Power Minimisation Techniques for Space-Based Wireless Sensor Networks

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by

Zaid Al-Shammari

Department of Engineering

University of Leicester, UK

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Abstract

Wireless sensor networks (WSNs) have received much attention in recent years. Such networks comprise spatially distributed sensors to monitor various parameters. Space-based wireless sensor networks (SB-WSNs) consisting of tiny, low power, inexpensive satellites flying in a fleet with a close formation can offer a wide range of applications. Since communication is typically the major factor in power consumption, the activity of the transceiver should be reduced to increase the nodes' lifetime.

To understand the network power behaviour, a space-based wireless sensor network consisting of 40 nodes was designed as an experimental testbed. Several tests were undertaken to investigate the nodes' lifetime and the packet loss with various sleep/wake up methods. The study found that the nodes with shorter paths to the sink benefit from improvement in their lifetime. In contrast, the other nodes with routes including many hops obtain less enhancement in their lifetime and high packet loss. To further reduce the power consumption, a novel sleep/wake up technique where the nodes have different sleep periods based on their locations has been proposed and tested. This modification enhanced the network operation time by 24% and increased the total delivered packets by 51% compared to when the nodes stay active all their duty cycle. Another concern was uneven power consumption due to the extra packet-relaying duties imposed on central nodes. This was addressed first by altering the connectivity of the network, and then by adding extra nodes dedicated to this task.

The proposed sleep/wake up scheme was extended further through the adoption of transmission power control (TPC) and the introduction of multiple sinks. Both mechanisms were used to decrease the power budget required to deliver a packet from source to destination by reducing the number of hops in the paths. This improves the nodes' lifetime and the total amount of collected data. Findings in this research have direct relevance to the use of commercial off the shelf (COTS) nodes in a SB-WSN and will provide an impetus for accurate estimation of the performance and design of such a network.

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AODV	Ad-hoc on-demand distance vector
ATPC	Adaptive Transmission Power Control
AWP	Asynchronous Wakeup Protocol
BS	Base station
CCA	Clear Channel Assessment
CH	Cluster Head
COTS	Commercial off the shelf
CR	Cognitive Radios
CSL	Coordinate Sampling Listing
CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
CST	Computer Simulation Technology
DEEC	Distributed Energy Efficient Clustering
DSN	Destination Sequence Number
DSSS	Direct Sequence Spread Spectrum
EAMR	Energy Aware Multipath Routing
ESA	European Space Agency
FFD	Full Function Device
FSPL	Free Space Path Loss
GPS	Global positioning system
HART	Highway Addressable Remote Transducer Protocol
HWMP	Hybrid Wireless Mesh Protocol
ISM	Industrial Scientific and Medical
LB	Load Balance
LEACH	Low Energy Adaptive Clustering Hierarchy
LEO	Low Earth Orbit
LOS	Line-of-sight
LQI	Link Quality Indicator
MAC	Medium Access Control
MCBR	Message-initiated Constraint-Bases Routing
MNL	Minimum Node Lifetime

NASA	National Aeronautics and Space Administration
NDT	Network Disconnection Time
OLSR	Optimise Link State Routing
OSI	Open System Interconnection
PAN	Personal Area Network
PSSS	Parallel Sequence Spread Spectrum
PTW	Pipelined Tone Wakeup
RAW	Random Asynchronous Wakeup
RD	Route Discovery
RERR	Route Error
RF	Radio Frequency
RFD	Reduced Function Device
RL	Reinforcement Learning
RREP	Route Reply
RREQ	Route Request
RSSI	Received Strength Signal Indicator
RTS	Request to Send
SM	Support Mode
SO	Sleep coordinator Option
ST	Sleep Time
STEM	Sparse Topology and Energy Management
SWIPE	Space WSNs for Planetary Exploration
TC	Topology Control
TDMA	Time Division Multiple Access
TPC	Transmission power control
TPL	Transmission Power Level
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WMSN	Wireless Multimedia Sensor Networks
WPAN	Wireless Personal Area Network
WRAN	Wireless regional area networks
WSN	Wireless sensor networks
WT	Wakeup Time

1 Introduction

1.1 Satellite networks

The space industry started using satellites as active transmission relays (the information received is neither originated nor terminated at the satellite itself). The first satellite launched to space for commercial purposes was in the mid-1960s. Nowadays, satellites are essential for everyday life with their applications in TV broadcasting, surveillance monitoring and military operations. In addition, they have become more developed with onboard processing, switching and routing. The development and launch of such satellites require significant resources which are available to only a few large organisations such as the National Aeronautics and Space Administration (NASA) and The European Space Agency (ESA) (Ippolito Jr, 2008).

Aerospace applications suffer from hurdles such as constraints on size, mass and power. Recently, the development of technology enabled the implementation of small aerospace instruments. CubeSat was suggested as an alternative solution to large spacecraft and to decrease unit cost. It is a 10x10x10 centimetres standardised miniature satellite with a mass about 1 kg. The CubeSat can be considered as a picosatellite if it has a mass under 1kg (Gill *et al.*, 2013). Figure 1.1 shows the CubeSat classifications and specifications. Also, the CubeSat can operate as a standalone satellite or could be used to establish a larger spacecraft by combining a number of them (Poghosyan and Golkar, 2017). CubeSats are mostly designed by academic organisations with a small fraction of all launches being by the commercial sector. Over the past few years, this trend has been changing as the contribution from the private sector is significantly increasing in development and launch of CubeSats (Buchen, 2015). However, a single CubeSat has not been able to meet its full potential and does not allow significant space science research into WSNs (Toorian *et al.*, 2008). A system consisting of tiny, inexpensive satellites flying in a fleet with a close formation, which became more applicable with the implementation of secondary payloads and satellite networks, can offer a wide range of applications that can be applied to many space missions. Examples include assisting a large mother ship, performing continuous earth monitoring in low earth orbit (LEO), sensing space environments and enabling continuous communication between low-powered vehicles used for planets or asteroids exploration (Vladimirova *et al.*, 2010). In the earth monitoring systems, the CubeSats are typically placed into the LEO with altitudes between 60 km to 2000 km with a typical lifetime of several years (Lokman *et al.*, 2017).

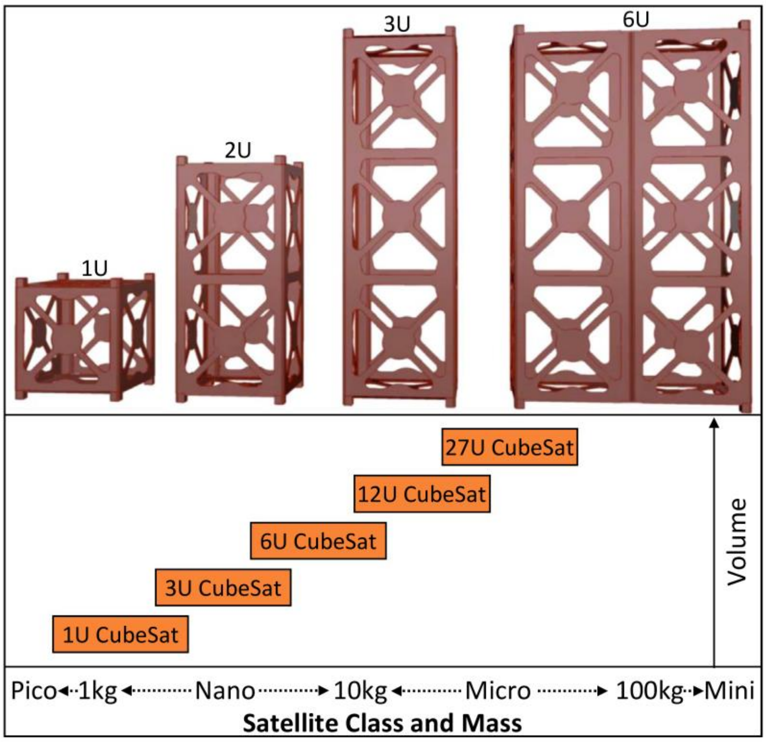


Figure 1.1 CubeSat specifications compared to overall small satellites classifications U1 unit equals to the volume of 10×10×10 cm^3 (Poghosyan and Golkar, 2017)

Extending the conventional WSN concept to space applications required inter-satellite communication to enable autonomous transfer of data between the network node members and the gateway which will forward the information to its final destination (i.e. terrestrial ground base or mother-ship). Inter-satellite communication assists in utilising network functions, such as data aggregation, distributing processing function and increasing node transmission range via performing a multi-hop operation. A typical scenario of SB-WSN consists of a number of satellites equipped with multiple sensors that need to communicate using a single-channel (Radhakrishnan *et al.*, 2016). Several examples are demonstrating the small satellites network such as the QB-50 mission (Gill *et al.*, 2013), ESPACENET (Arslan *et al.*, 2006) and Flock 1 (Portal, 2014).

However, the SB-WSNs have several constraints that limit their applications, such as limited power, antenna size and onboard processing. Power consumption optimisation is the main issue facing the design of SB-WSN nodes (Pinto *et al.*, 2015).

1.2 Wireless Sensor Networks (WSNs)

The similarity in the functions of satellite networks and the terrestrial wireless sensor network inspired the researchers to bring the WSNs technology to space with some modifications due to differences in environments (Vladimirova *et al.*, 2010). WSNs have received tremendous interest in the recent years. They can be deployed above or buried in the ground, underwater and in the space environment (Yick et al., 2008). The range of potential applications for WSNs is very large due to their flexibility, low cost and their adaptability to meet the user's demands. The development of WSNs was motivated by military applications such as battlefield monitoring (García-Hernández *et al.*, 2007). Today WSNs have found their way into a wide variety of applications such as health monitoring (Alemdar and Ersoy, 2010), environment monitoring (Othman and Shazali, 2012), transportation (Tubaishat *et al.*, 2009), building automation (Reinisch *et al.*, 2007) etc.

A WSN is formed by many sensors cooperatively monitoring large physical environments and these nodes communicate not only with each other but with the sink, utilising their wireless radios, allowing them to send their sensed data to a remote processing, visualisation, analysis and storage system. The capability of a sensor node in a WSN can differ widely, that is, a simple sensor node may operate to observe a single event, while more complex nodes may be equipped with many different sensing mechanisms. Also, they can vary in their communication abilities, such as utilising infrared, radio frequency or ultrasound with different latencies and bandwidths (Dargie and Poellabauer, 2010).

The structure of a wireless sensor node mainly depends on requirements of the specific application. However, there are common features in the structure of the diversified nodes. Typical WSN hardware node consists of five main parts: sensing subsystem, data processing subsystem, communication subsystem, memory and power supply, as shown in Figure 1.2. A variety of mechanical, chemical, physical, thermal, magnetic and optical sensors can be connected to the nodes. An additional component could be added to the node structure, such as a GPS unit for location update or special camera to record events (Akyildiz *et al.*, 2002).

The fundamental WSN node operation begins with the sensors subsystem detecting an event in the environment, which led to creating an analogue signal. Then the signal transformed from analogue to digital by an A/D converter and forwarded to the processing subsystem which will deal with signal locally, usually with the aid of a small-scale storage unit. Finally, the information is passed to the communication subsystem which will be responsible for data transfer to the gateway through the wireless network. Some information could be added to the data to identify the node or to help in the coordination of the sending process (Jin, 2010).

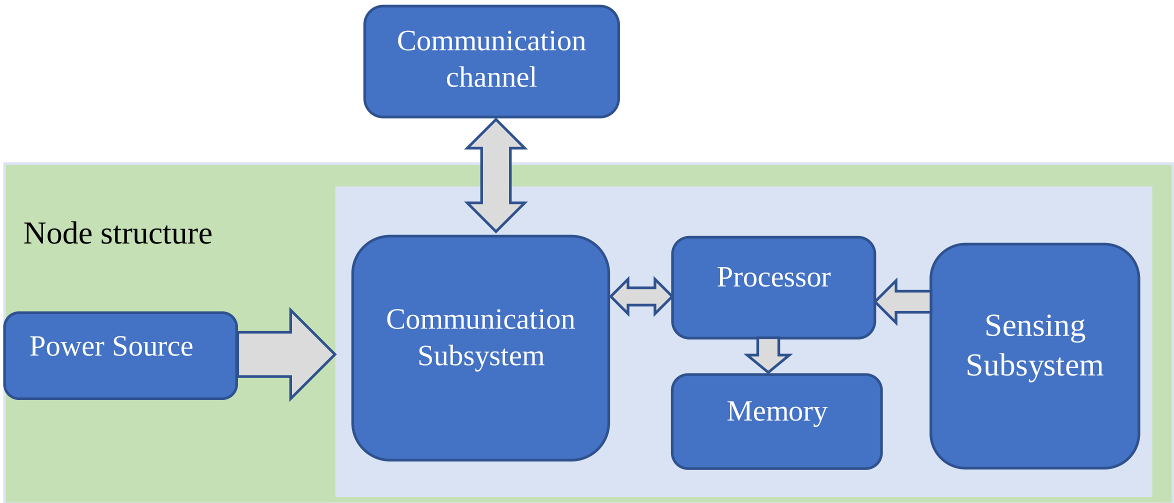


Figure 1.2 Typical wireless sensor node structure

The power unit is the most critical component in the WSN node structure, and the network designers pay attention to estimating the node power behaviour since it has limited capacity and is hard to replace. The wireless network device’s energy efficiency is the main limitation in the operation of communication networks containing battery-operated devices, and it is even more challenging in other wireless networks which depend completely on non-replaceable batteries such as wireless sensor networks (Ephremides, 2002). In satellite networks, the power must be designed carefully to ensure power supply during the mission period. Typically, power subsystem of small satellites consists of solar cells as a power source (Yang et al., 2016). However, this technique to generate the power has some limitations such as the small satellite should switch to battery power during the eclipse periods of its orbit (i.e. in earth monitoring applications where it placed in LEO). Also, it will not be feasible for lunar missions due to long eclipse period or in deep space application as the satellites will be far away from the sun. Therefore, minimising the power consumption is crucial to extend small satellite lifetimes and improve their performance.

The environment plays a significant role in defining the size of the wireless sensor network. For example, in the indoor environment, fewer nodes are needed to construct the network in a limited space while in the outdoor environment more nodes may be required to cover a larger area. However, in SB-WSN, the size of the network and nodes number in the network is somewhat determined by the launching capability of the auxiliary payload and the space mission. In addition, nodes' sensor coverage range can affect the size of the WSN which depends on the type of the parameters that are required to be observed in the monitored area. All the above will be true in the case of pre-planned network deployment (Fahmy, 2016). Most of the deployed or planned SB-WSNs configuration are pre-planned because these small satellites are expensive to distribute randomly with a high risk of being lost in space (Poghosyan and Golkar, 2017).

1.2.1 Wireless Sensor Networks Topologies

Since a wireless sensor network consists of a number of nodes, topology must be considered in its design to coordinate the communication between nodes and managing the data flow towards the gateway. The common deployment topologies for wireless sensor network are a star, mesh, and tree (Cecílio and Furtado, 2014).

1.2.1.1 Star Topology

In star topology WSN, all wireless sensor nodes communicate directly to the gateway in a single hop system as shown in Figure 1.3. The star topology is simple to implement, but it has a limitation in the number of nodes which can communicate with the gateway. When a sensor node fails, it will not affect the operation of the other nodes in the network unless it is the central sink. The gateway collects the data from the nodes and in some applications, it sends commands to them. All nodes act as an end device and do not communicate directly with each other, they utilise the gateway as coordinator where all the traffic is forwarded (Shen *et al.*, 2004).

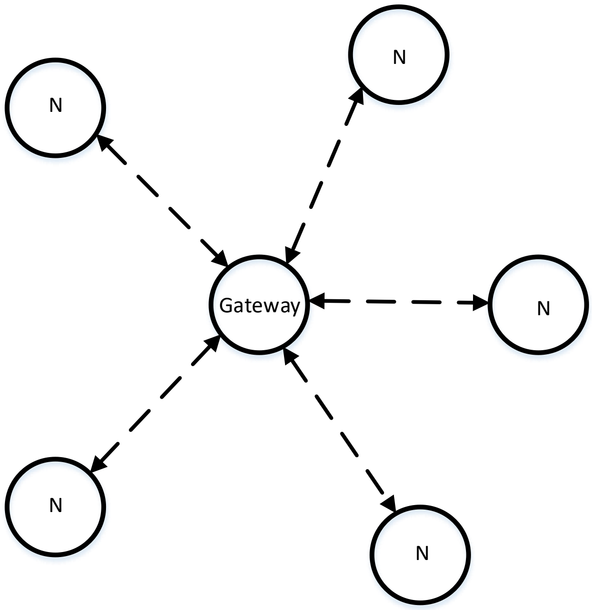


Figure 1.3 Wireless sensor network in star topology

1.2.1.2 Mesh Topology

The mesh configuration allows route creation from any source node to any destination node in the network, and all nodes in the network act as router and end device at the same time, Figure 1.4 shows mesh WSN. Hence, they send their own data and help to forward other nodes' data to the gateway. A WSN adopting a mesh topology is highly fault tolerant because each node has multiple routes through its neighbours that are located in its radio communication range (Dargie and Poellabauer, 2010). In a fully connected mesh network, all devices in the network are in radio range of each other. Typically a full interconnection is hard to achieve especially if the network nodes number is relatively high, or in the case of their sensing range being nearly or equal to their radio communication range, so they distributed with a limited number of neighbours. Therefore, WSNs utilise mesh in peer to peer communication method where each node can establish a path through using a multi-hop process by applying a routing algorithm (Fahmy, 2016). Figure 1.5 shows WSN adopting mesh topology with peer to peer communication method.

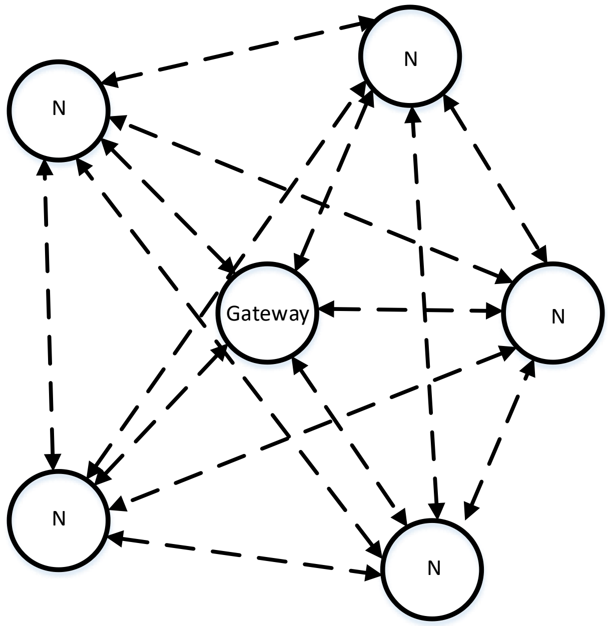


Figure 1.4 Fully-connected mesh WSN

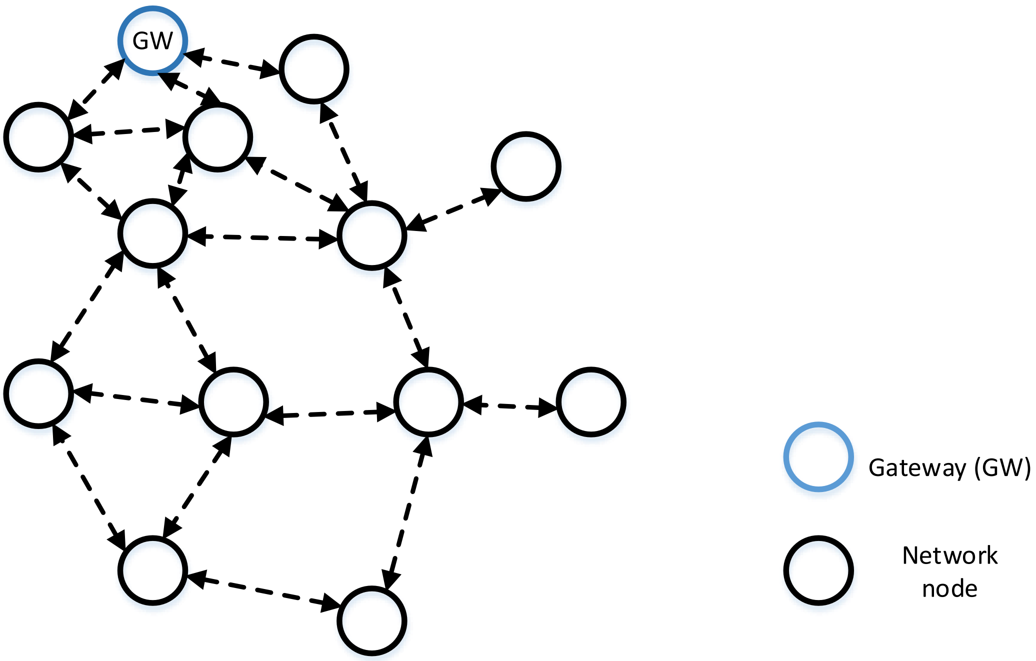


Figure 1.5 Mesh WSN utilising peer to peer communication

1.2.1.3 Tree Topology

WSNs configured in a tree topology have three types of nodes that are leaf or end devices, routers and central node or a gateway (see Figure 1.6). A number of devices will be connected to the router, and the routers communicate with each other to establish the path to the gateway which is responsible for data collection and relaying to the external network (Wang *et al.*, 2006). The tree topology can be considered as a hybrid between peer to peer mesh and star topology. Also, it is designed to enhance the communication range of star topology and meet the demand of increasing the number of nodes in the network (Chebbo *et al.*, 2012).

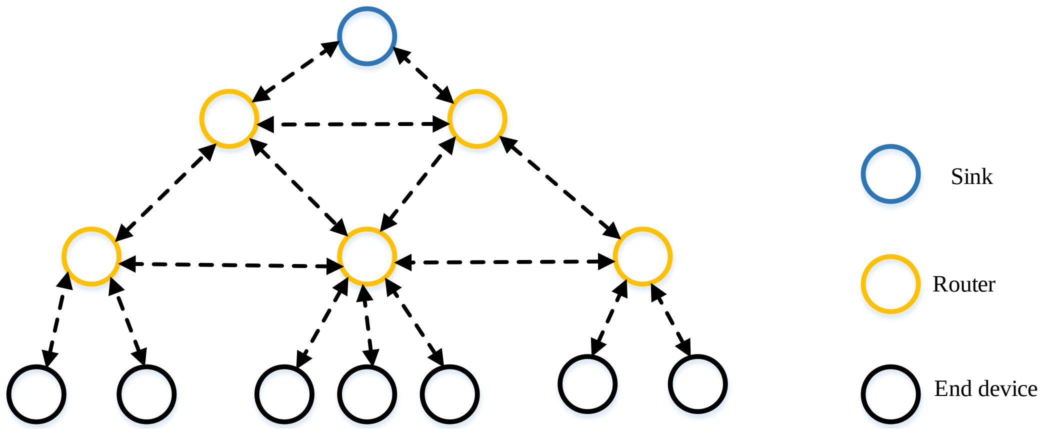


Figure 1.6 Wireless sensor network adopting tree topology

The WSNs topologies can be utilised in the SB-WSNs depending on the application requirements and the number of deployed nodes. Adopting a star topology will be more convenient in the situation where the number of nodes is limited, and their communication range is low. In contrast, a WSN using mesh topology could have a large number of nodes that are designed in the same structure to monitor a large area. Partially mesh topology could lead to power imbalance due to data traffic concentration in the nodes near the sink. Utilising tree topology in WSN requires the design of three different node infrastructures, and in addition, the coordinator cannot perform the sensing job. Therefore, it is cost more than the other topologies, but it can handle the implementation of large-scale networks.

1.2.2 Wireless Network Standards

Many communication standards have been proposed to meet the demand of wireless networks. The taxonomy of these standards is based on their operation in the PHY/MAC layer and the higher layers of the Open Systems Interconnection OSI model (Zimmermann, 1980) and the adopted radio communication standard. Figure 1.7 shows a comparison of radio standards used in wireless communication. A combination of several of these standards is utilised in many applications (Ma, 2014).

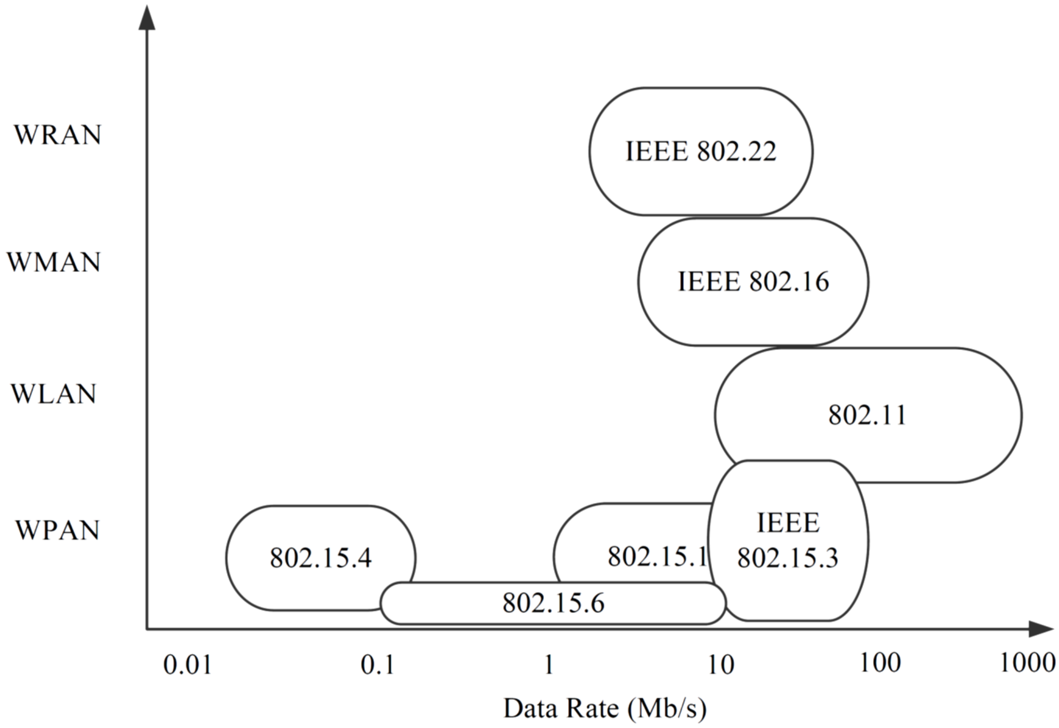


Figure 1.7 Data rates and working distance computation for IEEE 802 radio standards(Ma, 2014)

The IEEE 802.22 standard is based on Cognitive Radios (CR) and is proposed for the implementation of wireless regional area networks (WRANs). Its PHY/MAC layers share the vacant spectrum which is currently allocated to the Television (TV) service. The standard was suggested to deliver the broadband to the rural environments (Cordeiro *et al.*, 2005, Mitola and Maguire, 1999). On the other hand, IEEE 802.16 was designed to develop as a group of air interfaces depending on a common MAC protocol but with PHY layer specification relays on the utilised spectrum (Eklund *et al.*, 2002). It is also known as Worldwide Interoperability for Microwave Access (WiMAX)

(Andrews *et al.*, 2007). Neither of these IEEE 802 radio communication standards applies to WSNs, but they can be utilised by the gateway to provide an external link to a larger network.

