarises the transmission range, supported topologies, license and power consumption characteristics of the available wireless protocols.

The maximum distance over which a wireless node can transmit data is known as the transmission range in wireless communications. We assume that the width of the mine tunnel is the average distance between the SRN and the CH node. According to Ferrer-Coll et al. (2012) the maximum width of a mine tunnel is approximately 10m. Hence, we estimate the required transmission range for the detection system as 10m.

The network topology is the arrangement of the components in a wireless network. Star, tree, mesh, and Point-to-Point (P2P) are some examples of wireless network topologies. In a wireless network that uses the star topology, the end nodes do not communicate directly; instead, they forward data to the central node. In the case of the mesh topology, the end nodes can communicate with each other and the central node (Soparia and Bhatt, 2014). In the tree topology, the relationship between nodes differs. According to the hierarchy of the tree topology, the top nodes are the central nodes; the next are the routers or the parent nodes, while the end nodes are the child nodes. The child nodes can communicate with the central nodes only via their parent nodes (Yu et al., 2019). The P2P topology simply means that the end nodes can communicate directly with each other.

The arrangement of wireless network nodes in the proposed cluster-based detection system and the cluster tree topology are alike. The tags send data to the SRN via the CH node, similar to the way the child nodes send data via the parent nodes to the central nodes in the tree topology. The communications between the SRN and relay node or destination node has the characteristics of the P2P topology (Refer to section System Information). Therefore, the authors of this paper are interested in selecting a wireless protocol that supports both tree and P2P topologies.

The radio spectrum's Industrial, Scientific and Medical (ISM) frequency band is used for industrial, scientific and medical purposes. The ISM band includes the 900 MHz, 2.4 GHz and 5.8 MHz frequency bands (Minhas and Kumar, 2018). We prefer using the ISM band in this research as it is freely available. Another significant feature considered for selecting the wireless protocol in this research is the low power consumption for communications because of the power challenges found in underground mines.

In summary, we looked for low power consumption, a transmission range of up to 10m, support for both P2P topology and tree topology as well as license-free characteristics when selecting the wireless protocol for the wireless network. According to **Table 1**, BLE and ZigBee wireless protocols consist of all the required characteristics. The authors of this research chose BLE wireless technology as it consumes less power for communications than the ZigBee protocol. Besides, according to Li et al. (2018) BLE has shown promising results for range measurements in underground mines, which further supports the selection of the BLE wireless protocol for communications.

**Table 1: Characteristics of Wireless Technologies**

| Wireless Technology | Communication Range | Supported Topologies | Frequency Band | Power Consumption | License |
|---|---|---|---|---|---|
| Zigbee | $\leq 100$m | Star<br>Tree<br>Mesh | 2.4 GHz | Moderate | ISM band – License Free |
| Bluetooth Low Energy | $\leq 50$m | Star<br>Tree<br>Mesh | 2.4 GHz | Low | ISM band – License Free |
| Thread | $\leq 30$m | Mesh | 2.4 GHz | Moderate | ISM band – License Free |
| UWB | $\leq 25$m | Star<br>P2P | 2.4 GHz | High | ISM band – License Free |
| Wi-Fi | $\leq 100$m | Star<br>Mesh | 2.4 GHz | High | ISM band – License Free |
| LoRa | 2-5 km Urban<br>15 km Rural | Star | 169MHz<br>433 MHz<br>868 MHz<br>915 MHz | Moderate | ISM band – License Free |
| Sigfox | 3-10 km Urban<br>30 – 50 km Rural | Star | 862 MHz<br>968 MHz | Moderate | ISM band – License Free |
| NB IoT | 9 km | Star | LTE frequency bands | High | Licensed LTE frequency band |