The IEEE 802.11 family of standards are used to construct a Wireless Local Area Network (WLAN) which is consist of a group of specifications for the PHY/MAC layers (Gast, 2005). Also, it supports higher data rates than to 802.22 and is capable of providing wireless connectivity to fixed or moving devices. The IEEE 802.11 operates at 2.4 GHz, and it is extended to work in 5 GHz (IEEE 802.11a) or adopt both frequencies (e.g. 802.11n). Further, it has many other versions which are designed for specific applications with different data rates that could reach up to 1 Gbps (802.11 ac) (Ong *et al.*, 2011). The 802.11 radio communication standard is used in Wireless Multimedia Sensor Networks (WMSNs) due to its high data rate ability (Akyildiz *et al.*, 2007).

IEEE 802.15 set of radio communication technologies specify Wireless Personal Area Network (WPAN), and it contains four standards. IEEE 802.15.1 was adopted by Bluetooth, and it was proposed as low-cost, short-range device and cable replacement mechanism. It has three communication ranges depending on its operation class that are 100 m, 10m and 1 m respectively (Bluetooth, 2007). Also, it considers one possible alternative to WSN in the implementation. Later the interest towards Bluetooth-based WSN decreased due to insufficient power characteristics for sensors and high complexity (Gungor and Hancke, 2009). On the other hand, the IEEE 802.15.3 standard introduced as the first high data rate standard for the 802.15 group, since it can support up to 55 Mbps for distances more than 70 m (Walke *et al.*, 2007). Also, it is based on a centralised connection and oriented topology which splits the large network into several small sub-sets (Mehta and Kwak, 2009).

The IEEE 802.15.4 standard configures the PHY/MAC layer for low data rate communication (LAN/MAN Standards Committee, 2011). It is proposed to support a vast number of industrial applications which require small, high-reliability and low-cost devices. It trades off performance and high speed for architecture that is based on low cost and low power consumption (Sohraby *et al.*, 2007).

IEEE 802.15.6 is the latest standard in the IEEE 802.15 family. It defines the Wireless Body Area Network (WBAN), and it supports real-time health monitoring with up to 10 Mbps data rate. Also, it operates in the ISM band and other bands dedicated to medical technology (Kwak *et al.*, 2010).

1.2.3 IEEE 802.15.4 Overview

The analysis of radio communication standards confirms that the IEEE 802.15.4 is the most appropriate standard of the IEEE 802 family to meet the requirement of WSNs. Therefore it will be described in more detail in this section.

The main design requirement of the IEEE 802.15.4 is reducing the power consumption and maximising battery lifetime, assuming that the transmission rate is low and the amount of data to transmit is small. The frame structure is designed to have as small as possible overhead information (Xiao and Pan, 2009). Also, in IEEE 802.15.4 the WPAN nodes are classified into two types: Full Function Device (FFD) and Reduced Function Device (RFD). The FFD can communicate with other FFD and RFD devices in its transmission range. Also, the FFD node can serve in three modes of operation as Personal Area Network (PAN) coordinator, time synchronisation coordinator, sending the node the sleep and active periods and as an end device. In comparison, the RFD is designed for extremely simple operations and can communicate only with an FDD node (Iqbal, 2016).

The IEEE 802.15.4 can support two deployment topologies, star topology (Reviewed in Section 1.2.1.1) where many RFD devices connect to a PAN coordinator. Also, peer to peer mesh topology (Reviewed in Section 1.2.1.2) where the network consists of many FFD nodes that establish the route to the main PAN coordinator that is considered as a gateway. Further, the IEEE 802.15.4 defines the FFD nodes with either long address with 64-bit or 16-bit short address (Baronti *et al.*, 2007). The IEEE 802.15.4 has the following features defined in the PHY/MAC layers:

I. IEEE 802.15.4 Physical Layer Specifications

- It supports three frequency bands, all of them using either Direct Sequence Spread Spectrum (DSSS) or Parallel Sequence Spread Spectrum (PSSS) access mode. Also, IEEE 802.15.4 has 1 channel in the 868 MHz bands, 10 channels in the 915 MHz band and 16 channels in the 2400 MHz band (Baronti *et al.*, 2007, Ma, 2014).

- Activating and deactivating the radio transceiver.
- Perform Clear Channel Assessment (CCA) which is part of Carrier Sense Multiple Access (CSMA) and adopted by the IEEE 802.15.4 (Baronti *et al.*, 2007).

II. Medium Access Control layer (MAC)

The MAC sublayer establishes the interface between the physical layer and the network OSI layer. Also, it provides two services that are the named MAC management service and MAC data service. Further, it responsible for the following duties (Zheng, 2004) :

- If the device is the network coordinator, the MAC layer will be responsible for generating synchronisation beacons.
- The MAC layer of the devices that are attached to coordinator and listen to beacons will be responsible for the synchronisation process.
- Performing CSMA with collision avoidance process for channel access mechanism.
- Association and dissociation in WPAN, the IEEE 802.15.4 embedded these methods to support nodes self-configuration. This process will enable the automatic creation of star topology and self-configuring of peer to peer networking.

1.2.4 Industrial Protocols Adopting IEEE 802.15.4

The are several industrial protocols approved for WSN applications that utilise the IEEE 802.15.4 PHY/MAC layers such as ZigBee, Wireless Hart, ISA 100, 6LoWPAN and DigiMesh. They all define their networking and application layer according to their objectives and protocol requirements.

- ZigBee

Zigbee defines the network layer and the upper layers of the OSI model. It designed to provide simple, low power low-cost wireless communication technology in embedded applications (ZigBee Alliance, 2010). ZigBee has three network components: coordinator, router and end device (see Figure 1.8). A ZigBee network can have one coordinator which organises the global synchronisation through sending beacons. Also, the coordinator can be connected to routers which will relay the sensed data from the end devices. Further, ZigBee can support three deployment topologies: star, tree and mesh (Mihajlov and Bogdanoski, 2011).

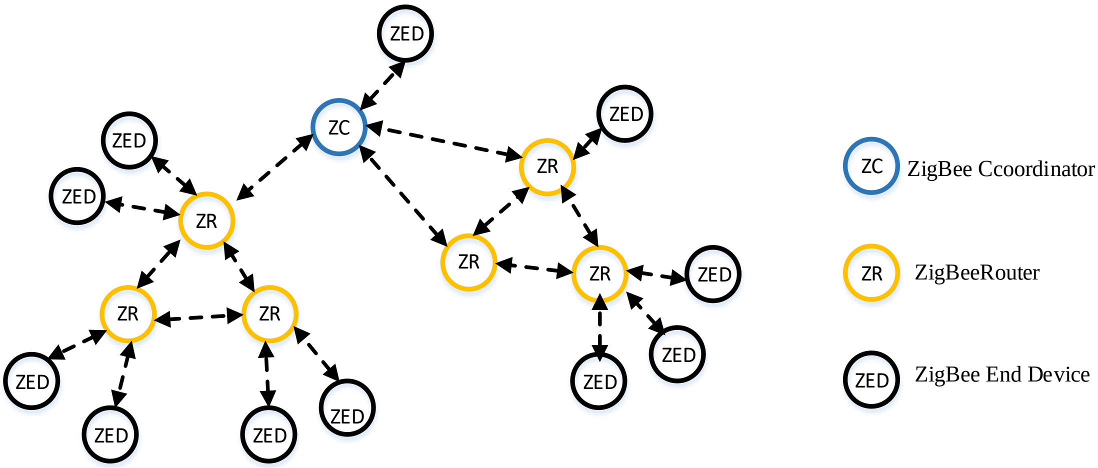


Figure 1.8 ZigBee network components and deployment topology model

- Wireless HART

This is the wireless extension of HART protocol and which is used for real-time automation and industrial application (Helson, 2009). Wireless HART uses the IEEE 802.15.4 physical layer parameters and operates in the 2.4 GHz band. Also, it utilises Time Division Multiple Access (TDMA) and CSMA to support the implementation of wireless mesh networking topology. In contrast to ZigBee, all devices in the Wireless HART protocol are allowed to route packets which make it more compatible with the mesh topology (Song et al., 2008)

- ISA-100

ISA-100 is proposed by the International Society of Automation (ISA) and designed for automation and low data rate wireless monitoring (Standardization, 2009). It uses the physical layer specification of IEEE 802.15.4 and operates in the 2.4 GHz band. Like Wireless HART, ISA-100 employs the CSMA to avoid packet collision and TDMA mechanism which allows the nodes to access the wireless channel without the need to wait (Petersen and Carlsen, 2011).

- 6LoWPAN

IPv6-based low-power wireless personal area network allows wireless communication using IPv6 addressing over an IEEE 802.15.4 based network (Minoli, 2013). The 6LoWPAN standard adopts all the benefits of the IP communication management. It allows the devices to directly connect to the available IP network (e.g. Internet and Ethernet), establishing easy access to the data from the monitoring devices (Gungor and Hancke, 2009).

- DigiMesh

This is a mesh protocol implemented above IEEE 802.15.4, which was developed by Digi (Digi International, 2015b). In DigiMesh all the nodes in the network exchange data and are interchangeable since it defines only one type of network component and all the nodes are configured as low-power/battery-powered devices (see Figure 1.9). Therefore, it offers more reliability as it allows the nodes to find an alternative path in case of node failure (Digi International, 2015a).

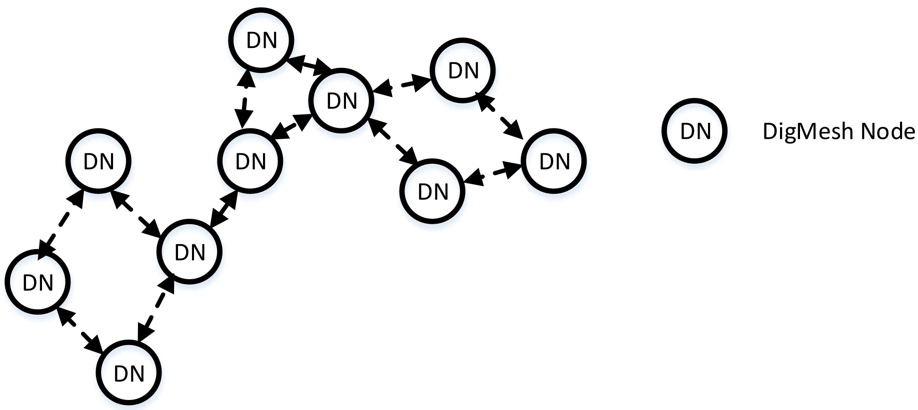


Figure 1.9 Network topology employing the DigiMesh protocol

There are some similarities and differences in the various industrial protocols since all of them are built over the IEEE 802.15.4 radio communication standard. Also, they are designed to meet specific application requirements, for example, ZigBee is proposed for commercial applications with various products to meet the user's needs, while Wireless HART is for industrial applications to monitor plant. On the other hand, Digimesh is proposed for commercial and educational purposes with an easy deployment and maintenance objective. ZigBee allows only the end devices to sleep while DigiMesh allows all nodes in the network to adopt low power sleep. Further, using mesh network topology in Wireless HART standard and DigiMesh provides them with more reliability in comparison to other standards because they allow the end devices to establish an alternative route. In contrast, coordinator failure in ZigBee will isolate the end devices connected to it.

1.2.5 Wireless Sensor Networks Challenges

- Resource constraints

The design and operation of the nodes in a WSN have three constraints: power, memory and processing. The sensor nodes are equipped with batteries with limited power and mostly hard to recharge. Also, they are restricted in memory to reduce the system complexity and have low computational capability to minimise energy consumption (Gungor and Lambert, 2006).

- Time synchronisation

Time synchronisation of sensor nodes is important in maintaining data consistency and coordination. Keeping clocks on all sensor nodes synchronised, as short time of even a few milliseconds is a difficult task. Sharing the time information will increase the network overhead which means spending a lot of power to relay clock synchronisation data (Noh et al., 2008).

- Localisation and positioning

In many applications, it is required to record the actual location where the measurement was made. As a result, each node in the WSN should have knowledge about its position. Establishing accurate information about nodes locations can be challenging due to the simple sensor device design and the other budgets required to add additional hardware to provide positioning data (Rudafshani and Datta, 2007). Typically the solution is either to equip the nodes with global positioning system unit (GPS) or by estimating their position to a reference node with a known location (Stanoev et al., 2016). However, these solutions need some modification before adoption in SB-WSNs since they suffer from low accuracy, high power consumption and large physical size (Griffiths, 2017).

- Routing

Establishing a path to deliver the sensed data to the sink is a challenging task in a WSN particularly in the applications where the network consists of a large number of nodes. The short transmission range of the wireless sensor node means that the data may travel many hops to reach the sink which makes it more vulnerable to transmission failure. The selection of routing protocol might differ depending on the application needs and network structure (Akkaya and Younis, 2005).

1.3 Wireless Sensor Networks Communication Channel

A radio communication channel between the transmitter (Tx) and the receiver (Rx) can be established if the power of the received signal is above the receiver sensitivity threshold. A direct link will exist between the Tx and Rx if $P_r \geq B$, where P_r is the power received at the receiver and B is the receiver sensitivity threshold. The value of B depends on the receiver transceiver structure (e.g antenna specifications), the communication data rate, the channel coding etc. P_r depends on the transmission power P_t and the path loss P_L which represents the degradation the P_t suffers while travelling through the medium Equation 1.1 indictaes the received power (Rappaport, 2002).

$$P_r = \frac{P_t}{P_L} \qquad 1.1$$

Modeling the actual propagation characteristics of the electromagnetic wave is the primary concern of the WSNs designer. The mechanisms of the signal loss are diverse but generally can be associated with reflection, diffraction and scattering (Santi, 2005). Reflection appears when the wave hits a surface with a very large dimension in comparison to its wavelength. Therefore, the characteristics of reflecting surface depend on the signal wavelength, i.e. some surfaces are considered as a reflector at high frequencies, but not for low frequencies signal (Born and Wolf, 1999). On the other hand, diffraction occurs when the communication channel has edges that are located between the transmitter and the receiver. Scattering is caused by features smaller than the signal wavelength lying in the medium through which the signal travels (Liao and Sarabandi, 2007, Rappaport, 2002).

The propagation models are mainly used to estimate the median signal strength. The variation in signal strength occurs due to changes in the propagation path caused by the mechanisms above which should be taken into account in the modelling of the wave propagation of WSNs (Kurt and Tavli, 2017).

1.3.1 Free Space Path Loss Propagation Model

The free-space path model can be used to estimate the signal behaviour when the transmitter and receiver have clear line-of-sight (LOS) path with no obstacles between or near them. It applies to satellite communication systems and microwave LOS links. The power at the receiver which is located at distance d from the transmitter is given by Equation 1.2 (Friis, 1946):

$$P_r = \frac{P_t\, G_t G_r\, \lambda^2}{(4\pi)^2\, d^2\, L} \qquad 1.2$$

where G_t is the gain of the transmitter antenna and G_r is the gain of the receiving antenna which assumes that the Rx is in the farfield region of the Tx. From Equation 1.2 and a knowledge of the receiver threshold power the maximum communication distance between two nodes can be calculated. The free-space path loss is not exactly applicable for terrestrial wireless sensor network because its rarely the case that a single direct path exists between the transmitter and the receiver.

1.3.2 Two Ray Ground Propagation Model

The two-ray ground model considers the earth as a perfect reflector, and the signal will take two paths: one directly from the transmitter and one reflected from the ground (see Figure 1.10) (Kurt and Tavli, 2017).

The difference of the received signal strength due to the combined direct and reflected rays, as path length increases, shows two regions of operation. Firstly when the path length difference between the two rays is more than a wavelength but decreases as the distance d increases, the two components of the signal pass periodically in and out of phase, causing alternate (i.e. reinforcement and cancellation) in the received signal (Barclay, 2003).

Secondly, at greater distance in the limit of $d \gg \sqrt{h_r h_t}$, the path length of the two rays is less than a half wavelength difference of transmitted signal the received power is progressively reducing towards zero given by Equation 1.5 (Goldsmith, 2005).

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \tag{1.5}$$

where h_t and h_r indicate the transmitter and the receiver antenna heights respectively Equation 1.5 shows that the receiving power will fall proportional to *(1/d⁴)*, instead of the square of the distance in the free space path loss model.

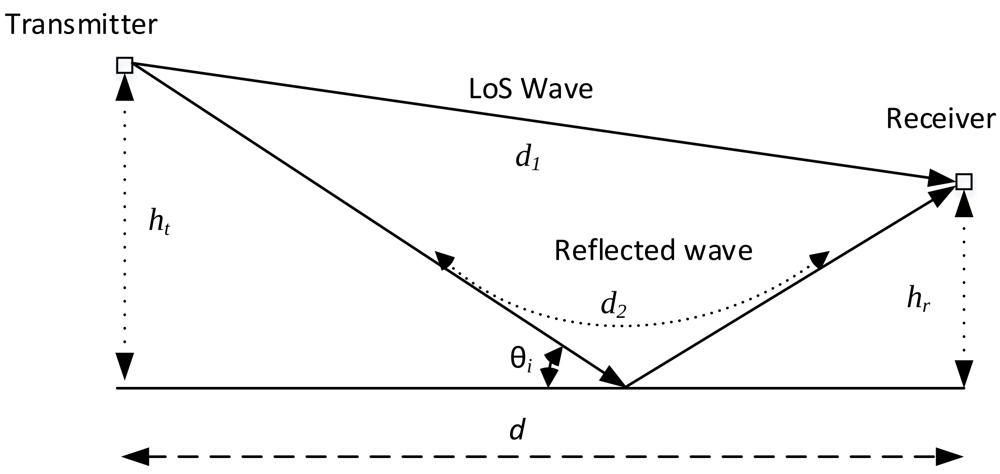


Figure 1.10 Two-ray ground propagation model

Investigating the performance of the SB-WSN using an outdoor field on the ground, required a modification in the two-ray propagation model to establish space communication channel characteristics, where the signal will follow the free space propagation model (as presented in previous Section) . This amendment will provide an estimation of the node transmission range hich is crucial to determine the path to the sink.

1.4 Research Aim

The main objective of the study described in this thesis is to investigate the performance of SB-WSNs experimentally and propose a new scheme to increase nodes' lifetime and enhance the overall network performance. The following chapter offers a review of the currently used methods to reduce nodes power consumption. A more detailed approach to achieve the research aim is presented at the end of Chapter 2 (Section 2.8).

2 Literature Review

2.1 Suitability of Commercial Off The Shelf (COTS) Wireless Sensor Nodes in Aerospace Applications

Underwood *et al.* (2001) studied the use of Commercial Off The Shelf (COTS) wireless protocols for inter-satellite connectivity in formation-flying. They demonstrated the utility of COTS nodes in nano-satellites by designing SNAP-1 (Surrey Nanosatellite Application Programme). Caulev *et al.* (2005) have discussed in an annual report of the National Aeronautics and Space Administration (NASA) about the use of COTS WSNs in planetary atmospheres. They suggested that wireless sensor networks can be used for spacecraft performance monitoring. Also, WSN nodes can be deployed inside the spacecraft to establish health surveillance systems. Efforts are being made to test and validate the use of selected COTS node kits for space and planetary exploration.
Vladimirova *et al.* (2007) have distinguished a set of requirements for spacecraft applications of WSNs. Further, they have tested selected commercially available node kits under different situations in line with spacecraft testing methods such as ElectroMagnetic Interference (EMI), ElectroMagnetic Compatibility (EMC), radiation, thermal and vibration effects. The results show that all the node kits passed most tests but failed the radiation test because they were designed for terrestrial applications and some modifications are required to meet space applications.
Two scenarios of deployment suggested and analysed by Medina *et al.* (2010) and Sanz *et al.* (2013) for WSNs in planetary space exploration. They are distributed surface sensor web instrument (i.e. in sensor web scenario the network nodes share the information such as pressure, temperature or gas type altogether) and networked planetary surface exploration. They investigated the node distribution in the target area and communication assessment by simulation and experimentation. The results confirm that WSNs can provide various types of data for both bigger volumes and longer periods of time in space-based WSN.

2.2 Investigation of Power Behaviour in Space-Based WSNs

The power consumption of the node is a key factor in designing the node architecture of Space WSNs for Planetary Exploration (SWIPE) (Rodrigues *et al.*, 2014). Zhai and Vladimirova (2015) proposed data processing techniques to minimise the amount of transmitted data and keep an acceptable level of data integrity at the sink. They defined four node types for proposed WSN: regular node, Cluster Head (CH), data sink and exit point. They developed this technique for moon exploration. Though, they did not consider the extra processing required at CHs that will lead to more required energy, Figure 2.1 shows the proposed configuration.

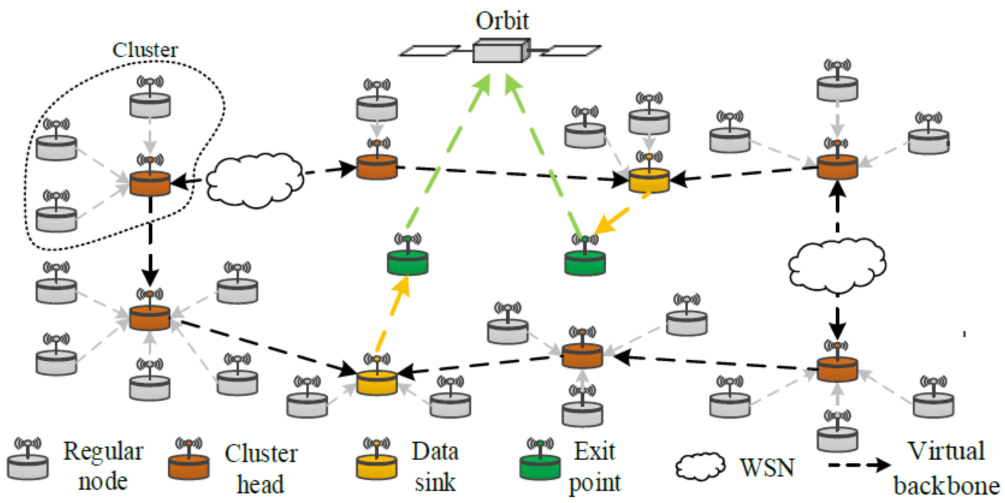


Figure 2.1 The proposed SWIPE WSN architecture for moon exploration (Zhai and Vladimirova, 2015)

Boyan and Littman (1994) introduced a routing algorithm based on reinforcement learning named Q-routing which learns the best paths considering the least latency to deliver the packets to the destinations. Q-value is allocated at all nodes for each pair of sink and neighbour which is the estimation of the time will the packets need to travel toward sink through this practical next hop. The Q-value is calculated, upon sending a packet to a neighbour, which replied back immediately with a reward that has the information of the minimum time this neighbour needs to forward the packet to the sink. Oddi *et al.* (2014) revised the Q-routing to increase network lifetime and meet the requirement of SWIPE project. They suggested adding the current residual battery in the feedback from the neighbours to balancing the effort of forwarding by avoid sending packets to lower energy nodes. Also, they indicate that reducing the continuous rewards for each received packet will minimise the network overhead which will optimise the Q-routing and lower energy consumption. For the sake of developing WSNs for moon deployment missions, Oddi *et al.* (2015) suggested modifying an Optimise Link State Routing (OLSR) (Clausen *et al.*, 2004) protocol to meet the SWIPE requirements (i.e. the Moon to be monitored and the line of sight limitation in that region). They developed an any-sink proactive approach which adopted the Hybrid Wireless Mesh Protocol (HWMP) by utilising the setup and dynamically maintained multiple distance vector tree. Further, they extended the tree, based on HWMP, by combining the energy-aware and distance based link cost. The approach has been simulated through an event-based simulator in MATLAB. In addition to that, it was implemented experimentally by Rodrigues *et al.* (2015) through the use of an emulator consisting of a source, two intermediate nodes and a destination node. The results show the ability of the suggested algorithm to balance the energy consumption among the nodes in order to extend the network lifetime by forwarding the packets through the nodes with higher remaining battery power. However, the information could travel a longer path to reach the destination, and this will affect the overall network efficiency.

Yang *et al.* (2016) suggested that the lifetime of satellite networks could be prolonged by steering the packet traffic towards a few nodes and switching the other nodes into sleep status to save energy. The simulation results demonstrated that the nodes at the edge of the network with fewer links attached to them, and located far from the sink, had longer sleep intervals. The drawback of this method is the network had an increase in path lengths.

Zhou *et al.* (2016) proposed an Energy Aware Multipath Routing (EAMR) mechanism. It is constructed by obtaining the optimum split ratio among the multipath according to the remaining battery levels, and traffic demands all satellites in the network. The simulation results indicated that EAMR enhances network lifetime and reduces congestion. On the other hand, it required extra processing to find the optimised split ratio.

Exploring the planets in our solar system is a big motivation steering the research for more studies. Del Re *et al.* (2009) investigated the possibility of deployment of WSNs with IEEE 802.15.4 standard in Mars exploration. The simulated results indicated that such network could work fairly well in a typical rocky area of the planet's surface and even in an ordinary dust storm which is common situation on the Martian surface. Sergiou *et al.* (2014) explored the challenges facing WSNs for Mars exploration. They investigated the operational power budget for a WSN consisting of hundreds of light and low powered nodes could operate continuously or inpredefined intervals. Also, they adopted Mica-Z parameters in the simulation which is one of the available COTS nodes. The results show that the ad-hoc on-demand distance vector (AODV) protocol can function and deliver packets to the sink. Further, AODV provided the lowest source to sink packet delay and offered better power efficiency compared to the Dynamic Alternative Path Selection Algorithm (DAIPaS) (Sergiou and Vassiliou, 2011) and Message-initiated Constraint-Bases Routing (MCBR) (Zhang and Fromherz, 2004). Table 2.1 gives a summary of the presented studies.

Table 2.1 Summary of research in COTS compatibility to aerospace applications and investigate power behaviour of space-based WSNs

Authors	Research area and Proposed solution	Targeted area	Method of measurements	Description
(Underwood *et al.*, 2001)	The development of SNAP-1	LEO	Experimental	Possibility of using COTS WSN in Space missions
Caulev *et al.* (2005)	Analysis the performance of IEEE 801.2.11a/b	Mars	Simulation (MATLAB)	Investigate the use of COTS WSN in planetary exploration applications
Vladimirova *et al.* (2007) and Dubois *et al.* (2009)	Investigate the effects of space environment on COTS mote	Space	Experimental /Simulation	Tested selected mote COTS for space environment conditions
Medina *et al.* (2010) and Sanz *et al.* (2013)	Identification of space exploration scenarios	Space	Simulation and Experimental	Deployment scenarios and network topology

Con. Table 2.1 Summary of research in COTS compatibility to aerospace applications and investigate power behaviour of space-based WSNs

Zhai and Vladimirova (2015)	Design WSN for SWIPE project	Moon	Simulation	Develop data processing to reduce transmission
Oddi *et al.* (2015)	Proposed routing protocol for SWIPE	Moon	Simulation	Modified OLSR routing protocol to meet SWIPE needs
Yang *et al.* (2016)	Reduce the power consumption of satellite	LEO	Simulation	Establishing energy efficient routing
Zhou *et al.* (2016)	Find the best split ratio of traffic among multipath	LEO	Simulation (OPNET/ MATLAB)	Improving network lifetime and reduce congestion
Del Re *et al.* (2009) and Sergiou *et al.* (2014)	Prolong node and network lifetime by utilising IEEE802.15.4	Mars	Simulation (OMNET++)/ (Prowler)	Evaluate the applicability of IEEE802.15.4

2.3 Energy Efficiency Enhancements for WSNs by Modifying Medium Access Control Protocol (MAC)

A significant number of articles have been published on improving the energy efficiency of WSNs for terrestrial applications which could be updated to meet the space and planetary observation requirements. Medium Access Control Protocol (MAC) optimisation is an important issue in the design of WSNs. It improves WSNs energy efficiency by establishing proper communications and coordinating the access and transmission time of the nodes in the network. Heinzelman *et al.* (2002) proposed the deployment of a clustering method in WSN through the utilisation of Low Energy Adaptive Clustering Hierarchy (LEACH). LEACH is Time Division Multiple Access-Medium Access Control (TDMA-MAC) protocol. It divides the network into clusters and then selects a cluster head randomly. The cluster heads (CHs) collect, compress and send the data to the base station (BS). After a fixed period, the selection procedure is repeated with less likelihood of selecting the previously selected CH. This change of cluster heads ensures energy usage balance in all nodes in the network and leads to a longer network lifetime. LEACH assume that all the nodes in the cluster can communicate directly with the BS which is not applicable in most of the experimental scenarios because it will be easier to construct a network with a star topology. Besides, LEACH cannot be applicable in the case of heterogeneous WSNs because the CH selection probability of nodes will be the same, despite the fact that some of them have lower remaining battery level. Heinzelman *et al.* (2002) suggested LEACH-Centralized which utilise the BS in cluster formation, unlike LEACH where the nodes self-configure themselves into clusters. In the setup phase, the BS receives the information from all nodes in the network regarding the energy level and location. After that, it identifies predominant CHs and organises the nodes into clusters, in the way that minimises the energy needed for non-CH nodes to transmit their data to their respective CHs. Simulation results show that LEACH-C is more suitable for heterogeneous nodes in WSNs. Qing *et al.* (2006) proposed Distributed Energy Efficient Clustering (DEEC), an improved version of the LEACH protocol. In DEEC each node sends its energy level to the BS at setup phase then the BS calculates the average network power and sends this information back to the nodes. The selection procedure in DEEC depends on the probability ratio of the node residual energy and the average network energy. This protocol requires that each node has knowledge of the power level of other nodes that will lead the network to spend more resources to provide such information. Zhai and Vladimirova (2015) adopted clustering techniques in the design of SWIPE. This project will not implement clustering in the investigated network, since choosing a node to be cluster head consumes power because the nodes need to share their power information. Besides, the fact that the packets will travel longer distance as consequence of selecting CHs located far from sink than other nodes leading to more energy wastage. However, if the CHs can be designed to have better power capability than the other nodes in the network then placing them in the best location for CHs occurs.

Contention-based protocols are another way to reduce the energy required for transmission such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) which developed by Milling (1986). They are less complicated than TDMA-MAC protocol in that the nodes contend for using the channel. In the case of receiving failure, the packet retransmitted with a delay. LAN/MAN Standards Committee (2003) presented the IEEE 802.15.4 standard for low rate low power Personal Area Network (PAN), it supports three network topology star (single hop), cluster-based, and mesh (multi-hop). IEEE 802.15.4 uses CSMA/CA for channel access and transmission. Rhee *et al.* (2008) introduced hybrid MAC protocol named Z-MAC, it combines the strengths of TDMA and CSMA. It is adaptable to the level of contention in the WSN by operating with TDMA in low traffic and with CSMA in high-traffic network. Z-MAC has been tested in simulation and experimentation through Network Simulator-2 (NS2) and TinyOS (Mica2) respectively. The results indicate that Z-MAC provides better energy efficiency with applications that have medium to high data rates. However, it required longer setup phase and more energy due to more processing because it uses the information of topology and synchronised clocks to enhance MAC performance in high contention.

2.4 Attempts to Develop Energy-Aware Routing

Routing Algorithms in WSNs can be classified into three categories; proactive, reactive (or on demand) and hybrid protocols. Clausen *et al.* (2004) presented Optimise Link State Routing (OLSR) which is a commonly used proactive protocol in Mobile Ad-hoc Networks (MANETs) based on link state mechanism. OLSR enables the nodes to have knowledge about network topology inside each node in the network via distributing Topology Control (TC) flooding message. Further, it uses Multipoint Relay (MPR) concept to reduce the overhead information. Once the routing table is completed, and all the information of network topology is exchanged between nodes, each node calculates the route to each destination by applying the shortest path Dijkstra algorithm (Dijkstra, 1959). The setup phase, transferring TC and the broadcasting of ‘Hello’ packets is regularly repeated to ensure continuously updated information about the network topology. De Rango *et al.* (2008) proposed an energy efficient update of OLSR built on establishing willingness values of the nodes in the network. Each node chooses to contribute low, default or high willingness depending on node’s residual energy and predicted lifetime. Loutfi and Elkoutbi (2015) introduced a hierarchical clustered energy aware OSLR protocol, that used the remaining energy of nodes. They suggested a set of cluster head election and simulations indicate an improvement in performance.

Perkins and Royer (1999) proposed ad-hoc on-demand distance vector (AODV). It is a reactive routing protocol as node routing tables are updated on demand. The AODV has three control messages: Route Request (RREQ), Route Reply (RREP) and Route Error (RERR), while Route Reply Acknowledgment (RREP-ACK) packet is used to confirm the RREP request reception. Figure 2.2 shows AODV messages. Once a source node needs to communicate with the destination node, it starts a path search through the network by flood RREQ control packets. When RREQ delivered at the destination node, it responds back with a RREP control packet to the source; then the route is configured. AODV uses Destination Sequence Number (DSN) to specify how new the route is, which is used to avoid the creation of loops. Chettibi and Chikhi (2012) proposed an expansion of AODV using Reinforcement Learning (RL), in order to create adaptive energy-aware routing protocol. Network nodes learn the best rate of RREQ forwarding depending on using RL resolution method and nodes remaining battery power. Sridhar *et al.* (2013) proposed ENergy-enabled based AODV protocol (EN-AODV). It relies on the announcement of nodes energy level, data transfer rate and size of transmitted data which will indicate whether node‘s energy level is preserved or reduced. Also, EN-AODV runs an estimation of nodes energy levels before they can be selected for a routing path. The threshold value is specified, and the nodes are considered for path selection only if their energy levels are above the threshold value. The simulated results through NS2 show decrease in a delay while throughput is maintained.

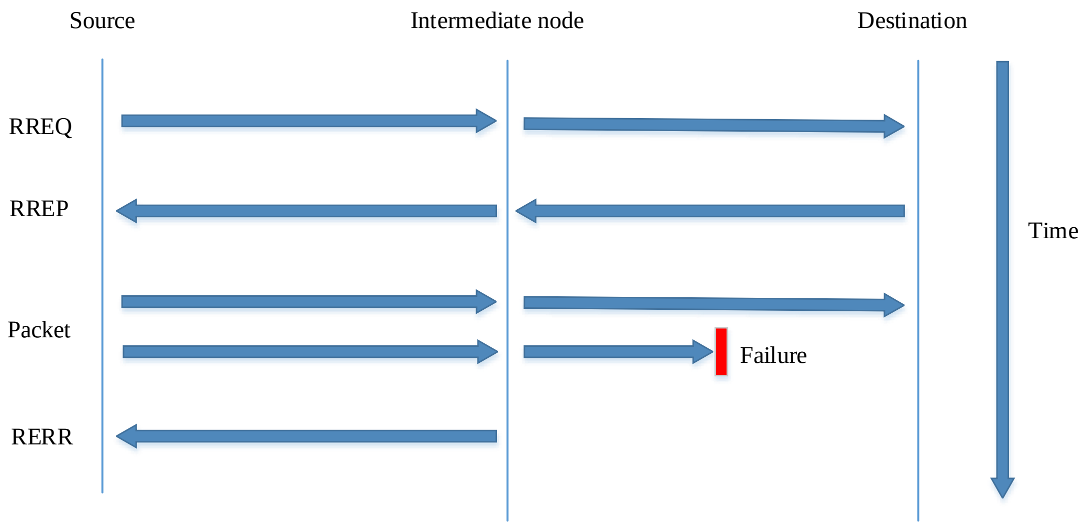


Figure 2.2 AODV setup process through time

Table 2.2 Comparison between reactive and proactive protocols

	Proactive (OLSR)	Reactive (AODV)
Network Density	Prefers high network density so that a lower number of MPRs is capable of reaching a larger number of nodes	Demand Small group of nodes in the network with overlapping radio coverage and lower data traffic
Initial setup phase time	More setup time because the route is establishing. However, lower latency in transmission afterwards	Less setup time required but more latency because path discovery required in transmitting attempt
The possibility for use in space applications	Extra processing and memory required to implement the computational algorithm to identify the best path, which is not convenient in space-based WSN	Fewer nodes would be able to transmit data at the same time. It needs modification to meet space-based WSNs requirement of all nodes in the network are valuable and required to transmit sensed data to sink

Joshi and Bahr (2006) and Bahr (2007) proposed Hybrid Wireless Mesh Protocol (HWMP) which adopts the mechanisms of reactive protocols in establishing the path and proactive protocols in the maintenance the links. The on-demand routing setup is achieved by utilising path discovery mechanism and MAC addresses similar to AODV. While HWMP applies a proactive routing tree, which helps to maintain the path to the gateway. HWMP protocol offers an enhance in network robustness. However, regularly broadcasting the information of the gateway will lead to a larger amount of overhead and will be inefficient in terms of overall network power in case of large networks.

2.5 Sleep Wake up Algorithms and Mechanisms.

The communication radio in WSNs nodes is not required to be continuously on. It can be put in lower power sleeping mode or switched off which will reduce node power consumption and prolong its lifetime (Anastasi *et al.*, 2009b).

2.5.1 On-Demand Sleep/ Wake up

The idea behind the on-demand sleep/wake protocols is that a node only needs to wake up just before another node in the network wants to communicate with it. Schurgers *et al.* (2002b) proposed Sparse Topology and Energy Management (STEM) protocol. STEM uses two radios channels for wake up signal and data packet exchange. Both radios used an asynchronous duty cycle to reduce power consumption. As soon as a node (originator) has to communicate with a neighbour node (destination), the originator node sends periodic beacons on its wake up channel. When the destination node receives a beacon, it turns on its data channel for data packet reception and replies back with an acknowledgement. Schurgers *et al.* (2002a) proposed STEM-T and suggested using a wake up tone instead of beacons, where the tone is transmitted for lower interval than beacons, and it is not required to wait for ACK to start sending data. The destination nodes wake up when they detect signal energy in their listening period. STEM-T offers better packet latency than STEM-B (beaconed). However, it suffers from overhearing because all nodes that receive the tone will turn on their radios. Yang and Vaidya (2004) proposed a Pipelined Tone Wakeup scheme (PTW) protocol. PWT is a development of STEM-T, that tries to balance between power preserving and the end to end transmission delay. PWT aims to minimise the period of unnecessary neighbours wake up by turning off all neighbours as soon as the targeted receiver replies to the sender.

The extra energy consumed by the wake up radio cannot be neglected even in the case of using a low-power radio. Further, the additional cost of the second radio will increase the node value. Another difficulty in having two radios on the same node is the possible mismatch between the range of the two radios.

2.5.2 Synchronous (or Scheduled Rendezvous) Schemes

In synchronous sleep/wake up schemes, the node and its neighbours wake up at the same time to exchange information and send packages. Then they return to sleep till the next scheduled wakeup period. However, synchronous schemes require nodes to be synchronised in order to wake up at the same time (Anastasi *et al.*, 2009b). Ye *et al.* (2002) proposed sensor-MAC protocol (S-MAC) which designed to reduce the energy consumption in WSNs with coordinating adaptive sleeping for the duty cycle operation of the nodes. S-MAC organises the nodes into clusters and nodes are locally synchronised inside each cluster, where the node duty cycle is divided into, SYNC, DATA, and SLEEP. At the beginning of SYNC period, all nodes in the same cluster wake up and turn on communication radio to synchronise clocks with each other. In DATA period, the node stays in wake up status and nodes with packet to send, compete to exchange Request to Send (RTS) and Clear to Send (CTS) frames. Then, nodes without a packet to send turn off their radios and return to sleep at the beginning of SLEEP period, while, other nodes return to sleep after they finish the data transmission and receive ACK. In S-MAC the packets suffer from latency because they can travel only one hop in each duty cycle. Ye *et al.* (2004) introduced adaptive listening in S-MAC to reduce packet latency, but the enhancement is limited because the packets can only travel by two hops at most in each duty cycle. Van Dam and Langendoen (2003) proposed Time-MAC (T-MAC) which is an improved version of adaptive S-MAC and specially modified for variable traffic load. In T-MAC, after the synchronisation phase ends, nodes listen to the channel for a short period. Afterwards, nodes that not involved in transmission during this time return to sleep status. While if a node receives a packet, it will stay awake until no more packets are received, or the wake up period ends. T-MAC can forward the packet three hops at most. However, it extends the forwarding hops and reduces latency, but it increases energy consumption.

While duty cycle synchronous schemes are energy efficient, they suffer from sleep latency because the nodes need to wait until the receiver wakes up before they can forward the packets.

Lu *et al.* (2004) proposed adaptive duty-cycled MAC protocol (DMAC) that organises nodes as data gathering trees and builds a staggered (backwards) wake up schedule based on node location. The authors introduced DMAC to investigate the scenario where data are delivered to the sink from many nodes. In DMAC the length of the wake up period can change dynamically according to network traffic. Each node has an active slot which is long enough to send a packet. If a node has more than one packet to send, then it requests additional slots in the next hop. DMAC used a prediction scheme to provide all the sources the chance to send their packets.

Keshavarzian *et al.* (2006) analyse the latency for the staggered wake up schedule and proposed forward path wake up schedule patterns that aim to reduce the end-to-end sleep latency from sink to nodes. Furthermore, they introduced a combination of the forward and backwards staggered pattern. The staggered scheme offers better performance in comparison with the fully synchronised approach, for instance, it reduces the number of collisions, since at each slot only a small number of nodes will be active because nodes are assigned different levels in the tree and wake up at a different time. For the same reason, the active period of the node will be shortened. Both staggered and fully synchronised scheme have a common drawback; the nodes in the same level suffer from collisions as they are assigned to the same active period. Also, the staggered mechanism has limited flexibility specifically due to the fixed duration of active and sleep periods. Vasanthi and Annadurai (2006), Sun *et al.* (2008) and Anastasi *et al.* (2009a) proposed different synchronisation wake up schemes; all of them aim to enhance network energy efficiency and decrease the latency caused by the implementation of sleep/wake up mechanism. Most of the available studies do not present a complete idea to the energy efficiency of WSNs in a practical network, and they are simulated through various simulators (for instance NS2 and MATLAB). Creating an energy-efficient sleep/wake up scheme is not a straightforward task. Network configuration, topology, and data rate can be used to help optimise the active and sleep periods. However, there is a trade-off between the packet latency and sleep interval length.

2.5.3 Asynchronous (random) Sleep/Wake up Schemes

Huang *et al.* (2013) stated that asynchronous methods allow each node to chose its active schedule autonomously of other nodes in the network by assuring that neighbours always have intersected active periods. Although, nodes have to search efficient paths to deliver packets to the destination. Zheng *et al.* (2003) proposed an asynchronous wake up mechanism based on a systematic approach for both ad-hoc networks and WSNs. They formulate the difficulty of generating a wake up schedule in a combinatorial design problem, and they created an Asynchronous Wakeup Protocol (AWP) depend on the optimal result derived from the theoretical framework. In AWP each node is related to a Wakeup Schedule Function that will be used to produce a wake up schedule which will be symmetric to node neighbours. Such a process will guarantee that any two schedules will overlap for one slot at most. Nevertheless, the packet latency introduced will be significant, particularly in networks that employing multihops. Besides, is it not possible to broadcast messages to all neighbours because that they will not all be active simultaneously. Rahimi *et al.* (2005) proposed Random Asynchronous Wakeup (RAW) which consists of a combination of routing protocol and wake up mechanism. RAW takes advantage of the fact that high node density typically characterises WSNs. The routing protocol in RAW sends the packet to any of the active neighbours in the Forwarding Candidate Set (i.e., the group of active neighbours that fit a pre-defined criterion). Also, RAW depends on nodes to make a local decision that makes it simple and well suited for WSNs with frequent topology changes. However, it is not convenient for sparse networks because of its required high node density.

Polastre *et al.* (2004) proposed Berkeley MAC (B-MAC). B-MAC adopted an alternative approach to ensuring an asynchronous node (sender) find its destination node (receiver) active when its wake up. It utilises low-power listening and the long preamble to achieve energy-efficient communication. Nodes using B-MAC periodically wake up and listen to the channel for a short period. If the node wishes to send data, it transmits a long preamble at the beginning that is to some extent longer than the sleep interval of the receiver. When the receiver detects the preamble, it replies back ACK during the active period and stays active until the end of the transmission. El-Hoiydi and Decotignie (2004) proposed Wireless Sensor MAC (WiseMAC). WiseMAC adopted schedule learning to reduce preamble length and minimise the power consumption when listing to the medium. The receiver adds its next wake up schedule in the data acknowledgement frame. Therefore the sender will learn the time of the next active receiver period and schedule its following transmission accordingly which will lead to minimise the length of the long preamble. Although WiseMAC and B-MAC efficiently reduce the power consumption in WSNs, the long preamble leads to significant overhearing problems, as in range neighbours need to receive the long preamble entirely to find out that they are a nontarget receiver. Buettner *et al.* (2006) proposed X-MAC a low power MAC protocol for duty-cycled WSNs. They suggested reducing the preamble length by using short and strobed preambles which allowed the nontarget neighbours to return to sleep after receiving the short preamble and the target receiver to reply with ACK quicker to interrupt the long preamble. However, even in X-MAC, the overhearing of the preamble still rises based on the wake up period increases, leading to a limit in the energy efficacy in low duty cycles situations.

Jang *et al.* (2008) proposed Asynchronous Scheduled MAC protocol (AS-MAC). AS-MAC uses low power radio listening to reduce the periodic wake up time. Furthermore, it is developed to coordinate the wake up times of neighbour nodes asynchronously which can lead to reduced delay, overhearing and contention. The nodes know when their neighbours turn active, as they store their wake up schedules. The disadvantage of AS-MAC is the inefficienct broadcast, since it has to send a packet individually for each neighbour to broadcast the packet.

Liu *et al.* (2009) proposed Convergent MAC (CMAC). They adopted anycast and convergent packet forwarding mechanisms to achieve low latency and less power consumption. They suggested breaking the long preamble into multiple RST packets, in order to alleviate overhearing problems. In CMAC, when nodes wake up they define the next hop as the neighbour node which is closest to the sink. Therefore, network node density has a large influence on the performance of CMAC protocol. Further, it designed to fit the requirements of the fixed data traffic network.

Dutta *et al.* (2010) presented the idea of shifting the transmission initiation from sender to the receiver side in WSNs. They proposed A-MAC, a link layer receiver-initiated approach in which the sender first listens to the probe frame from the intended receiver, then ACK back in receipt of the probe frame, afterwards wait for a short interval (i.e. random delay), and finally, if the channel is clear, transmit data. A-MAC shows that the per-hop packet latency decreases, as the receiver node can quickly know whether there is a packet for it by enabling auto-ACK to the probe frame. However, the energy consumption in the receiver initiated approaches can be similarly analysed as the sender initiated mechanisms (Challen *et al.*, 2010).

Ghadimi *et al.* (2014) introduced Opportunistic Routing in Wireless sensor networks (ORW) scheme. ORW exploits the advantage of opportunistic routing metric mechanism and the Expected number of Duty-Cycled wake-ups (EDC) to establish quickly and reliable communication between a sender and a receiver. This scheme allows nodes to develop the routing table before sending data to neighbours. Also, the ORW approach utilises the overhearing to evaluate the quality of the links between nodes and avoid packets collision by ensuring that only two nodes use the channel. In ORW, when a node has data to send it starts to broadcast probe packets. When neighbours wake up and receive sender probe packet, they reply with ACK information. Following receipt of the ACK information, the sender node starts to add the interface information building and updating the routing table. Thus, the sending node obtains the forwarding path before transmitting the data. ORW was suggested for use in WSNs applications that operate with low data rates, but is not appropriate for networks with variable traffic load.

Anchora *et al.* (2014) proposed a duty cycling asynchronous MAC scheduler called (AS2-MAC) which utilises a Coordinate Sampling Listing (CSL) to manage how the receiver can periodically monitor the channel in low energy mode. Nodes in AS2-MAC wake up according to their scheduled active intervals, and they stay in low power sleep status unless awakened by neighbour nodes periodic transmission information to help in forwarding packets to sink. Further, nodes build a table of neighbours wake up interval information and update it whenever they sense a variation in neighbours duty cycle. AS2-MAC improves the WSNs power efficiency. However, it increases the latency of the packets as consequence of nodes buffering the packets until the next active period.

Asynchronous sleep/wake up schemes aims to expand the nodes inactive status which will reduce their power consumption. However, in the situation where the data need to travel many hops to reach its destination, asynchronous sleep/wake up schemes will decrease WSNs performance because the packets will suffer from high latency since they need to wait till the next hop be available.

Rahimi *et al.* (2005), Polastre *et al.* (2004), Jang *et al.* (2008), Liu *et al.* (2009) and Anchora *et al.* (2014) suggested methods for intersecting the active period of the nodes in the path from source to destination. On the other hand, Ghadimi *et al.* (2014) adopted the ORW to enable the node to build and update the routing table for sending data neighbours. While Buettner *et al.* (2006) introduced minimising the coordination process by dividing the long preamble, and Dutta *et al.* (2010) suggested moving the listening mechanism from sender to receiver, both of them intend to achieve energy-efficient communication.

2.6 Avoiding a Bottleneck Near the Sink

Perillo *et al.* (2004) identified two scenarios in which the nodes energy imbalance could occur in multihop WSNs with uniform nodes distribution. In the first scenario, the amount of the traffic that the nodes are required to forward increase as the distance to the sink becomes smaller. Therefore, the nodes near the sink die sooner, which may lead to network partitioning or leaving areas of the network completely out of coverage. The second scenario is based on the assumption that all nodes have the ability to communicate directly with sink (i.e. star topology). Thus, the nodes located farthest from the sink consume their energy faster since they need to transmit the data with higher transmitting power. The authors suggested that each node in a WSN can vary its transmission range to reduce energy imbalance issue. However, the overall network energy will decrease due to spending more energy to deliver the packets to the sink. Also, transmitting with a higher power in WSNs is limited to a few hops which will reduce the effects of this method in a WSNs using several multihop.

Sichitiu and Dutta (2005) proposed that the node battery capacity should be inversely proportional to the distance from the sink. Therefore, nodes need to be equipped with different battery capacities. Authors formed a mathematical model to estimate the initial battery capacity. However, in WSNs practical deployment, it is not easy to design many nodes with different battery powers especially in the case of a large network. Padmanabh and Roy (2006) indicated that increasing the number of the nodes which are in proximity to the sink would reduce bottleneck effect. They convert the two-dimensional problem into multiple single dimensional problems in data forwarding which calculate the traffic of nodes near the sink.

Chen *et al.* (2009) suggested partitioning the nodes of WSN into clusters of various sizes, with the ones near the sink having fewer node members compared to the clusters which are located relatively far from the gateway. Hence, the CHs near sink will be involved in less communication and can preserve some energy for intra-cluster packet forwarding.

Rout and Ghosh (2014) investigated network lifetime in WSNs using random duty cycle and network coding. They found that for nodes near the sink (i.e. inside bottleneck zone) lifetimes were prolonged because they encoded packets using XOR network coding. However, XOR coding required more processing which will reduce nodes energy efficiency. Furthermore, it will increase packet latency and packet loss.

2.7 Transmission Power Control (TPC) in Multihop WSNs

TCP attempts to reduce the amount of energy needed for transmission at each node in WSNs. Narayanaswamy *et al.* (2002) presented a power preservation method by calculating the minimum Transmission Power Level (TPL) that is adequate to maintain the connectivity of the network. Utilising this minimum TPL will decrease contention at the MAC layer, the traffic carrying capacity and energy consumption. Jeong *et al.* (2007) proposed that adjusting the TPL of each node until it be able to communicate with the desired number of neighbours, will reduce energy consumption. Though, reducing neighbours will minimise, the packet successful delivery rate at the sink.

Cheng and Wu (2009) suggested a multilevel transmission power adjustment mechanism for WSNs. The proposed strategy assumes that each node equipped with an adjustable power transmitter. Nodes select the TPL according to the intended receiver distance. The authours showed that more power could be preserved by increasing the number of transmission power levels. However, nodes in WSNs are tended to be simple with lower transmission capabilities.

Other research investigates the effect of Adaptive Transmission Power Control (ATPC) in the energy efficiency of WSNs. Lin *et al.* (2006) proposed utilising the Received Strength Signal Indicator (RSSI) and or Link Quality Indicator (LQI) as representative for packet reception ratio. They offered a feedback loop to calculate the linear relationship between the TPL and the RSSI/LQI, then ATCP selects a proper TPL which can keep acceptable packet reception ratio. However, Hackmann *et al.* (2008)

showed that RSSI and LQI are not best indicators to packet reception ratio because of the dependence on the environmental parameters. Rukpakavong *et al.* (2011) suggested using only RSSI to adjust nodes TPL. The RSSI was measured by sending a HELLO message and waiting for the reply. Since the HELLO message could be sent periodically the node can dynamically update the TPL. The empirical result show that by using RSSI the transmission power adjustment reduces the power needed to forward the packets by 50%. The authors considered single hop and the testbed focus was on star topology (i.e. one node and sink). Nevertheless, this mechanism required more energy for the discovery process, as well as, another energy needed to update it dynamically.

2.8 Research Scope and Objectives

The scope of this study is to investigate the techniques to minimise the power consumption and deal with the problems associated with operating the WSNs in some aerospace scenarios. An outline of the research objectives is as listed below:

- Develop a near space radio communication environment to investigate the energy efficiency of WSNs in aerospace scenarios experimentally and suggest a network topology which can extend to help better understanding of energy efficiency for proposed future missions of aerospace WSNs. Sections 2.1 and 2.2 present the research in the area of space-based WSNs. Most of them depend on simulations, so creating a hardware testbed will provide a more realistic view of space-based WSNs power performance.

- Investigating the power behaviour of the suggested WSN under different sleep/wake up scenarios. Sections 2.3 and 2.4 review various studies of WSNs energy enhancement where energy efficient routing protocols and modified MAC have been developed. Examining the power performance of these routing protocols under different sleep/wake up approaches (surveyed in Section 2.5) will help in the future design of space-based WSNs regarding the expected network lifetime, and the amount of information will be delivered to the sink.

- Propose an energy efficient sleep/wake up scheduling mechanism. Section 2.5 reviewed the sleep/wake methods, the suggested sleep/wake up technique is a development of the conventional methods and takes into consideration space-based WSNs requirements.

- Investigating the effect of node density near the sink in the overall network power efficiency. Section 2.6 presents the research that tried to cope with the effect of the bottleneck near the sink. Adding extra nodes near the sink can prolong network life, an experimental evaluation about where to place and the mode of operation of these nodes can overcome network partitioning problem.

- Discuss the influence of utilising TCP in node lifetimes and overall network power efficiency and packet delivery. Section 2.7 discusses the using of TCP in WSNs, optimising the transmission power level will increase sleep period which leads to prolonging node lifetimes.

- Study the influence of multiple sinks in the performance of the space-based WSN.

3 Experimental Design and Network Setup

3.1 Selecting Commercial Off The Shelf (COTS) Motes

Motes is an abbreviation for remote nodes. They are the individual building units of WSNs which are tiny, low-power and low-cost devices (Vladimirova *et al.*, 2007). The single mote usually consists of a main board, microprocessor, transceiver and batteries. The energy consumption of motes limits the lifetime of the network because it is hard (or impossible in some situations) to change the batteries. A comparative analysis of well-known six COTS motes is presented in Table 1, which have been used in recent studies to investigate WSNs operation such as power consumption, congestion and reliability.