### BLE Wireless Protocol Stack

BLE is a low-power wireless protocol introduced by the Bluetooth Special Interest Group (SIG) for low-power controlling and monitoring operations. It is a short-range wireless technology that consists of 40 RF data transmitting channels in the 2.4 GHz ISM band (Gomez et al., 2012). The BLE protocol has five radio states: advertising, scanning, initiating, standby and connected. The BLE link layer directly interfaces with the physical layer and manages the above radio states. The process of broadcasting signals is known as advertising in the BLE protocol. Scanning is when a BLE device listens for broadcasting BLE signals. The process of discovering a BLE signal is known as Device Discovery. Initiating is when a BLE device requests a connection with another BLE device. Once a connection is established between two BLE devices, it is known as the connected state. When the device is not performing any Tx or Rx radio tasks, the radio goes to a low power-consuming state known as the Standby State. Out of the 40 RF channels in the BLE physical layer, three are advertising channels, and the rest are data channels. The BLE GAP layer defines two BLE operation modes, connectable and non-connectable BLE. Connectable BLE devices can perform all five radio states mentioned above, while non-connectable BLE devices can only perform advertising and device discovery. The experiments for this research use connectable mode BLE devices. In connectable mode, an advertising device is termed a Peripheral Device, and a scanning device is a Central Device (Comuniello et al., 2022).

## OPERATIONAL MODEL

This section describes the operational model of the SRNs in the proposed wireless network architecture. The operational model is used to explain the experiments for this research paper. In addition, the BLE operational model is the fundamental component of the mathematical energy model and simulation model, which the authors of this paper intend to develop in future work.

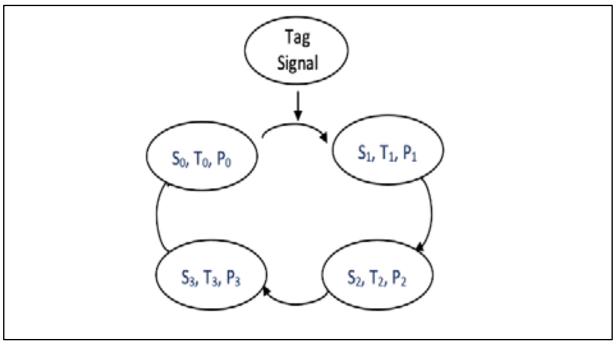

**Figure 2: Operational Model for SRN**

The SRNs used in the wireless network perform as connectable mode BLE central devices when scanning for CH nodes. S0, S1, S2, and S3 states of the state machine shown in **Figure 2** are the standby, scanning, connection initiation and connected radio states of the SRN. T0, T1, T2, T3 and P0, P1, P2, and P3 are the holding times and average powers of the respective states. **Table 2** shows the configurable holding times of the above states according to the BLE protocol. The holding time of S0 depends on the application, while for S2, the value depends on the hardware device used. The minimum and maximum configurable holding times for the S1 state are 2.5ms and 10.24s, while for the S2 state, it is 7.5ms and 4s. The experiments in the next section, determines the values of P0, P1, P2, and P3.

**Table 2: BLE state holding times**

| Holding time | Holding time range (ms) |
|---|---|
| $T_0$ | Application specific |
| $T_1$ | 2.5 - 10240 |
| $T_2$ | Hardware specific |
| $T_3$ | 7.5 - 4000 |

## EXPERIMENTAL SET UP

The experiments for this research were conducted to determine the optimal scanning configuration with low power consumption, high neighbour discovery performance and low latency for SRNs. The BLE experiments mentioned in this paper use the Texas Instruments (TI) CC2652 development kit which uses the BLE 5.0 protocol (2018).

### TI CC2652 development kit

The CC13x2 - CC26x2 Software Development Kit (SDK) and Code Composer Studio (CCS) version 10.3, an eclipse based Integrated Development Environment (IDE) owned by TI, were used for the firmware development. The hardware used in the CC2652 development kit is the simple link multi-standard CC26x2R wireless Launchpad. It supports the BLE 5.0, ZigBee and Thread protocols.

**Figure 3: a) Main channel of Monsoon Power Monitor connected to Launchpad. b) Measuring power consumption of the Launchpad**

**Monsoon Power Monitor**

In the experiments, the power consumption and the time interval readings were taken using the High-Voltage Power Monitor (HVPM) version of the Monsoon power monitor. The Power Tool software is the integrated software of the Monsoon power monitor that provides the Graphical User Interface (GUI). The power tool software for the HVPM version supports reading measurements at a voltage range of 0.8V to 13.5V and an electric current of up to 6A. The Monsoon power monitor consists of three power measuring channels: Main, USB and Auxiliary. The main channel was used in the experiments for this paper (Refer **Figure 3 (a)**). The power monitor was supplied with electric power and was connected to the laptop through the serial port (Refer **Figure 3 (b)**).