Table 3.1 Comparison of COTS motes parameters

	WSNs Motes					
Parameters	MICA2 (Crossbow, 2003)	MICAz (Crossbow, 2004)	TelosB (MESIC, 2011b)	IRIS (MESIC, 2011a)	SunSpot (Sun Labs, 2010)	Waspmotes (Libelium Communications, 2017)
Radio chip	CC1000	CC2420	CC2420	AT RF 230	CC2420	XBee
ISM band (MHz)	868-916	2400-2483	2400-2483	2400-2483	2400-2483	2400-2483
Radio standard	-	IEEE 802.15.4	IEEE 802.15.4/ ZigBee	IEEE 802.15.4	IEEE 802.15.4	IEEE 802.15.4/ZigBee
Current transmitting mode (mA)	25	17.4	23	17	50	45
Current receiving mode (mA)	8	19.7	23	16	50	50
Current sleep (µA)	10	5.1	21	8	500	100
Antenna type	Integrated onboard	Integrated onboard	Integrated onboard	Integrated onboard	Integrated onboard	RP-SMA
Current idle (µA)	1	20	1	-	32	-
Cost	£ 120	£ 60	£ 68	£ 75	£ 370	£ 200

Waspmote (see Figure 3.1) was selected for further evaluation to create an SB-WSN testbed because it is an open source wireless sensor platform which makes it more flexible regarding coding development. Further, it is relatively easy to program as its code is written in C++ language and has detailed documentation and big support group. Waspmote is equipped with 2300 mAh rechargeable lithium-ion battery that allows the sensor node to be completely autonomous and offering a variable lifetime between 1 and 5 years depending on the duty cycle and the radio used. Furthermore, Waspmotes are constructed upon a modular architecture (i.e. based on open hardware) which combines only the modules required for each node to reduce costs. It can work with different communication protocols (i.e. 802.15.4, Zigbee, Bluetooth, GPRS and WiFi) and frequencies (2.4 GHz, 868 MHz and 900 MHz). Also, it has an internal sensor that can measure the battery level and battery voltage, that enables the power behaviour of the nodes and the network to be investigated. Waspmote communication module has a RP-SMA antenna connector which using antennas with different gains to be used (Libelium Communications, 2017). Therefore, it will be possible to modify the antenna radiation pattern to establish a network with space communication channel properties which can be used to observe network power performance with different protocols, configurations and scenarios.

The selection of the communication protocol was based on the flexibility that protocol offers regarding adoption of modified sleep/wake up and routing schemes. SB-WSNs use batteries as a power supply so utilising low power communication protocol will enhance nodes energy efficiency and increase lifetime. Besides the nature of the sensing data by WSNs does not require high transmission rate. Therefore, the selection limited to IEEE 802.15.4 protocol provided by XBee S1 and Zigbee that is embedded in XBee S2.

In Zigbee standard, the router and coordinator need to be always in ON status and cannot in practical be battery supplied that is hard or impossible in some cases of SB-WSN. IEEE 802.15.4 was chosen as a communication standard for Waspmote which builds its communication layer at Data Link layer in the OSI model. It manages the communication between two nodes in the network. Also, it works as a homogeneous network where all nodes can route data and are exchangeable, so mesh network can be implemented as there are no parent-child relationships (Digi International, 2015a).

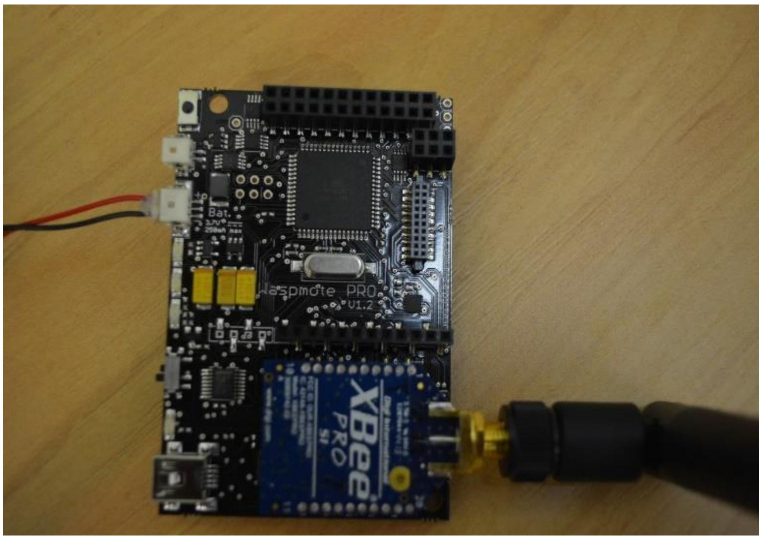


Figure 3.1 Shows the Waspmote with IEEE 802.15.4 XBee Pro S1 as communication module

3.2 Waspmote Validation by Experimentation

Some tests have been done to evaluate the match of Waspmotes to the research requirements (presented in Section 2.8):

3.2.1 Assessing Waspmote Battery Characteristics

The battery performance of the Waspmote was observed by making the node send 48 bytes packets continuously to the gateway. The Waspmote board had internal sensors which were used to measure the of battery voltage and remaining percentage. Figure 3.2 shows the battery voltage and percentage power against the number of the packets sent from Waspmote. At the start of the experiment the battery was fully charged, and the test continued until the battery was depleted. Characteristic curves of the remaining battery power were sketched based upon battery output voltage and the battery power remaining percentage that were measured versus the number of transmitted packets. Figure 3.2 shows that Waspmote's battery has different regions of operation depending on the battery power percentage. It depleted fast if the battery's power percentage between 100%-80% while it shows better performance between 40%-30%. Therefore, to obtain a complete understanding and accurate measurements about the node lifetime and network performance all battery operation regions should be considered in experimentation. This experiment implemented to calibrate the percentage of battery power remaining curve.

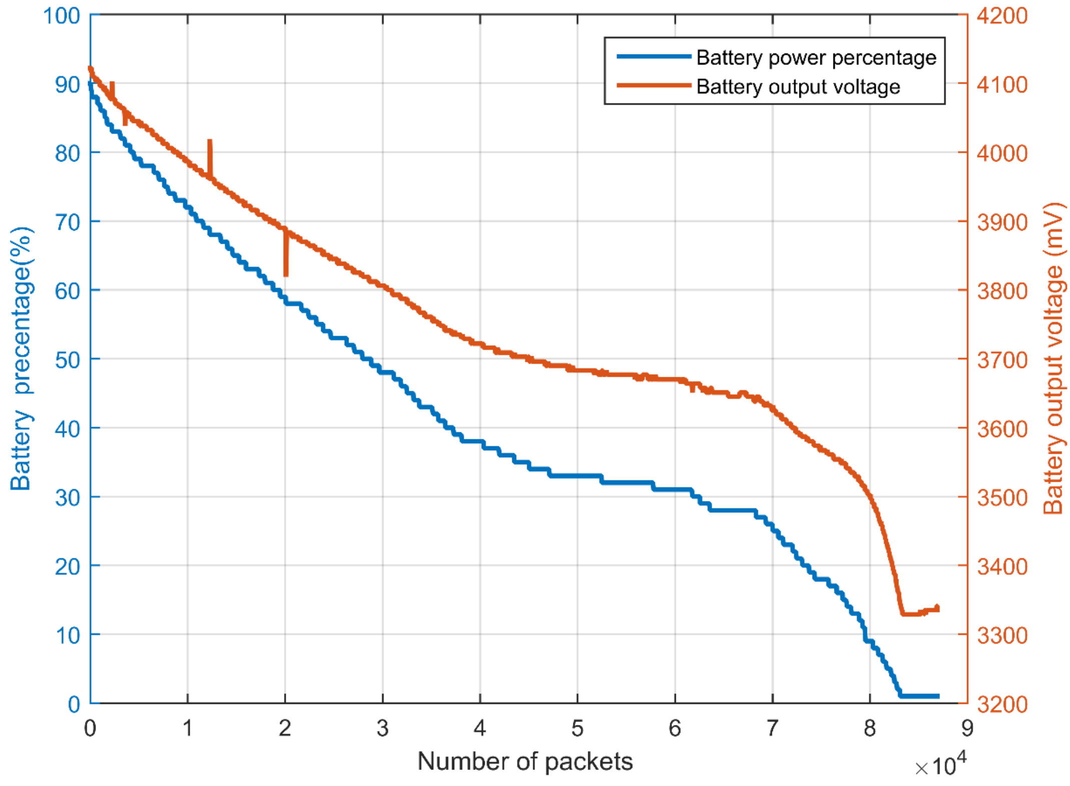


Figure 3.2 Battery discharging behaviour vs the number of packets sent

3.2.2 Evaluating Waspmote Transmission Range Capability

An experiment was undertaken to determine the communication range that can be obtained by Waspmote, in order to estimate the area needed for the network deployment. The XBee Pro Series 1 was used as a communication module which adopted IEEE 802.15.4 wireless communication standard. It has five transmission power levels (10 dBm, 12 dBm,14 dBm,16 dBm and 18 dBm) (Digi International, 2017).

Bruntingthorpe Proving Ground was used as field experiment area. It is an airfield base from World War II and is built on 670 acres of land in Lutterworth, Leicestershire UK. It has patches of flat land that Leicester University rents to use as an outdoor experimentation field. The receiving node was installed in a fixed place of about one metre height. Transmitter was installed at about the same height and moved in 10 metres steps while the RSSI level was recorded at the receiver. The transmitting power level of the XBee was set to 10 dBm, and its range tested in an outdoor environment with a Line of Sight (LOS). Firstly, the transmitter and receiver were equipped with 2 dBi antennas. Then, the same procedure repeated but the antennas changed to 5 dBi. RSSI levels measured by the receiving node are presented in Figure 3.3.

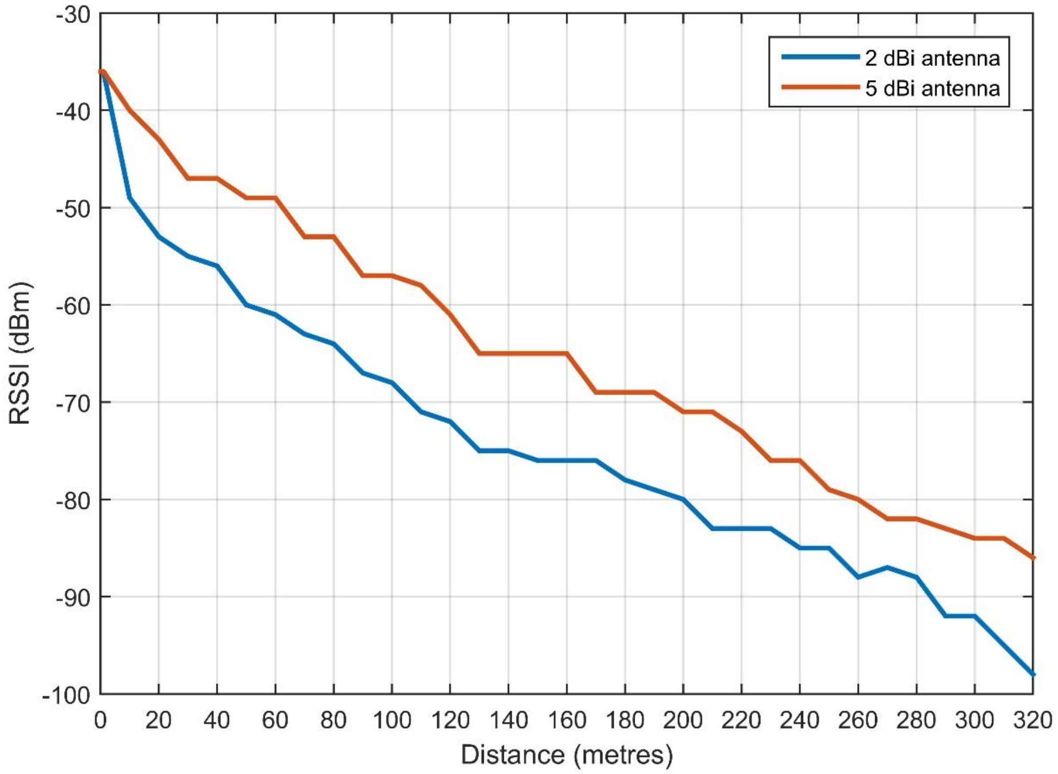


Figure 3.3 The RSSI levels at different distances from the receiver

In conclusion, the measurement results show that XBee Pro S1 has large transmission distance and in order to construct the network in a manageable area, a 20-dB attenuator was used at both ends to reduce the transmitted and received power so that the coverage range will be between 10-20 metres.

3.2.3 Emulating Space Conditions

The experimental investigation of SB-WSN on the ground suffers from the effect of the ground reflected ray. Reducing the level of reflected signal will lead to a near-space communication channel characteristics so that the received signal will be reduced proportionally by the distance as ($1/d^2$) rather than ($1/d^4$). Minimising the ray going down to the ground can be accomplished by mounting the antenna on a ground plane, including shielding the nodes to prevent unwanted radiation. In fact, the combination of the ground plane and the transmitter antenna will appear as a monopole antenna. The size of the ground plane should be more than the wavelength of transmitted signal. Figure 3.4 shows the radiation pattern at ($\Theta > \pi/2$) of a monopole antenna with different size reflectors (Weiner, 2003).

Computer Simulation Technology (CST) is a software package (STudio, 2016), that was used investigate the effect of ground plane reflector size. Since the nodes will be equipped with 2 dBi omnidirectional antenna (Low Power Radio Solutions, 2016), the antenna was modelled, and its radiation pattern in 2.4 GHz frequency is presented in Figure 3.5.

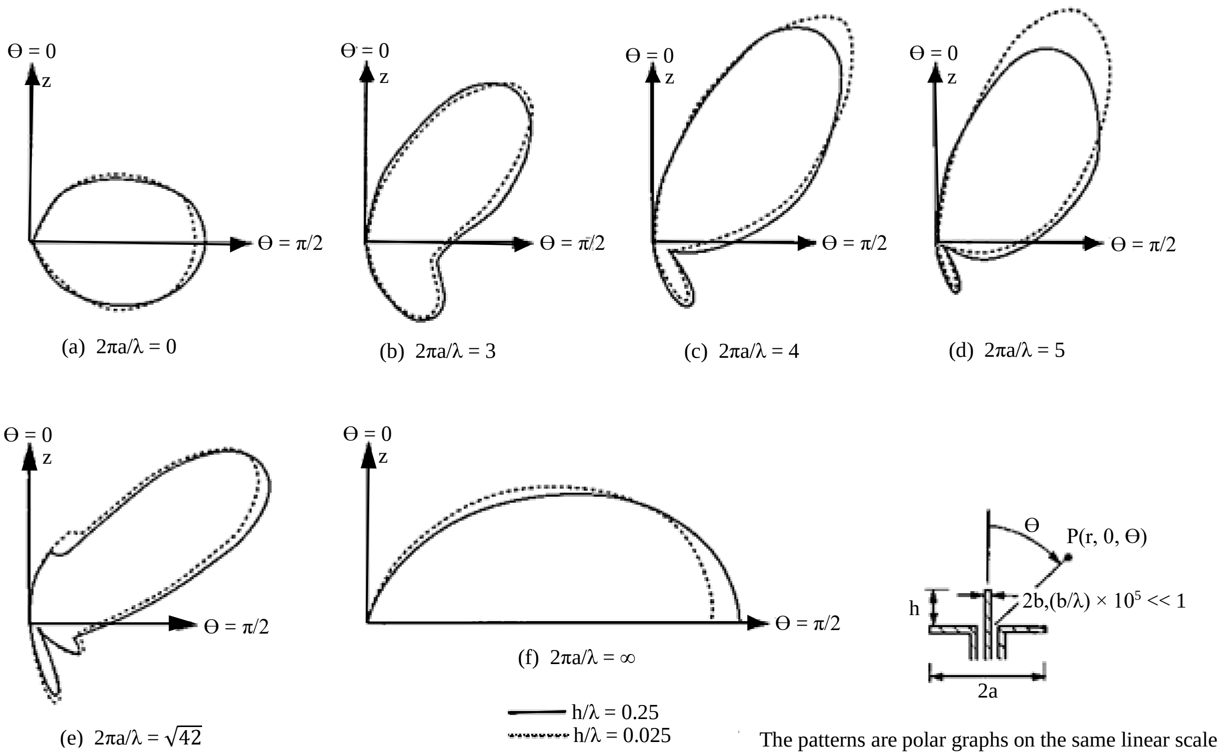
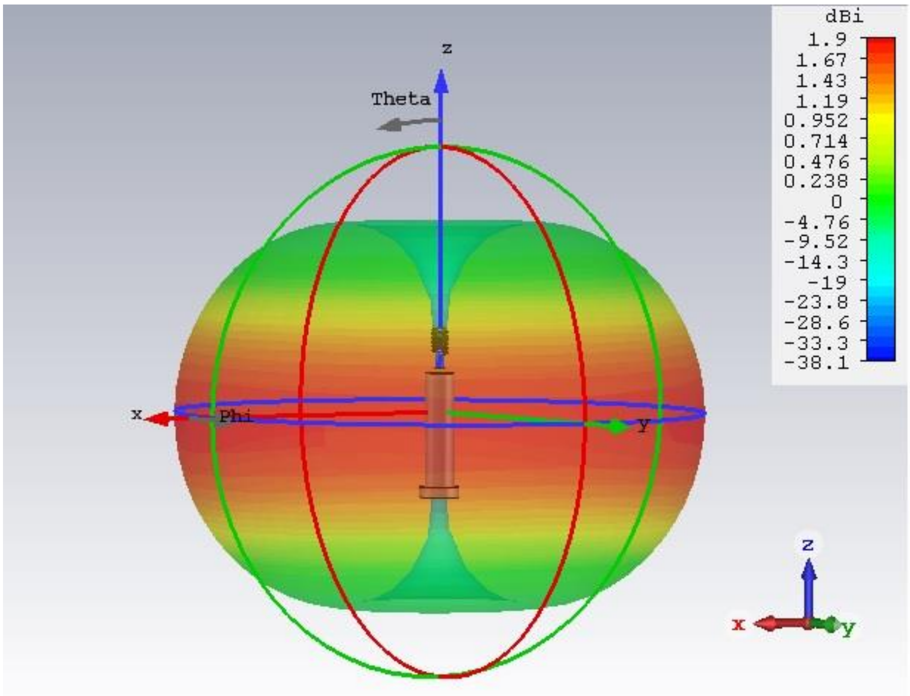
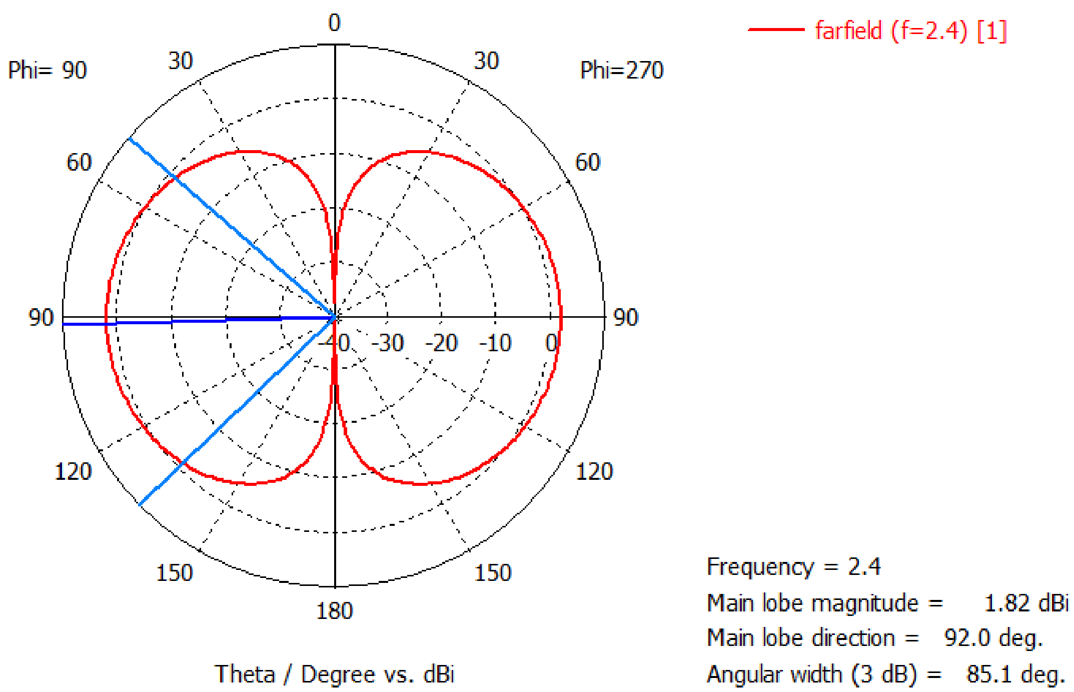


Figure 3.4 Elevation radiation patterns of the monopole antenna with a ground plane of radius *a* (Weiner, 2003)



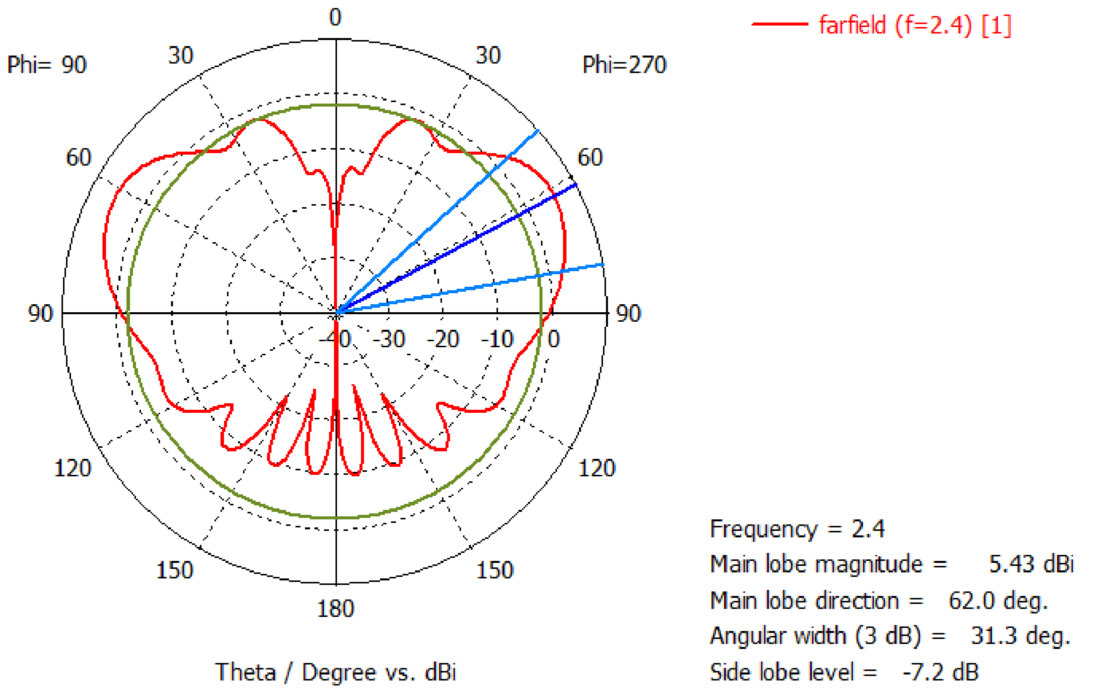
(a)



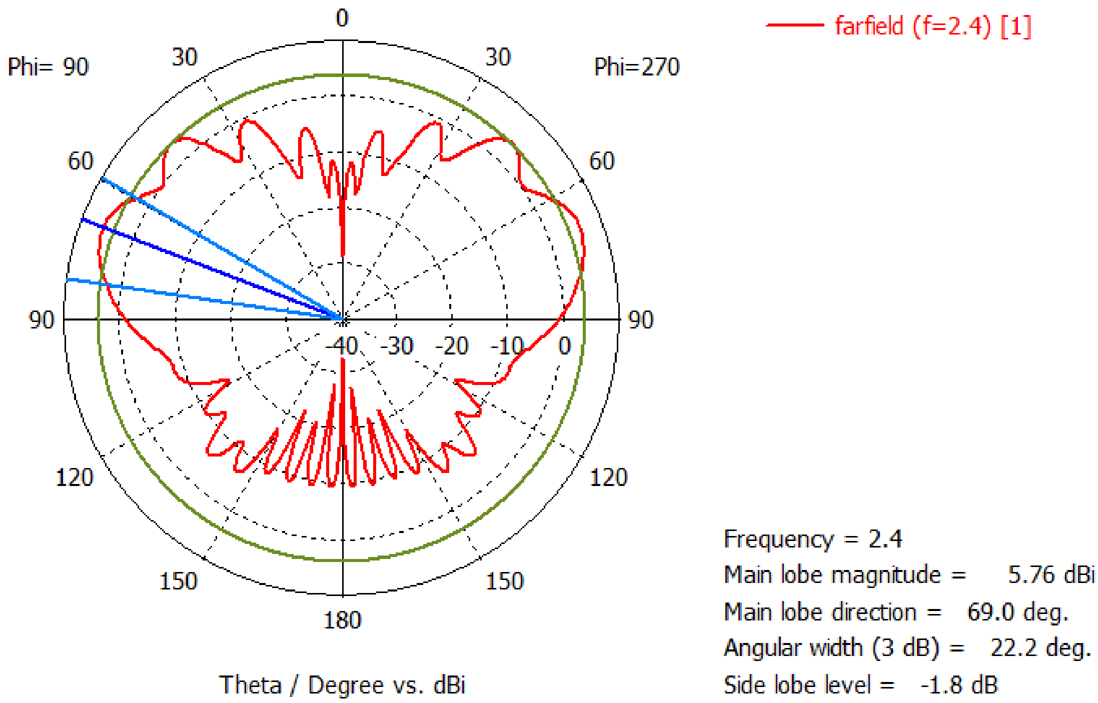
(b)

Figure 3.5 a and b. The radiation pattern of the antenna without a reflector in a) 3 dimensions and b) elevation

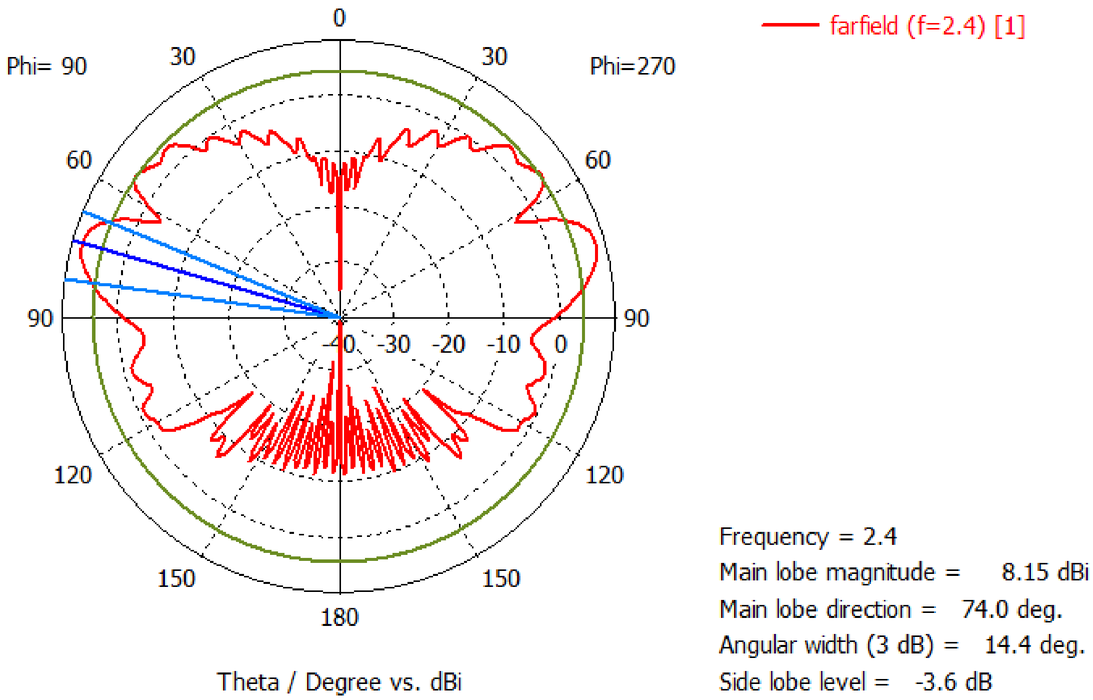
The simulation was repeated, but a thin ground plane of conductive material with 2 mm thickness was added to the geometry and size of the ground plane increased through the simulation. As shown in Figure 3.6 the elevation angle of the radiation pattern changed with increasing ground plane size with more of the radiation traveling upwards instead of being directed to the ground.