**Experiments**

The TI CC2652 launchpads in the experiments represent the SRN-central and the CH peripheral devices. The first launchpad which was considered as the SRN, was flashed with the simple central application, while the other device or the CH was flashed with the simple peripheral application. In Experiment 1, the power consumptions of the S0, S1, S2 and S3 states of the SRN were measured. Experiment 2 tested the rate of neighbour discovery with different configurations and compared the power consumption of the S1 state of the central device for each configuration to choose the optimal scanning configuration. To minimise the neighbour discovery's power latency, the lowest configurable advertising interval in the simple peripheral application was used. A detailed explanation of the experiments and results is presented in subsections Experiment 1 and Experiment 2

**Experiment 1**

In Experiment 1 the radio states of the SRN were changed by using the BTN1 and BTN2 buttons. The states were changed to complete a cycle of the state machine shown in **Figure 2** (S0 → S1 → S2→ S3). The power measurement readings were taken for each state using the GUI tools of the Monsoon power monitor. The scanning interval of the default simple central application in the SDK has a 100% duty cycle. The power reading for the scanning state was $19.9 \pm 0.43$ mW. Using Experiment 1, the authors compared the power consumptions of the different radio states of the central device; therefore, the errors of the power readings were neglected, and the average value was considered for the comparison. The table below shows the finalised readings.

**Table 3: Power consumption readings for BLE states of a central device**

| State | Power Consumption (mW) |
|---|---|
| Standby ($S_0$) | 0.02 |
| Scanning ($S_1$) | 19.9 |
| Connection Initiation ($S_2$) | 10 |
| Connected ($S_3$) | 0.78 |

**Observations:** According to the obtained results in **Table 3**, the scanning state consumes the highest power. The second highest power-consuming state is the connection initiation. The connection initiation interval is a fixed value as it is hardware specific. The scanning interval is a configurable value at the application level.

**Experiment 2**

Experiment 2 determines the optimal scanning interval to minimise the power consumption of the SRN. In this experiment the peripheral device broadcasted packets at an interval of 20ms which is the minimum advertising interval of a TI CC2652 peripheral device. The default simple peripheral application in the SDK was modified to use only one set of advertisements. The type of advertisements used was the legacy advertisements with 39 bytes. **Figure 4** shows the GUI screenshot of the advertising signal. According to the readings, the advertising window was 3.14$\pm 0.13$ms, whereas the advertising was 24.38$\pm 03.42$ms. The wake-up time was 0.72ms, and the power reading per advertising interval was 16.09$\pm 0.24$mW.

The serial terminal of Code Composer Studio (CCS) software was used to visualise the discovery of the peripheral device (CH node). The peripheral and central devices were placed in Line of Sight (LoS), 2.5m apart when obtaining the neighbour discovery results. For 100% neighbour discovery performance, the central device should discover the peripheral device each time. The central device's sleep/wake-up duty cycle was changed according to the values shown in **Table 4**. The manual state-switching procedure mentioned in Experiment 1 was followed to change radio state from the standby state to the scanning state. The power of the scanning state was measured for each configuration, and the average values of the readings were used to plot the graph in **Figure 5**. The experiment was repeated many times (20 times) to provide a more accurate neighbour discovery performance percentage.

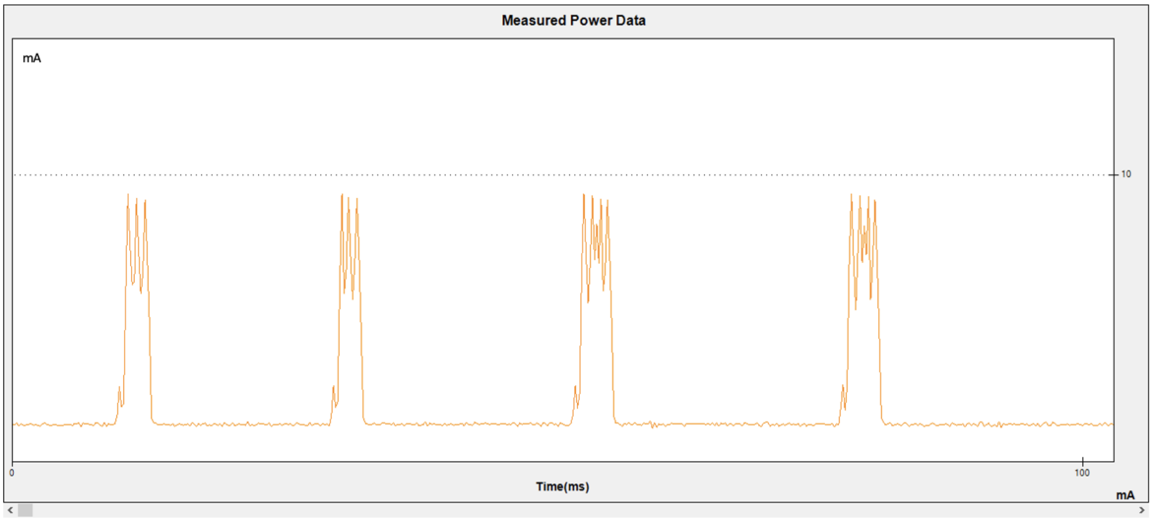

**Figure 4: 20ms advertising interval**

**Table 4: Central device configurations used for experiments**

| Configuration No. | Scan Window (ms) | Scan Interval(ms) | Scan Duration(ms) |
|---|---|---|---|
| 1 | 2.5 | 2.5 | 10 |
| 2 | 2.5 | 2.5 | 20 |
| 3 | 2.5 | 5 | 10 |
| 4 | 5 | 5 | 10 |
| 5 | 5 | 10 | 20 |
| 6 | 10 | 10 | 20 |
| 7 | 20 | 20 | 40 |

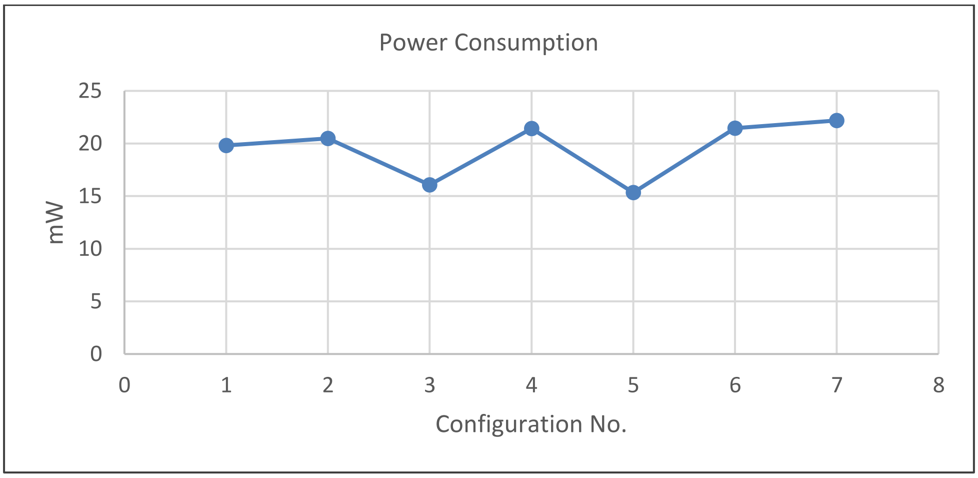

**Figure 5: Power consumptions of configurations mentioned in Table 5**

The graph in **Figure 5** illustrates the power reading of the scanning interval for the seven configurations. The total count of neighbour discovery for each configuration in the twenty repeated experiments is represented by the graph in **Figure 6**.