(a)



(b)



(c)

Figure 3.6 a, b and c. The elevation radiation pattern of a proposed antenna with ground plane size of (from the top) 0.5 × 0.5, 1 × 1 and 2 × 2 m

Modelling indicates that in case (a) the downwards energy at Ө = 120° was reduced by 7 dB while the results show 16 dB and 4 dB reduction for (b) and (c) respectively. However, in case (c) the rays between 150° and 180° are reduced to a lower level than (a) and (b).

The simulation results show that increasing the reflector size will lead to a decrease the ground-reflected signals in different levels depending on the angle. Using 1 × 1 m reflector provides the best distributed degradation in antenna downward radiation especially at Ө = 120° where the radiation travel minimum distance and has the maximum effect in the propagation model. Therfore, since using 2 × 2 m plate was not possible, only the reflector sizes in cases (a) and (b) were considered for further real in-situ measurements.

An experiment was carried out in Victoria Park to investigate the radiation behaviour of the simulated monopole antennas with clear LOS. Three nodes were assembled; one of them set as a transmitter while the second acted as a receiver, and third node was used to operate as a gateway. The transmitter node was programmed to continuously send packets to the receiver which measured the RSSI level of the received packets and forwarded measurements to the gateway node. The RSSI levels were recorded at the same node height and structure (i.e. with using a ground reflector). Two aluminium sheets size 50 × 50 cm and 1 × 1 m were used as ground plane reflectors, (see Figure 3.7).

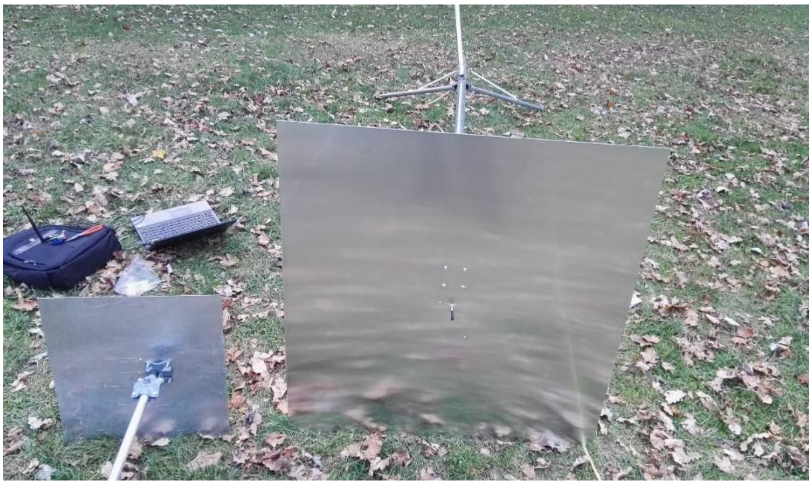


Figure 3.7 a Nodes installed with aluminium sheets (size 50 × 50 cm and 1 × 1)

Figure 3.7 b Shows nodes using aluminium sheets size 50 × 50 cm

Figure 3.7 c Shows nodes using aluminium sheets size 1 × 1 m

Figure 3.7. a, b and c Node set up during the experiment

Initially, the transmitter was set up in a fixed position, and the receiver was moved by one metre each step while measuring the RSSI levels. The XBee transmission power was set at 10 dBm (i.e. the lowest transmission power level). The first test used a 50 × 50 cm aluminium sheet as a ground plane reflector. Both the transmitter and the receiver were mounted at the same height. Then the test was repeated for the 1 × 1 m sheet. Figure 3.8 presents the RSSI levels measured at different distances. Three different heights of antennas were tested (1, 2 and 3 metres). The results reveal that the RSSI levels were not affected by antenna height because the same levels were recorded while the heights were changed. The measurement results in Figure 3.8 indicates that the gradient of free space path loss curve is – 20 while using 1 × 1 m ground curve shows -23.5 gradient cross the coverage area. Therefore, using 1 × 1 m ground reflector installed at 1 metre high will establish a space-like propagation condition before the signal was lost after 17 metres.

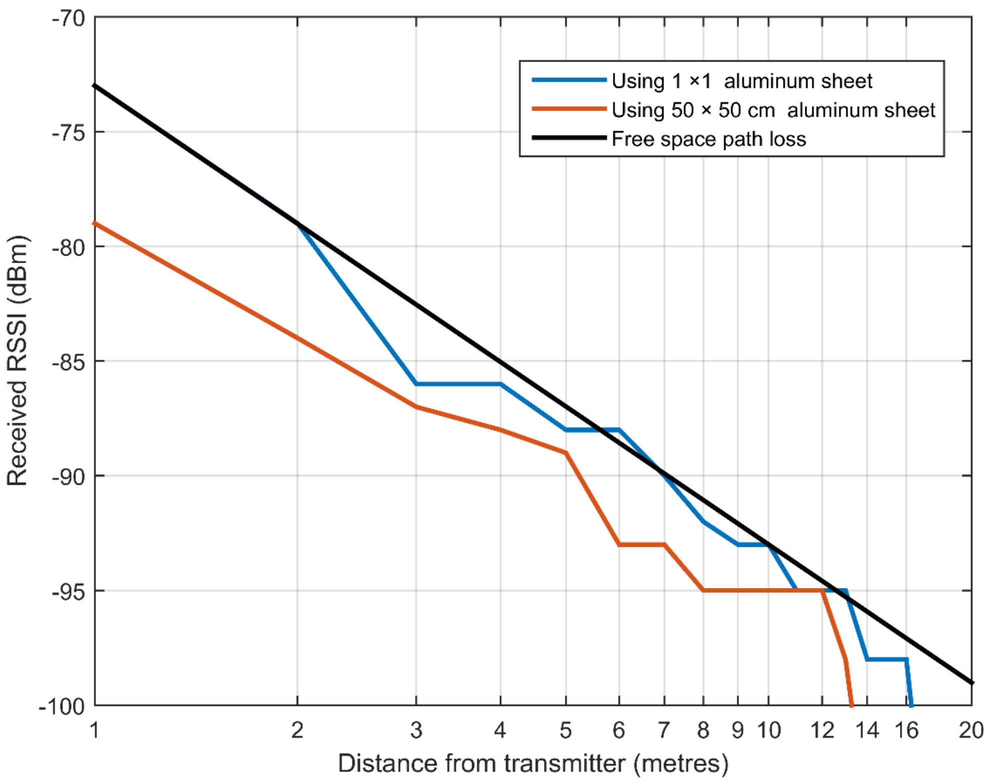


Figure 3.8 Shows RSSI levels vs distance

The proposed system was designed to minimise the energy of the signal radiated from the antenna downwards. Adding the reflector and attenuator will reduce that energy more. Further, in the case of the same system implemented in both transmitter and receiver, the ground reflected rays effect can be neglected (i.e. $1/d^2$ variation in signal strength at the receiver, rather than $1/d^4$ expected from over the ground systems). The total of 40 dB attenuation will reduce the XBee range to 16 metres. These findings will be adopted in this thesis to construct a network which will be capable of emulating space conditions.

3.3 Experimental Network Setup

A network consisting of 40 nodes and a gateway was installed at Bruntingthorpe. Figure 3.9 shows a satellite picture exported from Google Earth (Google Earth Engine Team, 2015). It was employed to investigate the power behaviour of a WSN in space-based communication channel characteristics.

Figure 3.9 Shows node distribution and gateway location

The antennas were elevated one metre above the ground. Also, the nodes were placed in a shielded metal box underneath the plate to prevent the unwanted radiation affecting the system operation. The gateway (GW) was connected to a computer so it could record the incoming data. Therefore, it was positioned at the hut which has a continuous mains power supply and can prevent the gateway from being damaged by weather (i.e. rain, wind or humidity).

As illustrated in Figure 3.9 nodes were disseminated in eight rows and five columns. They were distributed over 60 metres width and 105 metres length. The distance between nodes was selected to be 15 metres, this distance has been adopted according to the findings in Section 3.2.3. All nodes were programmed to send packets with the lowest transmission power (i.e. 10 dB), except the nodes in the first row (i.e. on the right in Figure 3.9). These used higher transmission power which allowed them to communicate with the gateway. The gateway was located at the end of the network rather than the centre, to investigate the scenario where the packets need to pass through multi hops to reach their destination. For example the packets at row 8 (i.e. on the left of Figure 3.9) need to travel at least seven hops to arrive at the gateway. Figure 3.10 presents the experimental deployment at Bruntingthourpe.

(a)

(b)

Figure 3.10 a and b Shows the deployed network and the surrounding environment

The proposed configuration can be used to investigate cluster head power performance as suggested by Zhai and Vladimirova (2015), Heinzelman *et al.* (2002) and Qing *et al.* (2006) by considering that each node represents a cluster head and the sensed data as the information collected from the cluster member nodes.

This configuration is suitable to investigate SB-WSNs in situations where the nodes in the network appear static to each other. For example, where a grid of sensing nodes located around or near a spacecraft, monitoring the space environment or near the surface of the planets or asteroids (National Aeronautics and Space Administration, 2017).

Also, it can model the deployment of SB-WSNs in Low Earth Orbit (LEO). In this case, nodes can suffer from unwanted perturbations to their orbit over the time because of aerodynamic drag, solar pressure and gravity gradients (Vladimirova *et al.*, 2007). Both solar pressure and gravity gradient affect all the nodes in the network at the same level, or they are weak and cancel out over the time. Aerodynamic drag is significant for small satellites in fleet separation, and it will be weak in the case of these satellites are placed above 700 km altitude. Besides, if the small satellites are deployed at the same altitude, they will suffer the same amount of aerodynamic drag forces (Omar and Wersinger, 2015). Orbital control is essential in fleet operations; conventional orbit control methods require to determine the precise altitude and position of satellites by using electrodynamic tethers (Shastri *et al.*, 2014) or an attitude control system (Li *et al.*, 2013), etc.

4 Developing Power Efficient Sleep/Wake Up Scheduling

4.1 Introduction

Presented in this chapter is the deployment of the space-based wireless sensor network and the analysis of the experimental data on investigations conducted for power performance under various sleep/wake patterns. The measurements also evaluate the node lifetimes and the amount of the data delivered at the sink.

4.2 XBee Parameters Setup and AODV Implementation

XBee Series 1 has two network communication protocols IEEE 802.15.4 (point to point), and DigiMesh (peer to peer), both of which are embedded in the same hardware chip and only firmware modification is needed to switch between them. DigiMesh behaves similarly to AODV for both message routing and route discovery. Also, it utilises CSMA to acquire a communications channel, which provides a method for detecting collisions and retransmission (Digi International, 2015b). In DigiMesh the routing tables are built only for the desired destinations, and its gives equal rights to all nodes including routers and endpoint nodes (Young, 2008). Further, if the source node has a packet to send and does not have a route to the destination, the packet will be queued waiting for the Route Discovery process (RD). Then, the source node starts the RD by broadcasting a Route Request (RREQ). The intermediate nodes may either drop or rebroadcast the RREQ depending on whether they receive a new RREQ with a shorter path to the source node. If this is the case, they keep the route information and rebroadcast the new RREQ after adding link strength information which is used later to estimate path quality. When the destination receives the RREQ, it replays a unicast transmission with Route Reply (RREP) using the path recorded in the RREQ regardless how many RREQs it received. Afterwards, the source node selects the best round trip quality route to forward its queued packets. In addition, in the event of path fail, the sender node utilises its network retries before starting the RD process again (Digi International, 2015b).

4.3 Evaluating SB-WSN Power Behaviour

The WSN system suggested in Section 3.3 has been tested under three sleep/wake scenarios. Firstly, measurements were collected in the situation where all nodes in the network are set to active status over all their duty cycle. Then, the experiment was repeated but the nodes programmed to turn off their communication module and enter into sleep mode asynchronously for 20% of their duty cycle. In the third test, the sleeping period was increased to 33%, and the nodes synchronously sleep and wake up. These experiments will be explained in more detailed in the following sections.

4.3.1 SB-WSN Performance Using DigiMesh Communication Protocol

This exercise has been conducted in the Bruntingthorpe area. The gateway was installed in the hut which was connected to the laptop at all times so that the collected data can be recorded. Firstly, the transmission range of the first row nodes was checked where each node link to the gateway was tested separately. The check has been done by programming each node to send packets to the gateway and measure the packet loss percentage, starting from node 33 and ending with node 1. The tests show that reliable communications links can be obtained between nodes in the first row and the gateway by setting the transmission power level of the XBee Pro to 4 (i.e. 18 dBm). The reason for this test was because the nodes in the first row had different distances from the hut. Some of them, especially nodes 25 and 33, required more transmission power to reach the gateway. The other nodes in the network were installed using minimum transmission power level (i.e. 10 dBm).
In the second test, an answer to was sought the question; “what is the performance of a WSN deployed into space in a grid configuration with all nodes in the network employing DigiMesh as a communications protocol”. The node deployment method was carried out column by column for instance in the first column, node 1 installed at the beginning and ending with node 8. The procedure repeated for the rest of the network columns and illustration of the installation method shown in Figure 4.1.

XBee Pro has 12 channels of operation, each with 5 MHz bandwidth numbered from 0C to 17 (hexadecimal). All nodes were set to operate on channel 0C to avoid any interference caused by the WiFi channel, which uses the same frequency channels but has a bandwidth of 20 MHz. As a result, the channels overlap, and only three nonoverlapping channels can be created in all the frequency band from 2.4 - 2.5 GHz. Further, the WiFi router often set to channel six as a default which is the channel used by the circular antennas project shown in Figure 4.2 (Libelium Comunicaciones, 2012, Poole, n.d.). In addition, nodes in the same WSN should be set on the same channel otherwise they will not be able to communicate or listen to each other.

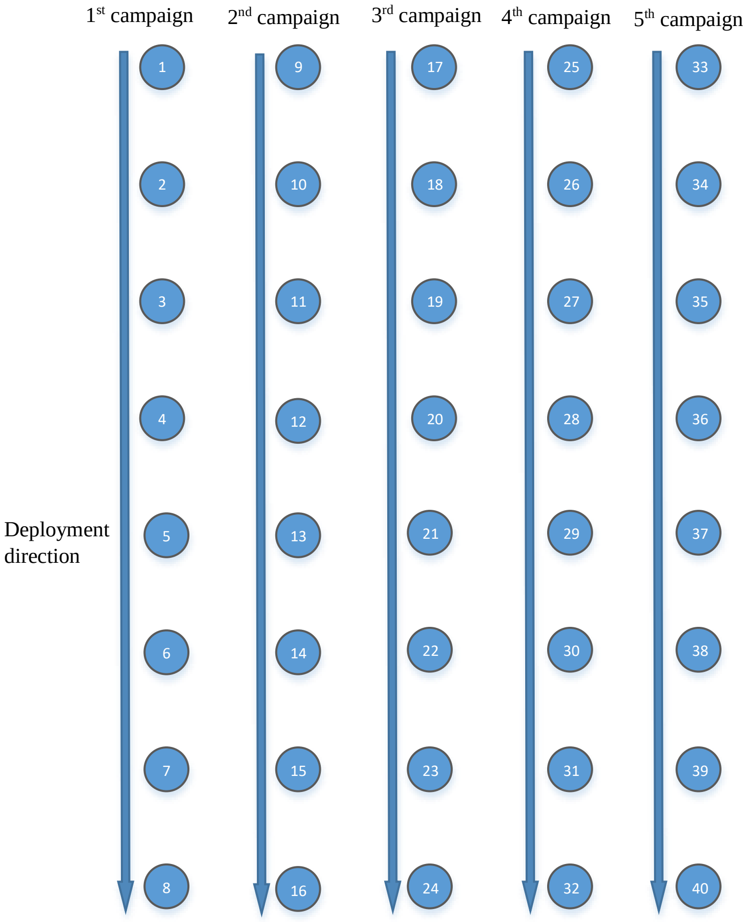


Figure 4.1 Deployment procedure

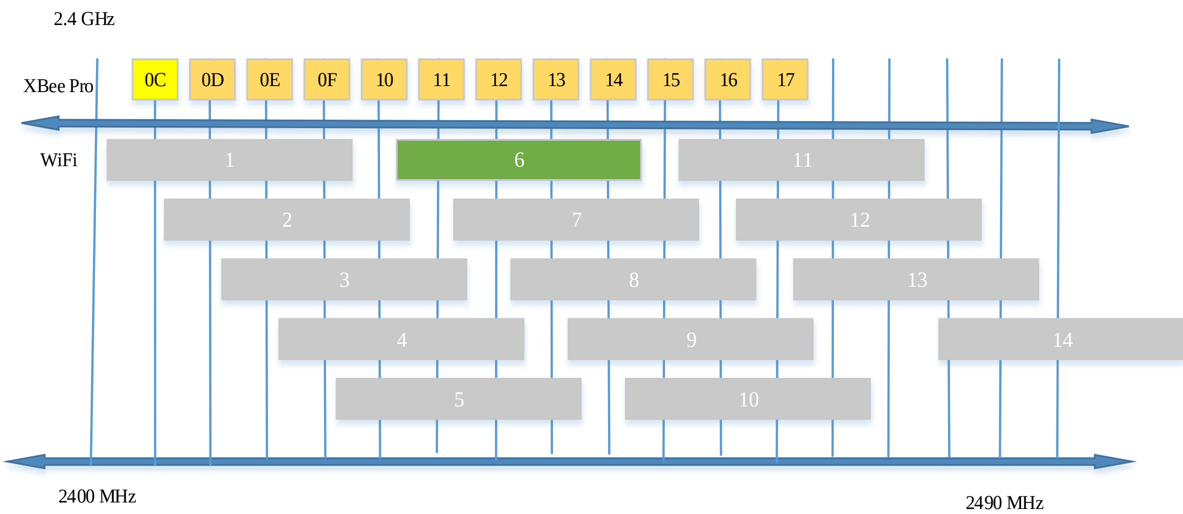


Figure 4.2 Graphical representation of WiFi and XBee Pro channels

In the first experiment, the XBee Pro was set to no-sleep mode because it will be either sending packets or helping to forward data of other nodes in the network. The maximum number of hops (Network Hops NH) was set to 8, in order to prevent the packets from travelling longer paths that reduce the overall network performance. Furthermore, all the XBees were configured as a standard router so that they can work as an intermediate node on a route and act as end device at the same time. All the Waspmotes were programmed to send their packets to the gateway by including its address in the packets. A flowchart of this program is presented in Figure 4.3. In order to observe network power behaviour regarding the nodes' lifetime, the number of packets delivered to the sink and the battery energy left at the end of the experiments were measured. Information about the nodes' battery level, packet counter and battery output voltage were added to the packet data.

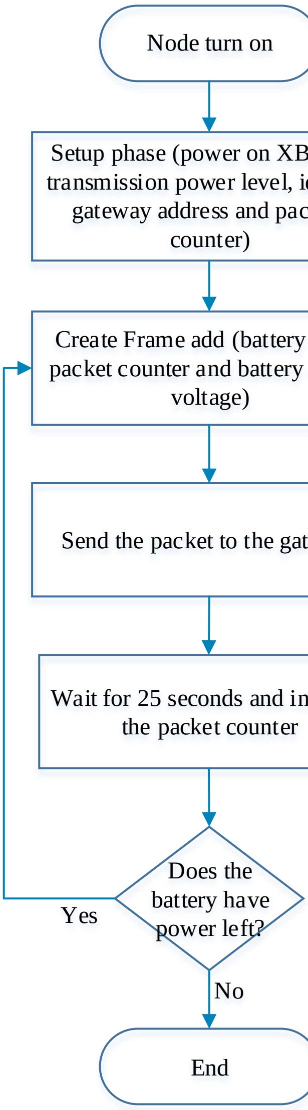


Figure 4.3 Flowchart of Waspmote programming in the first scenario

The nodes’ duty cycle was set to 25 seconds in order to complete the experiment in a feasible time which will be 75 hours for the dual sink scenario presented in Section 6.4. Further, choosing a duty cycle of less than 25 seconds will lead to a higher packet loss because the adopted SB-WSN has 40 nodes some of them required up to 7 hops to communicate with the sink, those hops need time to complete receiving and retransmission.

The frame was constructed by the Waspmote before being forwarded to the XBee for transmission. The length of the packet was 44 bytes and contained information about the remaining battery percentage, battery output voltage and packets counter. Table 4.1 and Table 4.2 shown example of the received packets.

Table 4.1 Packet information contents

Header								Payload					
<=>	#	400569844	#	N2	#	24	#	STR:25	#	BAT:94	#	STR:4154	#
A	B	C	B	D	B	E	B	F	B	F	B	F	B

Table 4.2 Description of fields structure in the packet

A	Packet start delimiter
B	Information separator
C	A Waspmote identifier which labels each node uniquely, it is built in the hardware and can be read
D	A node ID (defined as a string) which can be changed that represents the node number in the network
E	Internal packet counter which can only count up to 255
F	The data from the sensors, in this experiment packet counter, battery level and the battery output voltage

4.3.2 Results for SB-WSN Implemented DigiMesh where Nodes are Awake all the Duty Cycle.

The data packet described in tables 4.1 and 4.2 were recorded in a text file then the packets are analysed to produce the measurements results. Node lifetime values for each of the 40 nodes are presented in Figure 4.4. The summary of the average node lifetime values for individual rows of the network is provided in Table 4.3. The mean lifetime values are averaged across the five nodes' lifetime values in each row and the standard deviation was calculated from that values.

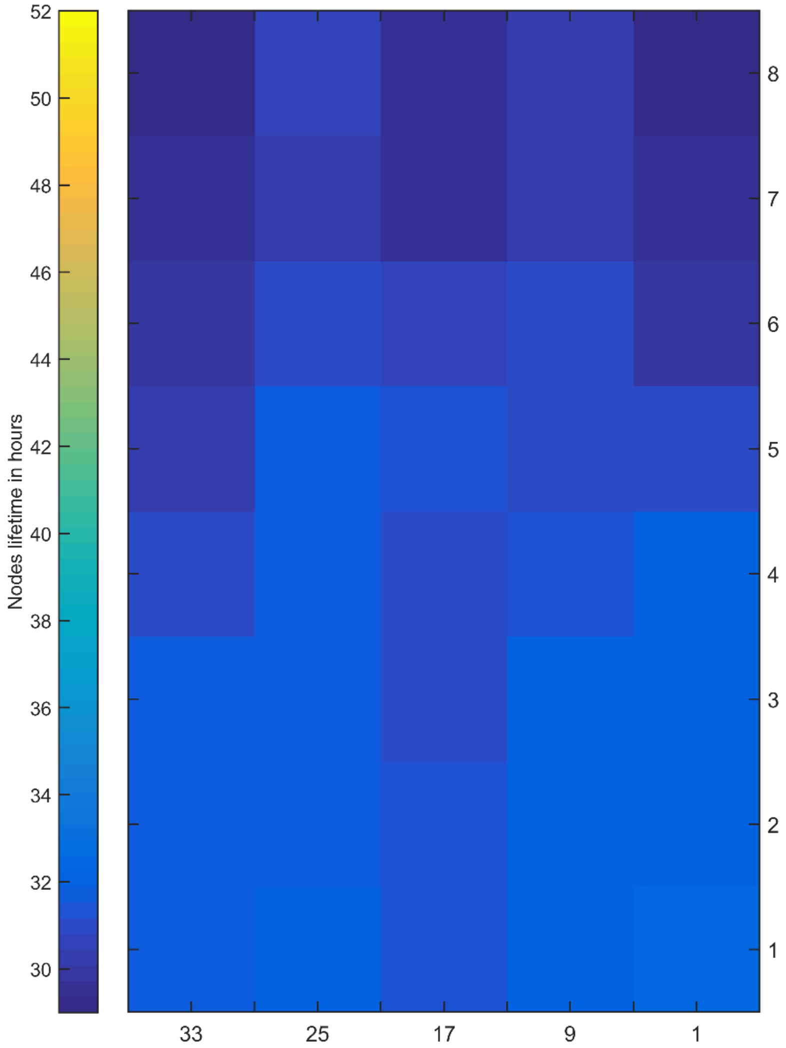


Figure 4.4 Nodes lifetime values while they are awake all the test

Table 4.3 Average lifetime values for nodes in rows and they are awake all the test

Rows number	1	2	3	4	5	6	7	8
Average node lifetimes (hours)	31.8 ± 0.4	31.7 ± 0.4	31.7 ± 0.4	31.3 ± 0.5	31 ± 0.5	30.4 ± 0.4	29.9 ± 0.4	29.7 ± 0.7

Nodes in the first row have a longer life period because they have direct access to the sink, while nodes in row 8 consumed all their battery power around 2 hours sooner. These nodes consume more power since they need to repeat the route discovery process as the intermediate nodes could be busy sending their data which increase the possibility of route failure. Also, nodes in the same row have slightly different in their lifetime values (± 0.7 at maximum see Table 4.3). The reason behind that is the nodes have different initial starting battery power charge, for instance, some nodes battery fully charged at 93% while the in another node the battery indicate 97% power percentage after fully charged.

Node packet loss percentage is defined as the ratio of the number of packets that are not delivered to the destination to the number of packets initially generated by the source (Periyasamy and Karthikeyan, 2017). It calculated using following equations:

$$Packet\ loss\ = No.of\ packets\ sent - No.of\ packets\ received \tag{4.1}$$

$$Packet\ loss\ ratio = \frac{Packets\ lost}{No.\ of\ data\ Packets\ sent} \times 100\% \tag{4.2}$$

Equations 4.1 and 4.2 were utilised to determine the packet loss ratio values in the network for the first scenario. Figure 4.5 represents the packet loss ratio values mapped by node positions. Further, the average packet loss ratio for nodes in each row is outlined Table 4.4.

Nodes located at the edge of the network far from the sink (i.e. nodes in row 8) suffer from large packet loss ratio values because they had a longer path and the data required to travel through many hops to reach its destination (i.e. the sink). All the nodes in the network stay active throughout all their duty cycle period, which presumably gives a stable route but while router nodes are busy with creating and forwarding their own data, they stop working as an intermediate node and cause more packet loss. On the other hand, nodes in rows from 1 to 4 had better performance because they had shorter paths compared to the nodes positioned afterwards. Further, nodes in the same rows had a slight variation in the packet loss ratio values (see Table 4.4) because they are switched on at a different time and more packet loss encounter due to packet collisions if the node and next hop try to send it packets on the same time.