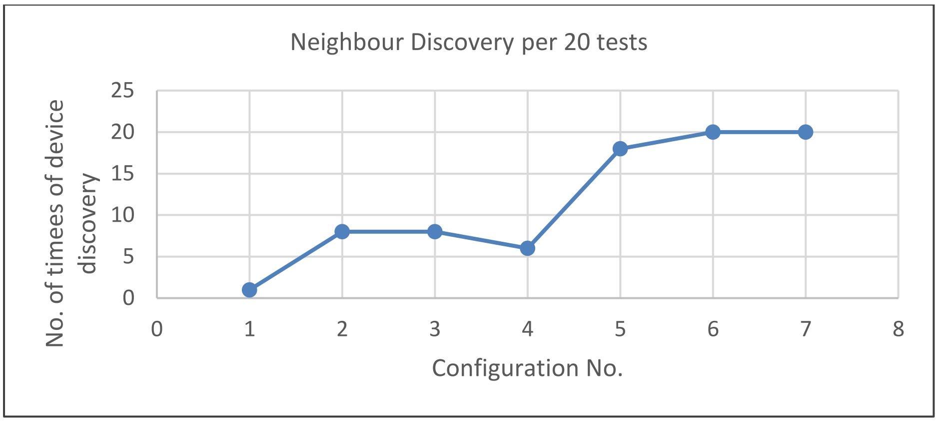

**Figure 6: Neighbour discovery results for the configurations mentioned in Table 4**

**Result Analysis**

The power consumption (**Figure 5**) and the neighbour discovery percentage performances of the configurations are plotted in the same plane in **Figure 7** to find the optimal configuration for neighbour discovery. Comparing the two plots, configurations 1,2,3 and 4 show a low neighbour discovery percentage, while configurations 5,6 and 7 show a high neighbour discovery percentage. Configuration 2 and configuration 5 are the lowest power-consuming configurations as they have the lowest total scanning windows. Between the two, configuration 5 has the lowest average power reading of 15mW with a high neighbour discovery performance percentage of 90%. Therefore, configuration 5 is concluded as the optimal neighbour discovery configuration for the SRNs in the proposed wireless network.

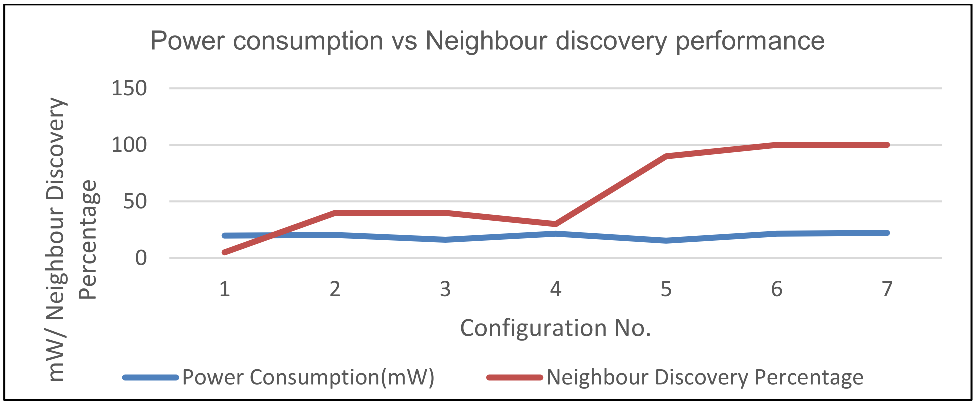

**Figure 7: Comparison of Power Consumption and Neighbour Discovery Performance of the Configurations in Table 4**

## CONCLUDING REMARKS AND FUTURE WORK

According to previous studies, the effective configuration for neighbour discovery is when the scan and advertising intervals are the same (Jeon et al., 2017). The approach of this paper is different as we selected the optimal configuration for neighbour discovery based on the scan window and the time taken for the advertising event. According to the results, the optimal scanning configuration has a 5ms scan window, 10ms scan interval and a scan duration of 20ms when the advertising interval is 20ms. According to the readings of the peripheral device, the average advertising window is 3.14ms for the legacy advertisements. When the wake-up time is added to the advertising window, the total time taken for the advertising event is 3.86ms, which is 1.14ms less than the 5ms scan window.

A peripheral device advertises in all three channels. The three advertising channels are three peaks in the advertising window shown in **Figure 4**. Once the interval respective to the channel peak aligns with the central device's scanning channel, the peripheral device is discovered. Therefore, according to this study, the optimal configuration occurs when the scanning window is slightly greater than the advertising window. In an application, after deciding on the broadcasting data and flashing the peripheral device, a measurement of the peripheral's advertising interval should be taken using a power monitor or an analyser. The reading should be used to determine the power-effective scan interval for the central device.

The experiments described in this paper were performed when the CH node (peripheral device) was stationary. In the mine sites, the CHs are mobile. There is a probability that the use of the stationary CH in the experiments resulted in better neighbour discovery performance than using a mobile CH. Therefore, future work in relation to this research will include developing an Omnett++ simulation model to test the impact of CH mobility on the neighbour discovery procedure. Furthermore, the authors will extend the simulation model to test the power and latency performances of a BLE/LoRa hybrid wireless network architecture, where the communication system is LoRa, and the detection system is the cluster based BLE system proposed in this paper.

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