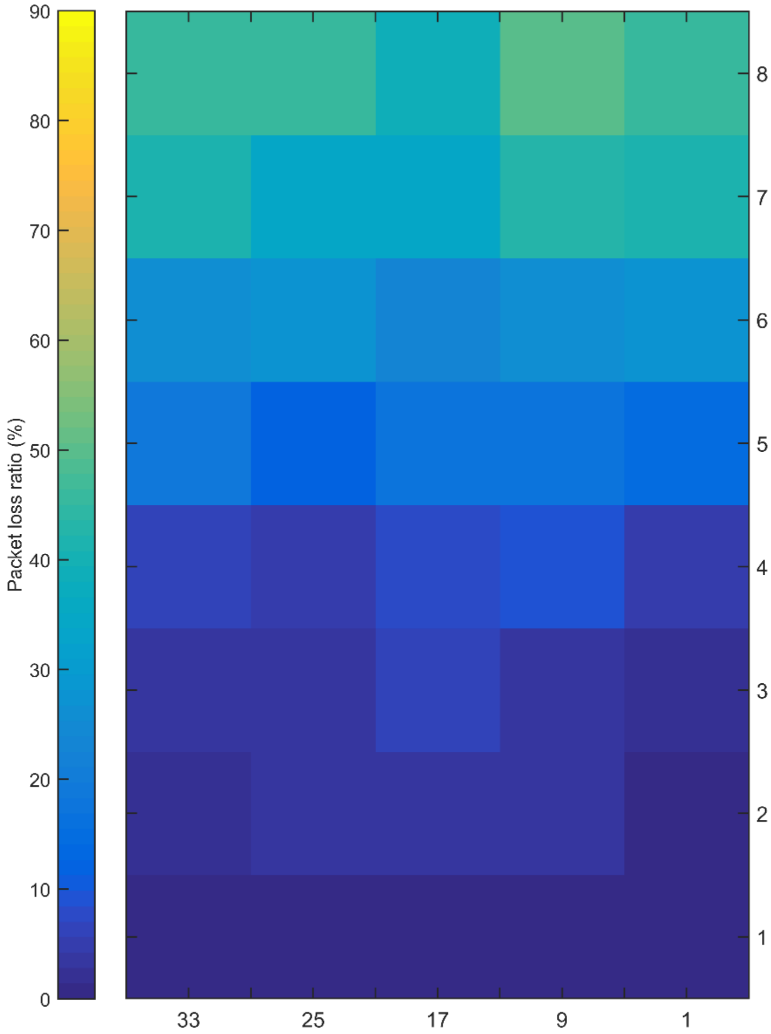


Figure 4.5 Packet loss ratio of nodes while they are awake all the test

Table 4.4 Average packet loss ratio of nodes in rows and they are awake all the test

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	0.54 ± 0.3	2.75 ± 1	3.83 ± 2	6.61 ± 2	16.2 ± 3	26.3 ± 2	39.2 ± 4	45.3 ± 4

4.3.3 Results of Using Asynchronous Sleep/Wake up Scheme to Increase Nodes Lifetime

Investigating the effect on nodes' lifetime and network performance while utilising asynchronous sleeping in the implemented SB-WSN was the objective of the second experiment. The same frame structure was adopted from the first scenario, and the 40 nodes were each set as a router. Also, the nodes were programmed as described in the flowchart shown in Figure 4.6.

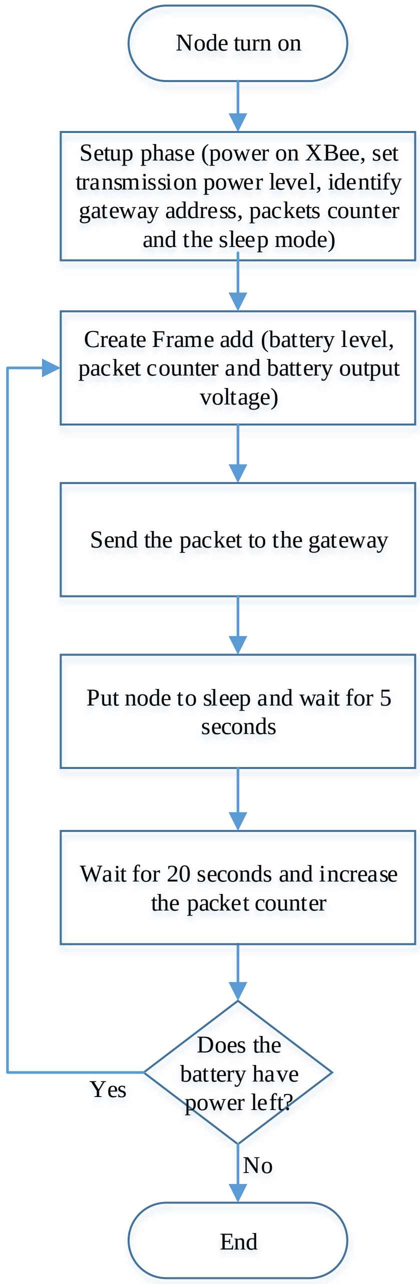


Figure 4.6 Flowchart of node programming in the second scenario

The deployment method and XBee Pro settings were adopted as the first scenario, apart from the sleeping parameters that were changed to asynchronous cyclic pin sleep mode (Pin [1]). According to this mode, the XBee will sleep and wake up according to the status of the Sleep_RQ pin. As soon as it set to high, the node will enter a low-power sleep state, after finishing any transmitting and receiving operations. The module will return to the active mode when the Sleep_RQ pin is set to a low state (Digi International, 2013). The Waspmote microprocessor will control the Sleep_RQ pin status according to the uploaded code sketch which identified the sleep and awake periods (see Figure 4.6). Figure 4.7 represents node lifetime values plotted on the node position in the network. The average values of node lifetimes are shown in Table 4.5.

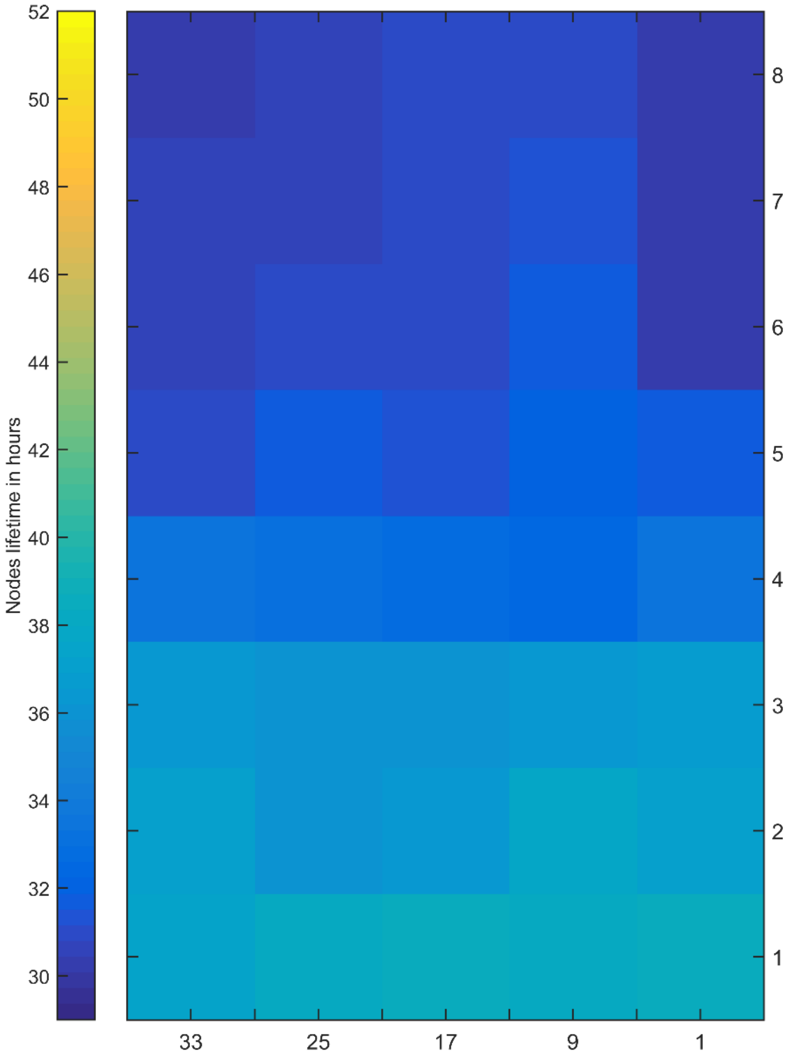


Figure 4.7 Nodes lifetime values while adopting asynchronous sleep method

Table 4.5 Average lifetime values for nodes in rows while using asynchronous sleep method

Rows number	1	2	3	4	5	6	7	8
Average node lifetimes (hours)	38.1 ± 0.4	36.9 ± 0.6	36.3 ± 0.3	33.0 ± 0.4	31.5 ± 0.4	30.9 ± 0.4	30.7 ± 0.4	30.5 ± 0.4

The experiment started with all nodes fully charged and lasted for 38.45 hours when the last node battery power finished. Figure 4.7 indicates that asynchronous nodes sleep/wake up enhance the network lifetime for the devices located near the gateway. For instance, the average node lifetimes in first-row increased by 6.3 hours (see Table 4.3 and Table 4.5) because these nodes are set to low power operation throughout the sleep period which was configured to be 5 seconds (i.e. 20% of their duty cycle). The effect of the asynchronous sleep/wake up technique on node lifetime reduces as the distance from the gateway increases. From Table 4.5, nodes in row 8 have 30.5 hours average values lifetime compared to 29.7 hours in Table 4.3. The reason for the relative poor improvement for row 8 nodes is because they will stay awake till they finished any sending or receiving operation as these nodes required the availability of some hops to deliver packets to the gateway which may be in their inactive sleep period or busy forwarding their own data.

Figure 4.8 provides the nodes packet loss ratio using asynchronous sleep/wake while Table 4.6 summarises the average values for each row of nodes in the network. Figure 4.8 indicates that the nodes positioned in the first row have a packet loss ratio averaged about 0.9% (see Table 4.6) because they can send data directly to the sink. Further, this ratio increased as the number of routers in the nodes' path increased due to route failure. Therefore, the packets are dropped when the communication module reaches its maximum network sending retries (the XBee default is three retries). Also, measurements in Table 4.6 can be compared with the outcomes in Table 4.4 which shows additional packets have been lost in the second scenario, particularly in rows 7 and 8; the packet loss ratio increased from 39.2% and 45.3% to 85.9% and 87.7% respectively.

Table 4.6 Average packet loss ratio of nodes in rows adopting asynchronous sleep method

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	0.90 ± 0.6	9.48 ± 0.4	12.0 ± 1	36.9 ± 3	59.6 ± 4	73.3 ± 7	85.9 ± 4	87.7 ± 2

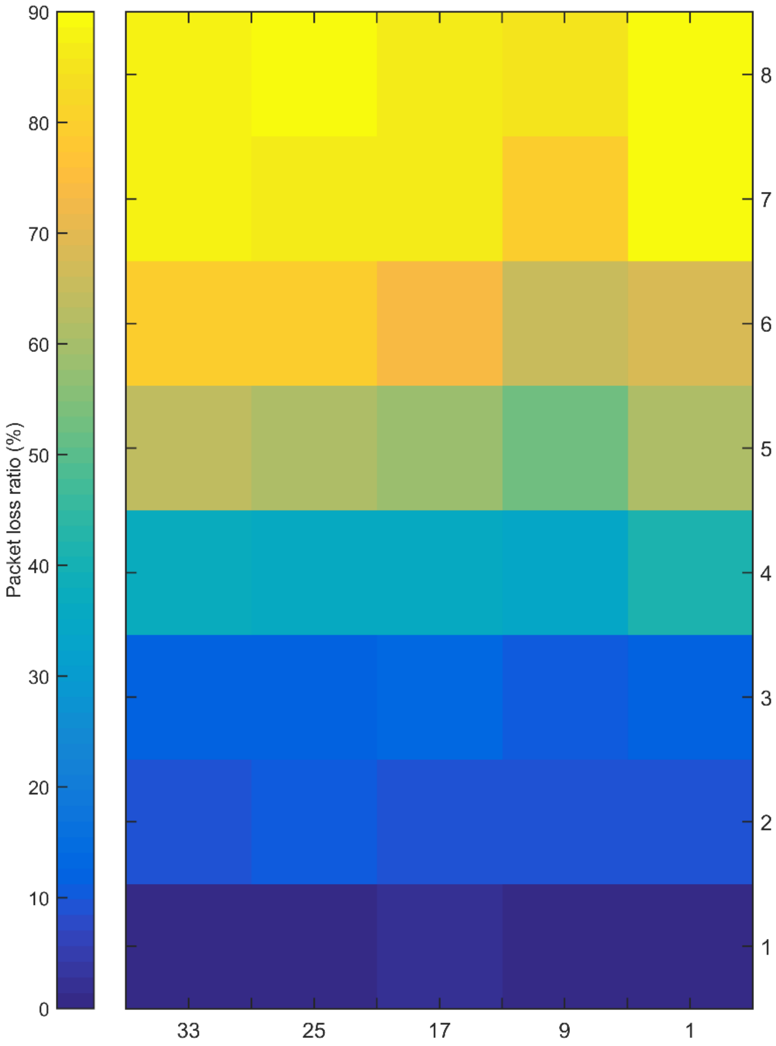


Figure 4.8 Packet loss ratio of nodes adopting asynchronous sleep method

4.3.4 Results of Using a Synchronous Sleep/Wake up Technique Implementation

An experimental campaign was conducted to examine node and network power consumption when nodes are using synchronous cyclic sleep. In this scheme, a node is programmed to sleep and wake up in unison with other nodes, exchange packets and synchronisation messages, and then return to sleep. The coordinator will be responsible for originating the synchronisation packet which is broadcasted and repeated to all nodes at the beginning of the wake up period.

This experiment used an extra node to work as coordinator which settings were modified by enabling the preferred Sleep coordinator Option (SO = 0) and activating the synchronous Sleep support Mode (SM = 7). Also, it was programmed to set the sleep period to 10 seconds while the active period was 20 seconds. The test utilised the same length awake interval used in the asynchronous experiment to observe node power efficiency in the larger inactive period, but the nodes implemented synchronous wake up. The coordinator was installed near in the hut and switched on throughout the experiment. It was used to broadcast the sleep and active intervals without assisting in network data traffic flow. In XBee, each node can be a coordinator based on SO and SM configuration, but having more than one coordinator in the network will disturb the sleep wake patterns as it is a difficult task to synchronise the coordinator's internal clock. Therefore, the rest of the nodes were programmed as shown in Figure 4.9 and configured to support synchronous cyclic sleep, so they never act as sleep coordinator (i.e. SO = 1 and SM = 8). In order to decrease packet collisions, nodes in each row transmit their packet at the same time, but they have two seconds time difference from the nodes located in the next row which was achieved by modifying the delay before and after transmission.

The node sleeping period was increased from 5 seconds in the second scenario to 10 seconds in this experiment, to address the effect of the node synchronisation on the network performance when larger sleeping interval has been used. The measurement will provide information to optimise the future implementation of SB-WSN in a situation where the sensed data need to be recorded and transmitted in longer time interval.

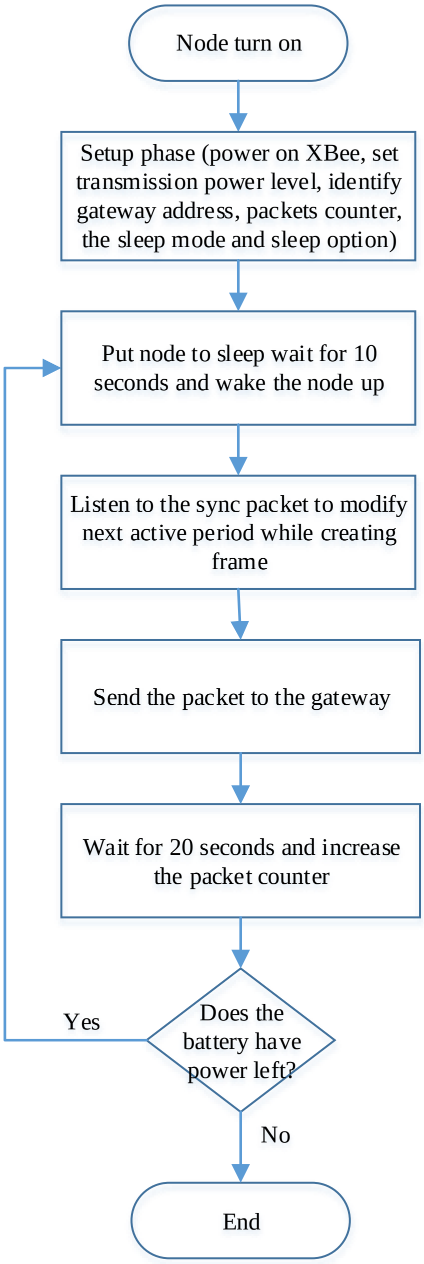


Figure 4.9 Flowchart describing script used in coding nodes in the third scenario

The results of the nodes' lifetime are displayed in Figure 4.10 and Table 4.7. Nodes' lifetime have slightly different values (i.e. around 49 hours) because utilising the synchronised sleep wake up will reduce the number of attempts to establish a route to the gateway. Nodes in row eight still had shorter average lifetime value compared to nodes the first row, 48.4 hours and 50.9 hours respectively (see Table 4.7), due to packet delivery failure and retransmission which happened while the next hop is busy receiving and sending other nodes' packets.

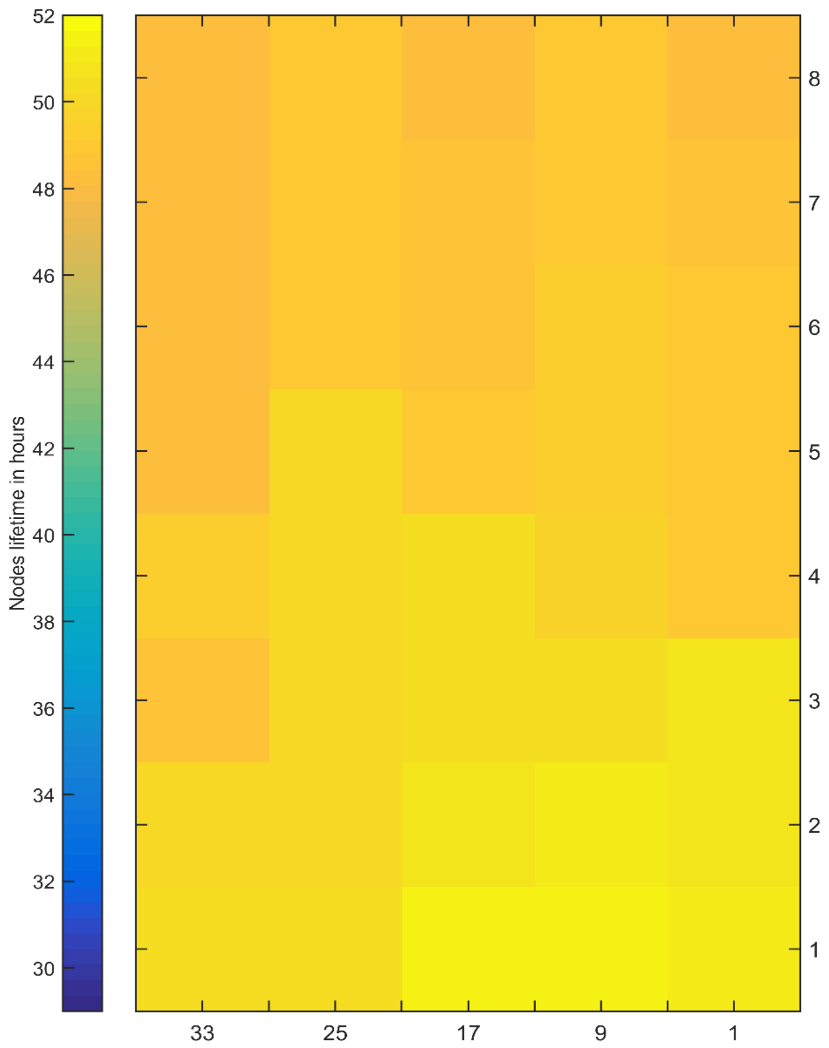


Figure 4.10 Nodes lifetime for SB-WSN utilising synchronous sleep scheme

Table 4.7 Average lifetime values for nodes in rows utilising synchronous sleep scheme

Rows number	1	2	3	4	5	6	7	8
Average node lifetimes (hours)	50.9 ± 0.5	50.6 ± 0.4	50 ± 0.8	49.6 ± 0.5	49 ± 0.6	48.8 ± 0.3	48.6 ± 0.3	48.4 ± 0.5

Figure 4.11 presents the packet loss ratio in the third scenario, as the nodes synchronously wake up at the same time and send their packets sequentially in two seconds gaps, lower packet loss ratio was achieved for nodes up to the fourth row. However, nodes in rows 7 and 8 still have significant average packet loss 65.4% and 74.5% respectively (see Table 4.8). Also, first row nodes in the third experiment have 1.5% average packet loss ratio. It is more than 0.9% value found in the second experiment because while the nodes in the same row wake up and try to send their data

at the predefined time, the possibility of packet collisions increased, causing this increment in packet loss ratio.

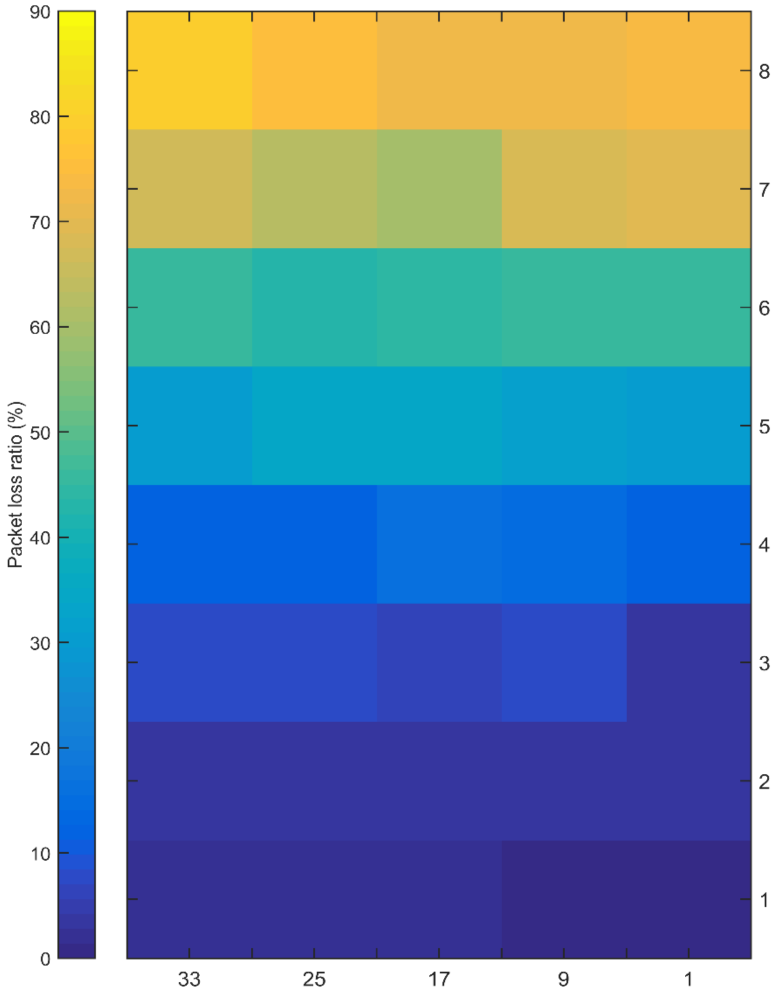


Figure 4.11 Packet loss ratio for nodes utilising synchronous sleep scheme

Table 4.8 Average packet loss ratio of nodes in rows utilising synchronous sleep scheme

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	1.5 ± 0.4	3.39 ± 0.4	6.87 ± 2	13.5 ± 2	32.4 ± 2	44.5 ± 1	65.4 ± 3.9	74.5 ± 2.6

4.3.5 A Scheduled Sleep/Wake up Scheme for SB-WSN

In this section, a novel sleep/wake up method is presented, which aims to provide better node and network power performance. Firstly, the XBee firmware setting was changed to support the IEEE 802.15.4 communication protocol in order to control the next hop selections. The frequency channel, node transmission power and deployment method were adopted from the first scenario. Also, pin hibernate sleep mode is utilised for XBee which puts the node into a low energy consumption mode. This will allow the node completing any RF associative activity (i.e. transmission or reception), to enter sleep mode (Libelium Comunicaciones, 2012).

The suggested sleep/wake scheduled schemes rely on the time needed to process a packet in the hop node. This period is defined as the required time to receive the data and forward it to the next hop. Figure 4.12 explains packet sending process and the execution of Clear Channel Assessment (CCA) procedure. An experiment was carried out to estimate the time Waspmote spent to transmit one packet. Two cases are considered: the best scenario where there is only the node and gateway and the worst case when the node could not reach the destination and the packet is dropped. The results show that in the best case the Waspmote needed 87 ms to send the packet and receive the acknowledgement while in the worst case it needed between 1400 and 1600 ms to report back packet failure.

In scheduled sleep/wake up method, the worst packet transmission case has been considered to minimise the packet loss. Let node A be an end device, and node B is the intermediate node while C represents the gateway. If node A wants to send a packet to node C, then it will use node B to forward the packet to the destination. The minimum time required by the hop (i.e. node B) to deal with two successive packets from node A was set to 3 seconds. This time is calculated as the time required to receive and retransmitted node A packet plus the time needed to send node B its own data. In this research, it has been assumed that all nodes in the network will have the same duty cycle. Accordingly, row 8 nodes will act as end devices, and they will only do single transmission before entering the inactive period of their duty cycle, while the next hop nodes (i.e. one of row 7 devices) required one receiving and two transmissions. The intermediate node retransmission number will depend on how many nodes will use it as a next hop.

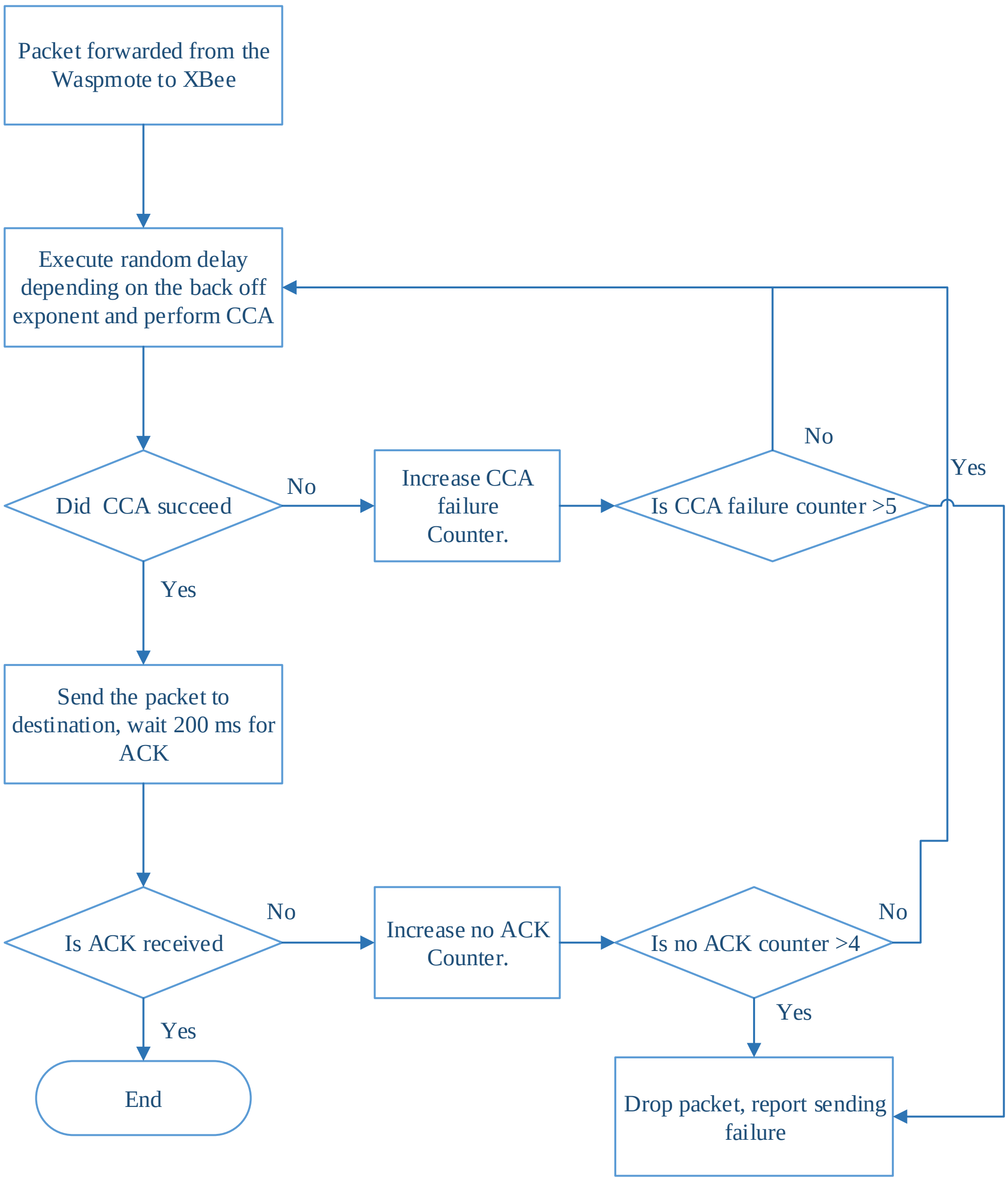


Figure 4.12 Flowchart of packet transmission and CCA operation

Each node in the network will estimate its active and sleep period based on its position by utilising the Dijkstra algorithm which will calculate the shortest path to the destination (Dijkstra, 1959). Also, this algorithm was used to develop knowledge about other nodes routes. In other words, each node will learn about its path and number of other nodes that will use it as a router. The node position in the SB-WSN application is already planned because they are expensive, have low capability to manoeuvre and are supposed to monitor the desired area effectively (more details are presented in Section 3.3). Figure 4.13 shows a flowchart of the node programme in the fourth scenario.

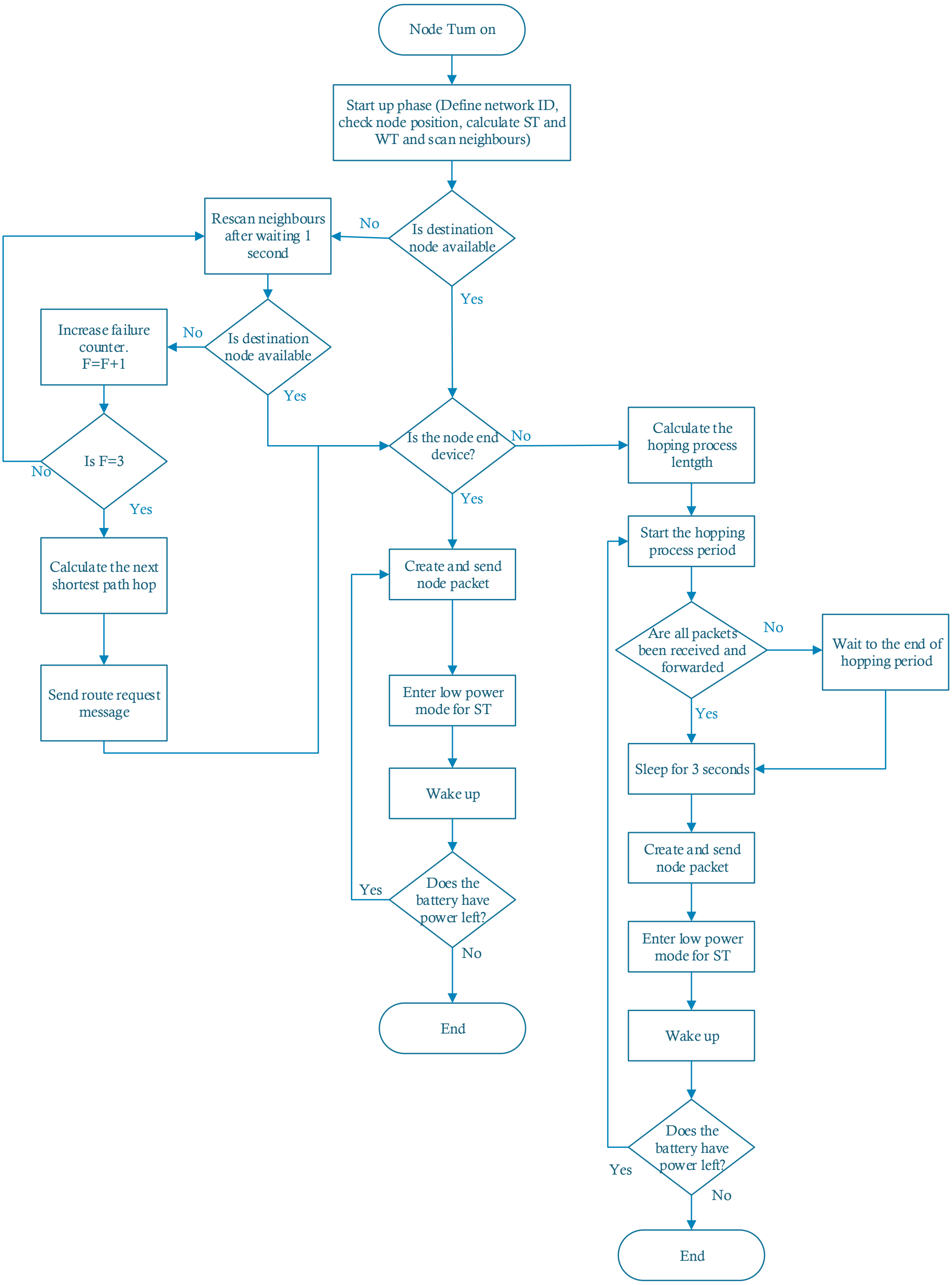


Figure 4.13 Flowchart of nodes programming in the fourth scenario

In this experiment, for the sake of easy implementation, the node positions have been stored in the nodes' memories, so each node has information about its location and the locations of the other nodes in the network. Also, each node executes (scan brother) in the setup phase, which is a function provided by the Waspmote to check its neighbour's availability and whether it can communicate with a further hop to create a shorter path to the destination. The nodes' location information can be shared among the nodes using flooding messages, as in OLSR (described in Section 2.4) which can be created from the gateway to reach the edge of the network.

The proposed sleep/wake up algorithm behaves as an on-demand method when the node waits on active status to forward other nodes' packets and send its data then enters sleep period (presented in Section 2.5.1). This method acts as synchronous sleep while nodes in the column wake up at the same time (reviewed in Section 2.5.2), these nodes have different active period depending on their location. Figure 4.14 plots the nodes duty cycle in the fourth scenario, Sleep Time (ST) and Wakeup Time (WT) will vary based on node position.

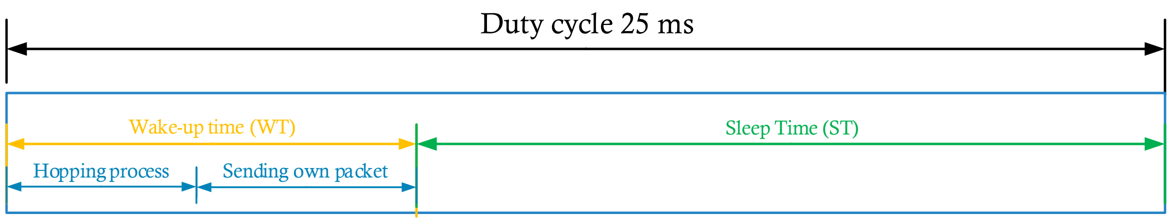


Figure 4.14 Nodes duty cycle divisions

This investigation was undertaken on a situation where no node failure occurs due to accidental reasons such as hardware fault, or external physical force displaced the node far away from its position in order to investigate power use in transmission due to peer positioning. The result in Figure 4.15 represents the time before the sink stops receiving data because nodes in the first row consume all its battery power. Hence it has a longer active period because it is required to relay more data than nodes located in other rows. Also, it has an average nodes' lifetime 39.24 ± 0.5 hours. On the other hand, the rest of nodes still have some power left, but the gateway was out of their transmission range capability.

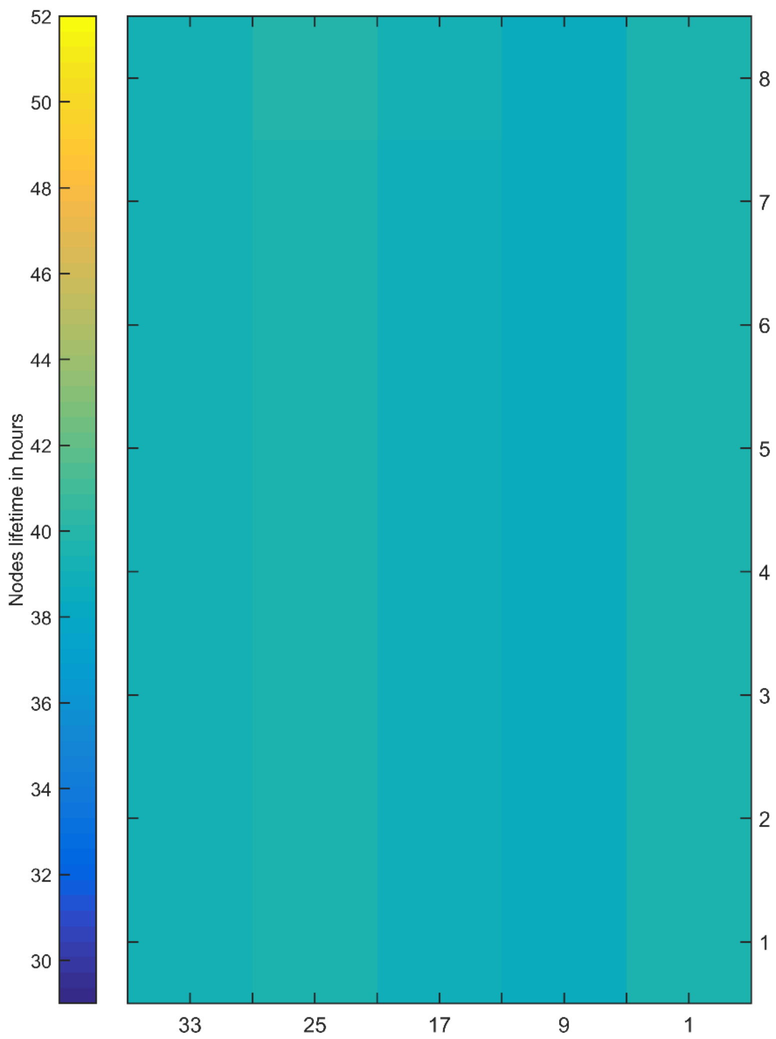


Figure 4.15 Nodes lifetime using scheduled sleep/wake up scheme

Figure 4.16 and Table 4.9 indicate nodes packet loss and show that the packet loss increases proportionally to the length of the route. Nodes in row eight have an average packet loss value 1.74% which is more than the 0.23% value for nodes in the first row due to longer path effect on packets delivery. In addition, some of the packet loss happened between the sink and first row nodes because packets collisions as five nodes try to reach the gateway.

Table 4.9 Average packet loss ratio of nodes in rows using scheduled sleep scheme

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	0.23 ± 0.1	0.38 ± 0.2	0.55 ± 0.2	0.77 ± 0.1	0.99 ± 0.2	1.26 ± 0.2	1.59 ± 0.3	1.74 ± 0.4

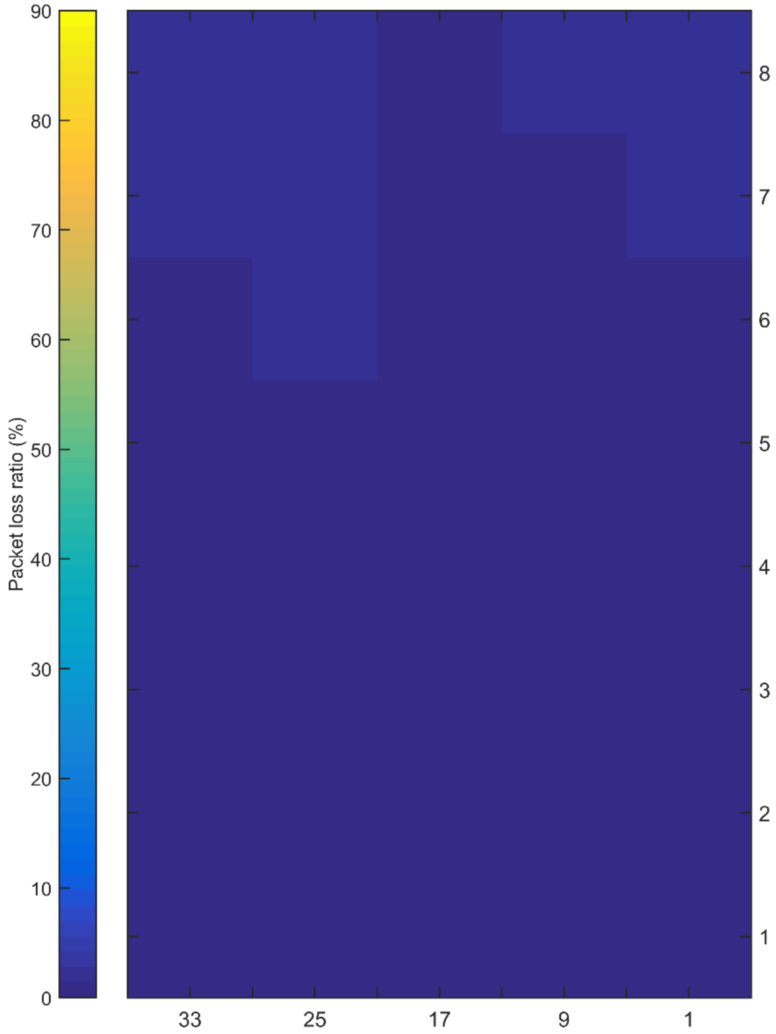


Figure 4.16 Packet loss ratio for nodes utilising scheduled sleep/wake up

4.4 Comparison and Discussion of Measurements

Figure 4.17 shows the total number of delivered packets to the sink in each experiment. It indicates that in the first scenario, although the nodes stayed on active status all their duty cycle, the system suffered from 17.5% overall average network loss (see Table 4.4) and delivered 147561 packets. Most of the packet drops happened in the nodes located at the end of the network far from the gateway (i.e. nodes in rows 8 and 7) due to the route breaking when the relay nodes were busy sending their data or forwarding other nodes' packets. Programming the nodes to sleep 20% of their duty cycle asynchronously from neighbours, made the network lose around 45% of its packets (see Table 4.6). Since the nodes will not be active at the same time with their neighbours, the possibility of finding active route will decrease as their sleeping period increased. Therefore, the total number of the delivered packets was reduced by 27% compared to the first scenario.

Employing the synchronous sleeping method in SB-WSN increased the packet loss, and the overall network packet loss was 30.2% (see Table 4.8). On the other hand, it increased nodes' lifetime which allowed them to send more packets. Although 13% more packet were delivered to the sink compared to the first scenario, the system suffers from packet collisions because nodes in the same row synchronously send their information. Also, the packet loss percentage increased as the number of intermediate nodes in the path increased, so it will not be useful in scenarios with more than 4 hops from the furthest node to the gateway. The proposed scheduled sleep/wake up technique reduces the packet loss by coordinating the transmission process to ensure the route availability. Accordingly, each node was programmed to schedule its data transmission after finishing the hopping process (i.e. all receiving and retransmission duties). Therefore, the scheduled sleep scheme reduced the overall network packet loss to 0.93% (see Table 4.9) and increased the packet delivery at the gateway by 51% compared to nodes never sleep case.

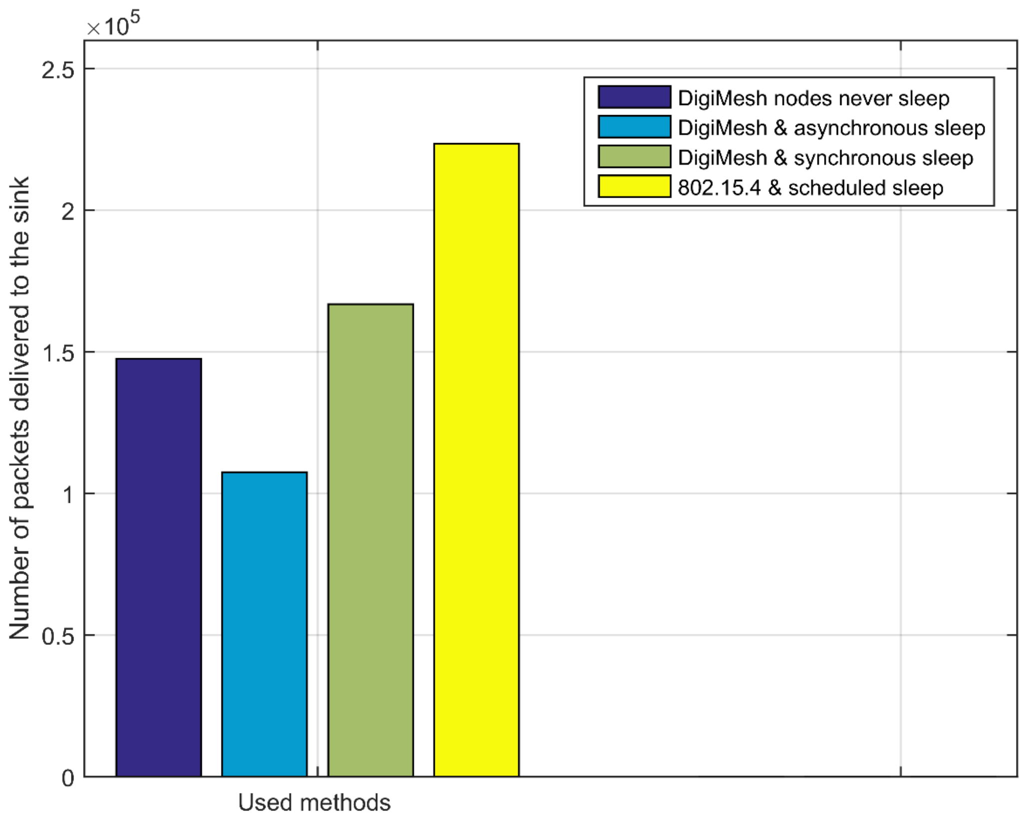


Figure 4.17 Total number of packets delivered to the sink of each scenario

Figure 4.18 indicates the Minimum Node Lifetime (MNL) and the Network Disconnection Time (NDT). The MNL is the time of experiment when the first nodes consume its battery power represents. The network disconnection time was defined as the time when no more packets were received at the gateway.

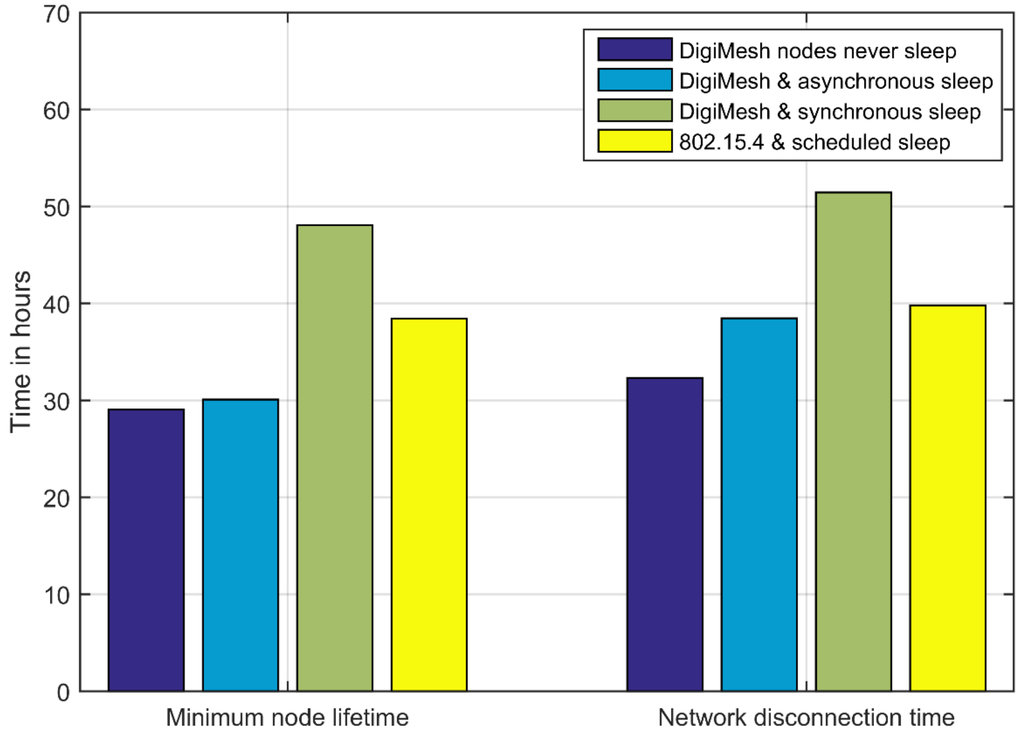


Figure 4.18 Comparison of MNL and NDT

The SB-WSN was disconnected after 32.2 hours while the first nodes battery power runs out after 29 hours in the case of programming the node to be active all the experiment period, and reporting the sensed data every 25 seconds. Adopting asynchronous sleep technique improved the NDT by 6 hours in comparison to the first scenario. However, only a slight change in MNL was obtained because while the nodes located near sinks (i.e. in rows 1, 2 and 3) benefit from the inactivity, the rest used more power to reconfigure broken paths. Utilising synchronous sleep mechanism improves both measured parameters in Figure 4.18 because the nodes had an extended sleep period and they were activated simultaneously so less power consumption was used in route fixing. The proposed scheduled sleep scheme allocated the nodes a different duty cycle based on their locations so that the nodes near the sink had a more active period in their duty cycle as they were required to receive and resend other nodes packets. Therefore, one of row 1 nodes was the first node in the network consume its battery in the fourth scenario which occurred after 38.4 hours while the network was disconnected at 39.8 hours from the test time. The disconnection time is slightly higher than the minimum node lifetime because nodes batteries fully charged at different battery level. Both of these parameters will increase in the case of extending nodes' sleeping period.

Figure 4.19 plots the remaining battery power levels in the network at the end of each experiment. Some of the nodes still did not consume all their battery power while using scheduled scheme because they had a different duty cycle. In contrast, all the 40 nodes consume all their battery power at the end of the experiment due to that all the nodes had the same duty cycle. The scheduled sleep coordinate the sleep/wake up periods and specify their long according to the location of the nodes. Therefore, the 5 nodes in row 8 had more than 60% power at the end of the experiment while 13 nodes had power between 40%-60% and were classified in the third group.

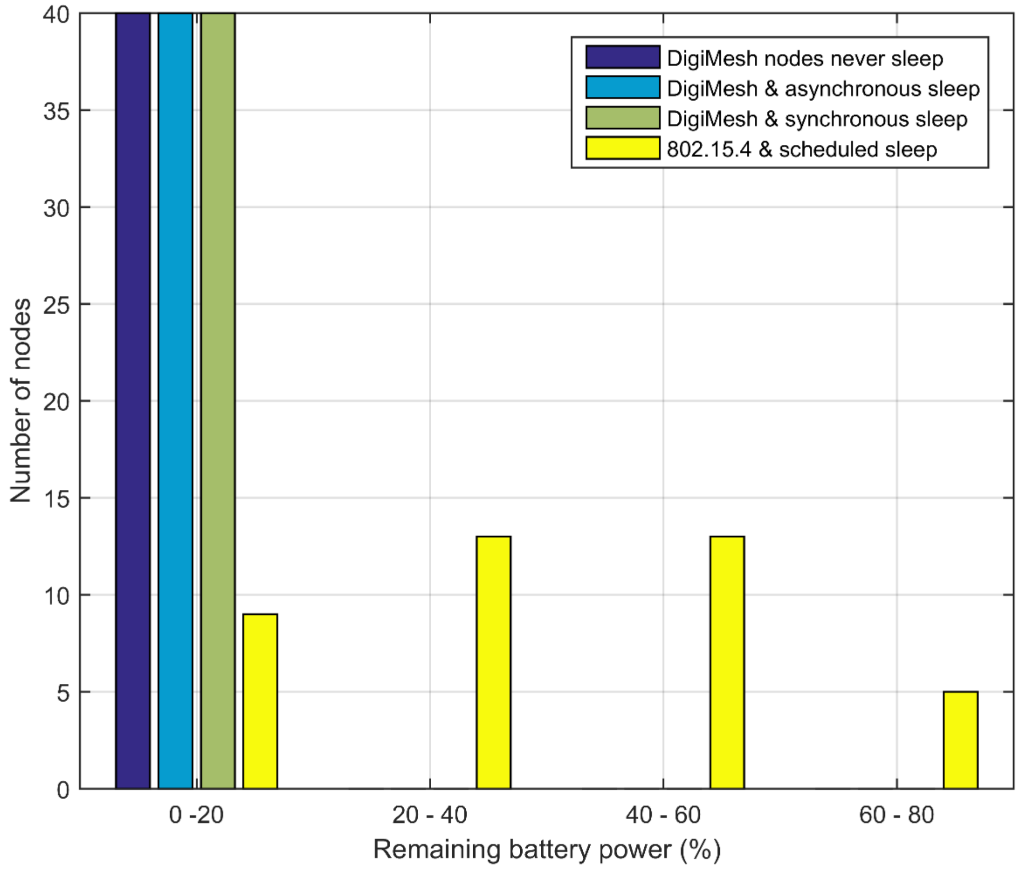


Figure 4.19 Remaining node battery power level at the end of tests

In addition, 13 nodes characterised in the second group (i.e. their batteries power between 20% - 40%) and 9 nodes had less than 20% energy left which indicates that while row 1 nodes die, row 2 nodes had power less than 20% at the end of the test. The scheduled sleep technique achieve better overall network power while delivering a larger number of packets.

4.5 Summary

This chapter focuses on the effect of sending nodes to inactive sleep status on their lifetime and overall network performance. The purpose of the experiments undertaken was to offer an experimental investigation of power consumption for SB-WSN. Several sleeping techniques have been investigated, and their power performance has been compared to reveal the experimental hurdles that can face real network implementation.

The investigations indicate that the nodes' lifetime will increase proportionally to the sleep percentage of the duty cycle spent in sleep. However, increase in the inactive period will affect the nodes' work as a router. Deploying an SB-WSN and setting its communication modules in active status for all their duty cycle will offer less than 10% packet loss up the three hops. The node lifetimes were up to 31 hours because having the communication module on all the time reduce nodes' power efficiency. This method could be useful in the situation of the SB-WSN needing to monitor particular area continuously and capture the sensed data to transfer it immediately to the sink. In the second experiment, the nodes' wake up randomly send their data and return to sleep, regardless of their neighbours' active period. The sleep interval was set to 20% of the duty cycle. The packet loss was less than 12% when the number of intermediate hops was less than 3. Asynchronous sleep/wake up can be adopted in the SB-WSNs where the node transmission range is higher than the sensing range. In such configuration, nodes will have many neighbours (i.e. more than 4) then the availability of next hops which can make a potential route to the sink will increase. Also, power performance will improve as they will create the path faster and back to sleep afterwards. In the third experiment, the case of synchronous sleep/wake up is discussed. The nodes duty cycle increased by about 5 seconds in comparison to the previous tests and were programmed to turn off their communication module for 33% of the duty cycle in order to identify the effect on lifetime and packet loss of nodes being simultaneously activated. This method can increase the nodes’ lifetime to around 50 hours. However, the packet loss rate was high and approaches 13% when nodes route include 3 intermediate hops. The packet delivery ratio of SB-WSN utilising synchronous sleeping can be enhanced by expanding nodes active period proportionally to the number of multi-hop in the adopted configuration. Also, extending the nodes’ lifetime via applying synchronous sleep/wake up scheme has a wide range of applications in SB-WSN such observing space weather, temperature or the intensity of sunlight.

The first three tests were implemented using the DigiMesh communication protocol which utilises the AODV protocol to create the path from sources to the destination. Accordingly, even extending the active period while adopting synchronous sleep/wake up will not eliminate packet drops and collisions. Section 4.3.5 presented a novel sleep/wake up scheme which aimed to reduce the packet loss ratio and increase node lifetime. It coordinated nodes awake period and transmission period, based on their location in the network. Further, in the scheduled sleep/wake up scheme nodes developed a previous knowledge about the time expected for the arrival of neighbours packets, which need to be forward toward the sink. In addition, the proposed method allowed the nodes to forward their data at the end of the hopping process rather than sending it first, as in the asynchronous or synchronous scheme, to minimise packet collisions. The measurements show that the proposed method offers better performance over the conventional sleep/wake up approaches. The packet loss decreased to 1.7% for the route consisting of 7 hops while network operation time is extended to 39 hours. The Scheduled sleep technique can be utilised in SB-WSN applications to support a multi-hop scenario, inside or outside spaceship for surveillance and space weather monitoring.

All the measured data assume that nodes are required to transfer sensed data and forward it in a 30 seconds maximum duty cycle, expanding the duty cycle will reduce the amount of data collected in the first experiment when the nodes were always in active status. Also, develop more packet loss while applying asynchronous sleeping methods. In contrast, it will increase network operation time in case of using synchronous or the proposed scheduled scheme.

5 Topology Control Effects in Power Behaviour of SB-WSN

5.1 Introduction

Measurements of network lifetime of a novel sleep/wake up scheme introduced in the previous chapter show that the system disconnected due to the bottleneck problem. This issue appears when the traffic is concentrated towards a small number of nodes in the network which are located near the sink. Topology control technique will be examined in this chapter to enhance network power efficiency.

5.2 Topology Control by Increasing Near Sink Node Density

This research investigates the power behaviour in a situation where nodes have a limited number of neighbours. As the network was designed to monitor a predefined area, it was assumed that the node sensing coverage is the same as its communication range. Full details of network setup and the reasons behind network configuration are presented in Chapter three. The measurements results in Section 4.3.5 reveal that node residual battery imbalance occurs because nodes have a different inactive sleep period which led to energy holes in the network. Also, the bottleneck zone was in the first row where nodes die sooner. Several techniques to cope with bottleneck effects were presented in the literature have been reviewed in Section 2.6. In this study increasing node density near the gateway is investigated. The node power consumption, location selection, operation time and transmission range is experimentally evaluated in the following sections.

5.2.1 Network Configuration Adjustment

The network configuration which was used in Chapter four was modified because of the limited number of available nodes, 38 nodes were utilised as sources and the other two configured as repeaters. Nodes number 40 and 8 were displaced and relocated to new places near the sink to work as R1 and R2, Figure 5.1 shows the adjusted SB-WSN configuration. Their location was selected to give them the transmission range ability to act as a bridge between the gateway and nodes 10, 18 and 26. This will maintain the network operation after nodes 9, 17 and 25 depleted all their battery energy. These devices represent the bottleneck zone nodes in the suggested network configuration.

The repeaters XBee mode of operation has been changed to the transparent mode that makes it behave like a serial line replacement and reduces the time to receive and forward packets. Further, they were programmed with different codes which will make the node work as a pipeline and utilised high transmission power (i.e. 18 dBm) to allow them communicate with the sink directly. Any data sent to the repeater XBee module is immediately forwarded to the remote node identified as the destination (i.e. sink). The repeaters could not create their own data in the transparent mode of operation.

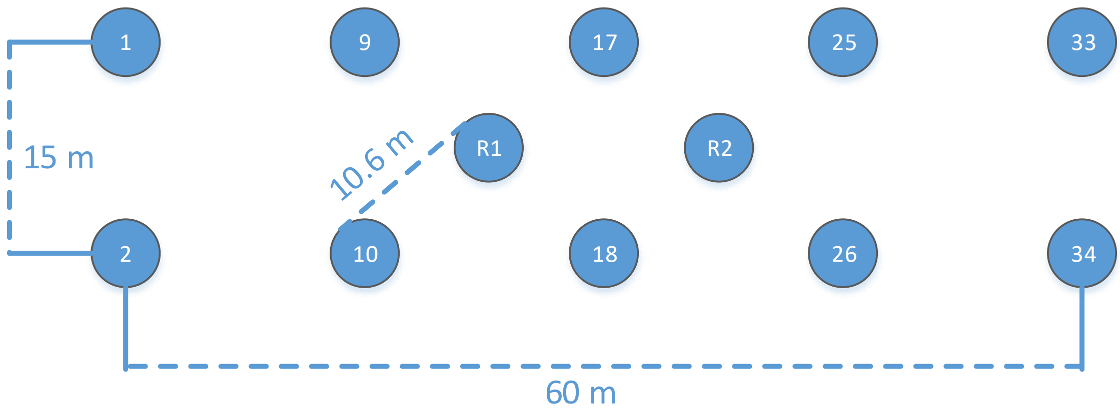


Figure 5.1 Near sink network topology update

Nodes, excluding the repeaters, were programmed using the same coding applied in the proposed scheduled sleep/wake up scheme (see Figure 4.13). However, nodes 10, 18 and 26 had their codes updated to add route fixing through repeaters when the batteries of bottleneck zone nodes power run out. Since node 18 has the ability to communicate with both repeaters, it was configured to utilise both of them, in order to balance the traffic load. On the other hand, R1 and R2 Waspmote internal clock were set to turn on the nodes an hour before the network disconnected time which was estimated from the measurement of scenario 4 (see Section 4.3.5).

5.2.2 Analysis of Experimental Results

Figure 5.2 presents node lifetime at the end of the experiment with applying topology control. The sink keeps receiving data even after bottleneck zone nodes batteries drained after 39.6 ± 0.2 hours. Hence the packets delivered through alternative paths using R1 and R2 repeaters. Nodes 1, 10, 18, 26 and 33 batteries last around 45.5 ± 0.5 hours because they had a bigger sleeping interval than bottleneck area nodes. However, the sensing coverage of nodes 40 and 8 were lost as their function changed to work as repeater.

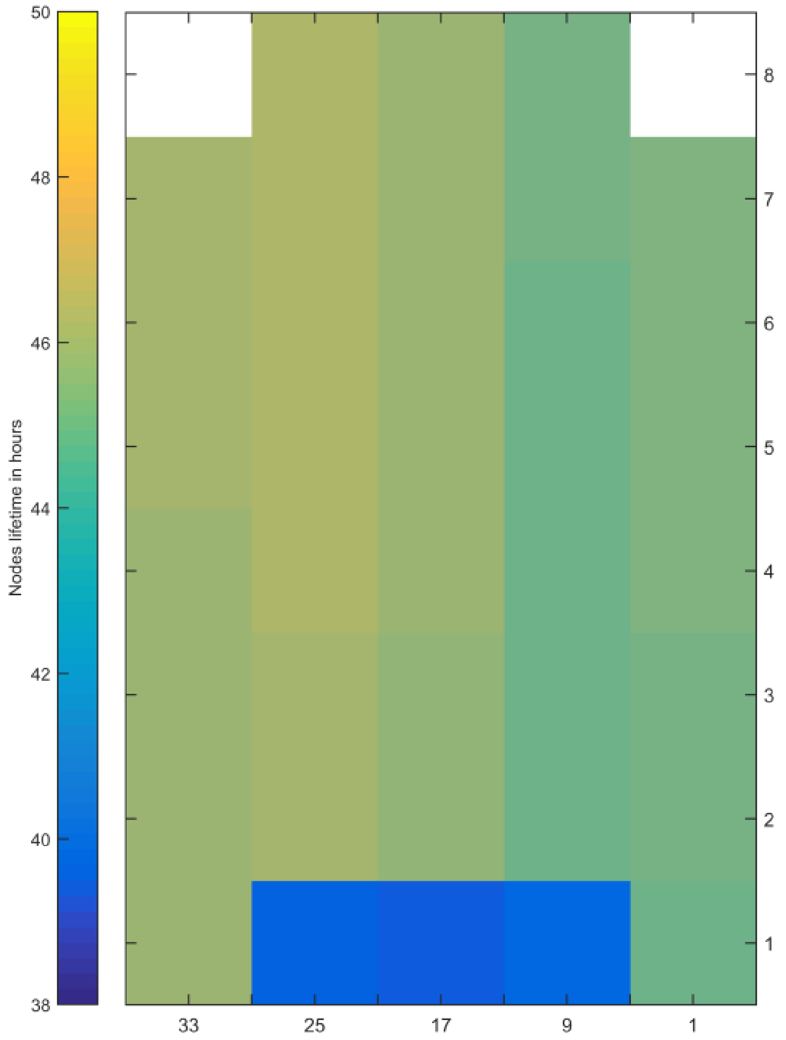


Figure 5.2 Nodes lifetime utilising topology control

Figure 5.3 indicates the packet loss ratio when using topology control to modify network configuration. Nodes in row 8 (i.e. nodes 16, 26 and 32) had slightly more packet loss rates than nodes 7 and 39 because the extra packets lost as their path are longer at the beginning of the experiments. In addition, the route fixing process causes further drops in packets as the nodes before the repeaters will be busy for short time while the others keep sending them data to forward to the sink.

Table 5.1 present average packet loss value in each row at the time when the network disconnected and no more packets were received at the sink. The packet loss ratio values increase as the path become longer. Nodes in row eight have the maximum data drop around 1.96%, and each row has a small variation with the highest value 0.3 at rows 3 and 5.

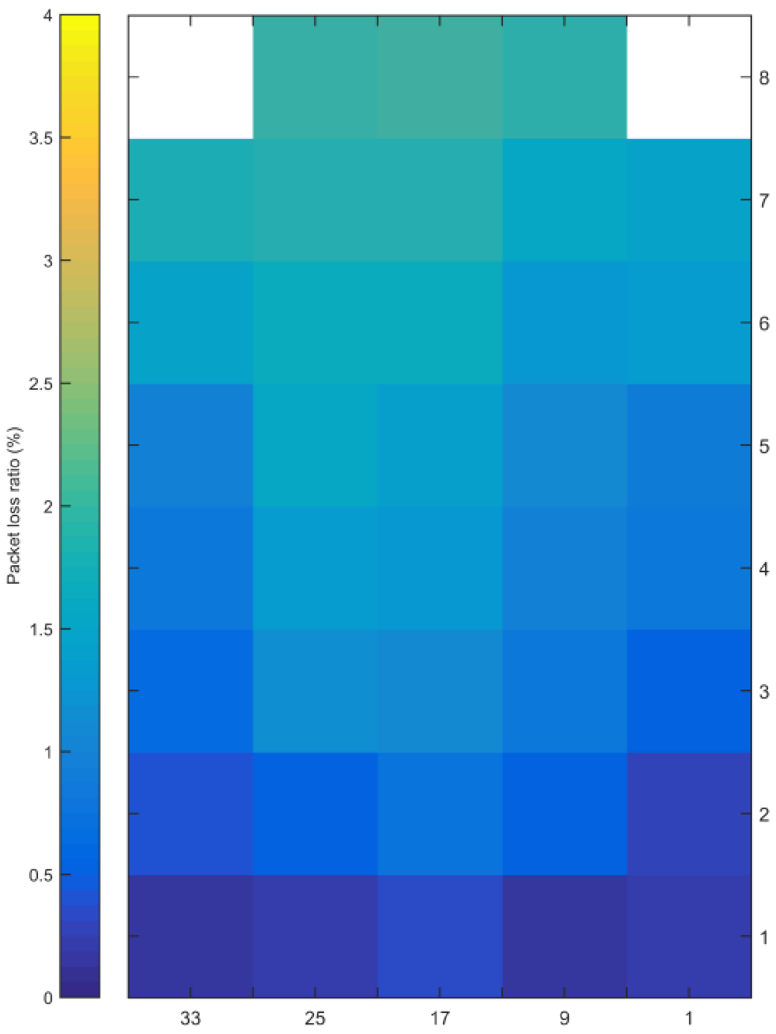


Figure 5.3 Nodes packet loss values using topology control

Table 5.1 Average of nodes packet loss ratio in rows using topology control

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	0.21 ± 0.08	0.5 ± 0.2	0.86 ± 0.3	1.04 ± 0.2	1.19 ± 0.3	1.48 ± 0.2	1.67 ± 0.2	1.96 ± 0.05

5.3 Topology Control and Maintain Sensing Coverage

As seen in section 5.2, adding repeaters to the SB-WSN improves node lifetimes, but bottleneck zone nodes stop working earlier than others causing a drop in the sensing coverage. One solution to this problem is to balance the traffic load between nodes near the sink, including the repeaters. In this section, an experimental investigation was undertaken to preserve sensed data and expand node lifetimes for near sink node (i.e. nodes 9, 17 and 25). The same experimental arrangements were adopted from Section 5.2. Bottleneck zone nodes were programmed to change the XBee setting from router to end device when their battery level went lower than 10%. Also, these nodes switch to low power operation, as they only send their sensed data and then go to sleep. Other network nodes will send their packets through the repeaters which will be programmed to be active before that time. Figure 5.4 plots SB-WSN nodes' lifetime while they were utilising Topology Control (TC) and Load Balance (LB).

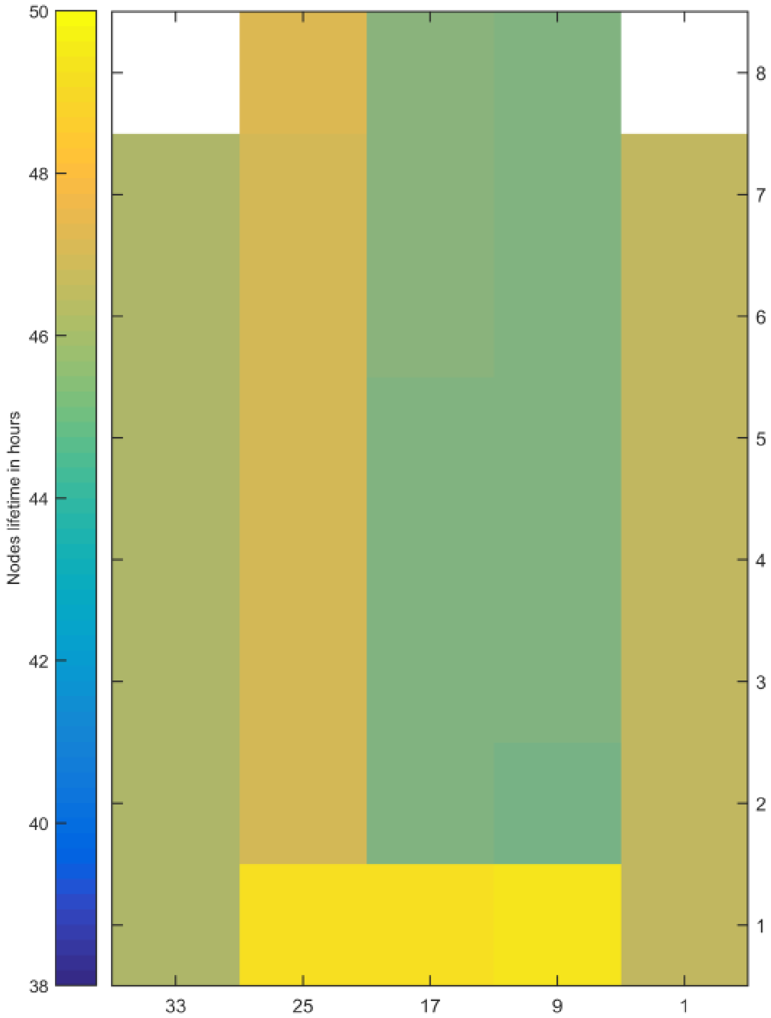


Figure 5.4 SB-WSN node lifetimes values employing TC and LB

The measurement show that bottleneck zone nodes existence periods were extended to 49.15 ± 0.2 hours which meant sensing coverage was maintained. While nodes numbered 1, 10, 18, 16 and 33 batteries' run out of power after 46.1 ± 0.8 hours, this slight difference in their lifetimes due to the inequality of batteries full charging level at the beginning of the experiment. Also, nodes located far from the gateway (i.e. rows 3, 4,…,8) couldn't deliver their packets to the sink after 46.1 hours because of the network partition, and the gateway became out their transmission range. The packet loss values are indicated in Figure 5.5 and Table 5.2.

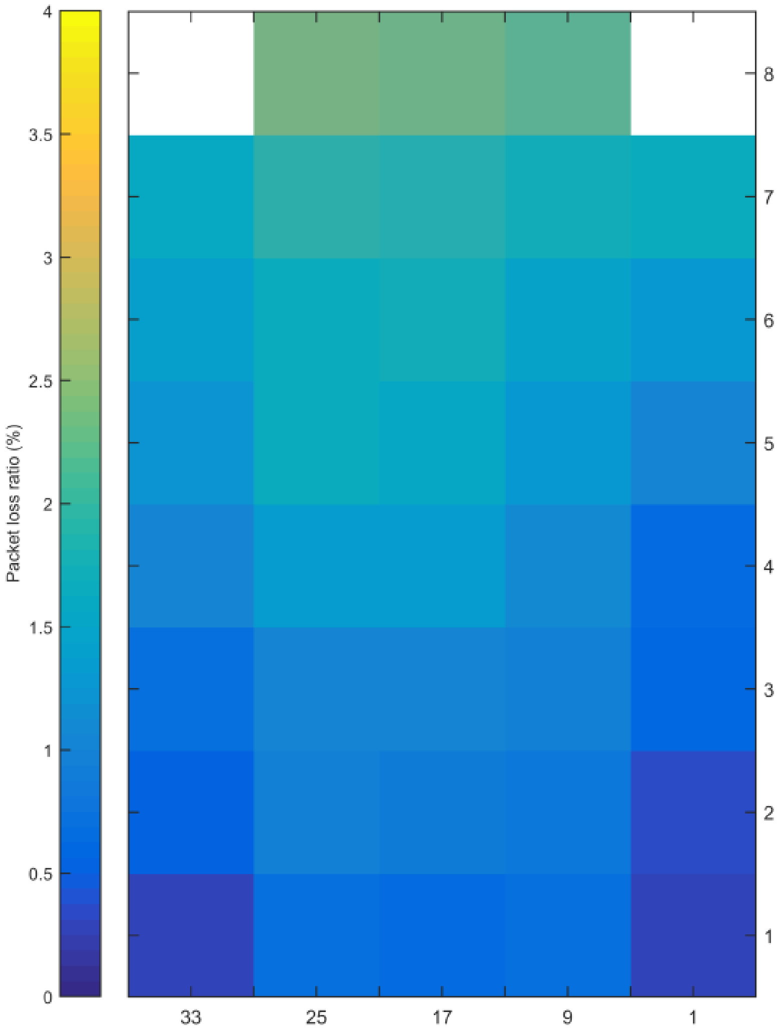


Figure 5.5 Packet loss values by node applying TC and LB

Table 5.2 Average packet loss values for nodes in rows employing TC and LB

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	0.52 ± 0.2	0.73 ± 0.3	0.87 ± 0.2	1.1 ± 0.3	1.34 ± 0.2	1.51 ± 0.2	1.73 ± 0.1	2.32 ± 0.1

The measurements in Figure 5.5 show that the packet loss is higher for nodes located farther from the sink since the path will have a more intermediate nodes. Nodes 16, 24 and 32 had the larger packet loss percentage because at the beginning of the experiment they were using longer paths. Also, they have slightly more packets lost 2.32% (see Table 5.2) than the previous scenario 1.96% (see Table 5.1) because they were utilising the repeaters sooner and that causes more packet loss since two paths used the same repeater.

SB-WSN adopting topology control and load balance enhances node lifetimes and maintain sensing coverage by balancing the traffic between nodes. Although, some packets have been lost through the experiments when the SB-WSN only employ TC or both TC and LB, the packet loss is still small compared to the conventional methods tested in Chapter 4.

5.4 Measurements Comparison and Results Discussions

The outcomes of the experimental investigations of implementing topology control and load balance were compared to the result of sleep scheduling introduced in Section 4.3.5. The total number of the delivered packets to the sink is presented in Figure 5.6. The gateway has received more data as the repeaters used to establish alternative routes. Also, the time of experiment selected to activate the repeaters (i.e. R1 and R2) affects the amount of delivered data. In the first experiment, the repeater activated and used after the paths were broken which led to 9.5% more packets received in the gateway in compared to employing only scheduled sleep scheme. On the other hand, in the second experiment, 12.2% extra packets were collected when R1 and R2 were set to turn on earlier as bottleneck zone nodes started to act as end devices.

This increment in the total number of delivered packets comes from the lifetime extension of bottleneck area nodes (i.e. nodes numbered 9, 17 and 25). Further, nodes 1, 2 and 3 maintain sensing coverage by utilising load balance to switch the traffic toward the repeaters and increase the number of a delivered packet at the sink by 2.5%.

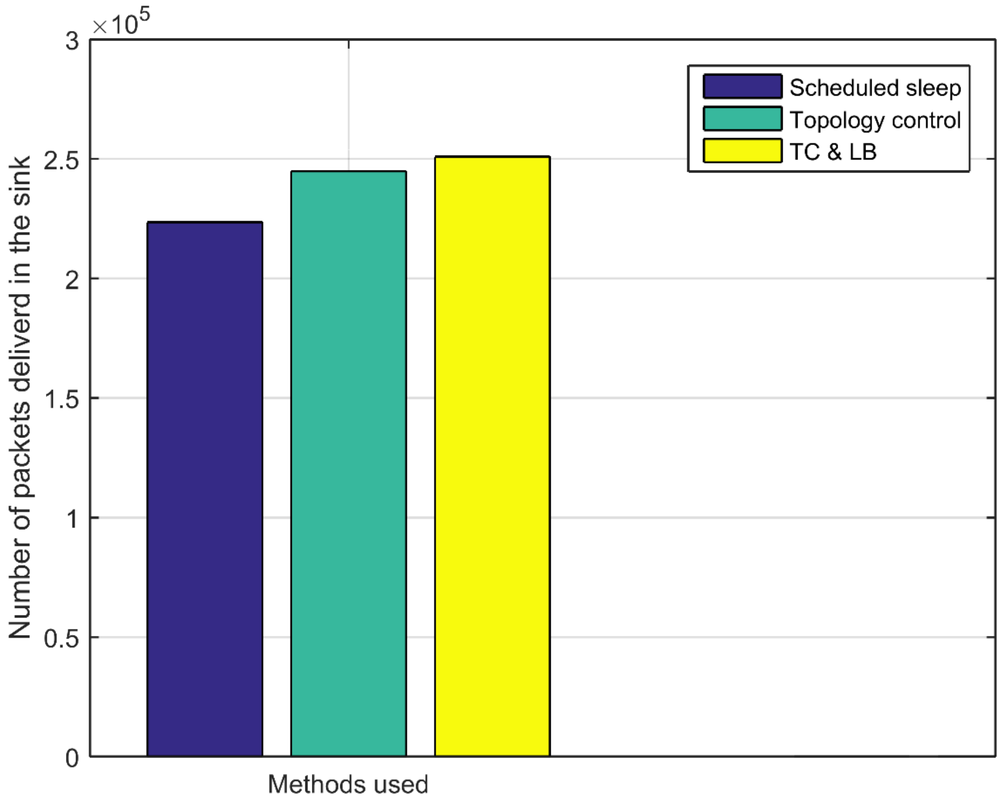


Figure 5.6 Total number of packets received in the sink using TC or TC and LB

Figure 5.7 shows the repeaters' residual battery power at the time of the experiment where the gateway was stopped receiving packets. R1 and R2 stayed online on all their duty cycle because they didn't have the previous knowledge about the packet arrival times. Also, they were busier since more traffic pass through them to the gateway because they supported two paths for around half of their operation period. Therefore, they were using more battery power than a regular node in the network. In the first experiment, R1 and R1 Waspmote internal clock's were set to turn them on after 38 hours from the test beginning time and remained active for 8 hours which cause about 24% reduction in their batteries power level. While in the second experiment, the repeaters active period started after 34 hours after the test starting and remained awake around 13 hours that depleted level their batteries around 48%.

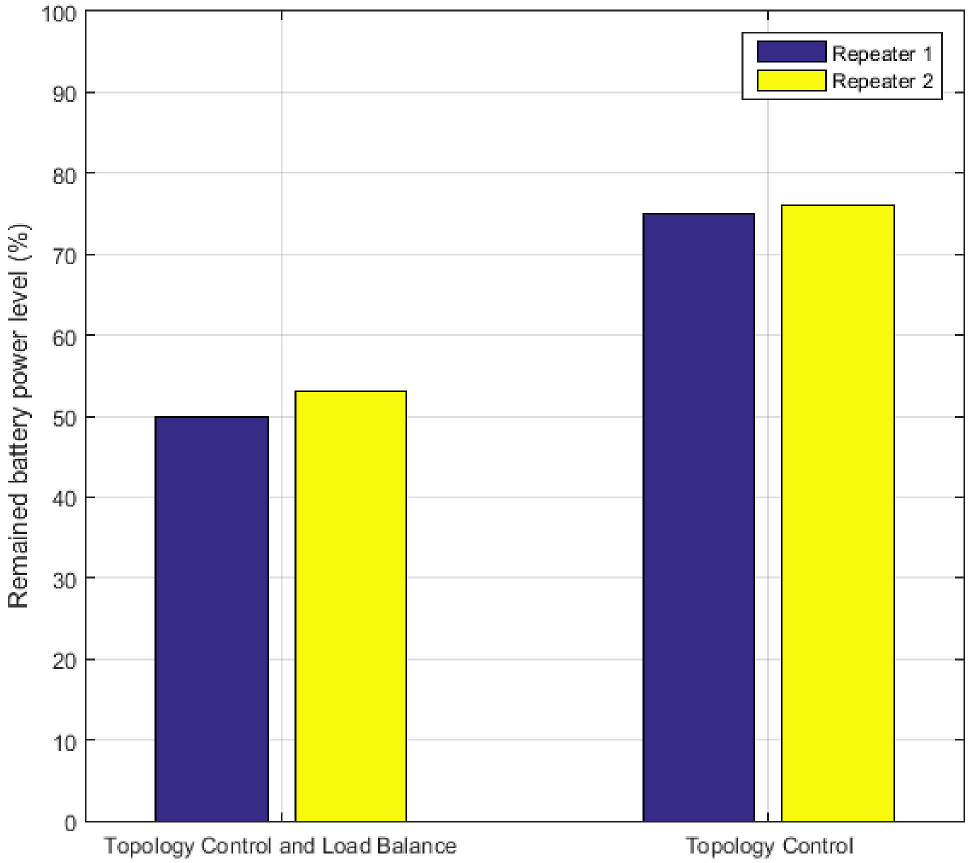


Figure 5.7 R1 and R2 remained battery power level at the end of the experiment

Figure 5.8 compares the effect of the different methods in reducing bottleneck effects on the time during the test when the first node in the network consume all its power and the moment when the network disconnected and the sink stops receiving packets. The minimum node lifetimes for the SB-WSN employing scheduled sleep was 38 hours in comparison to 39 hours while utilising only topology control, so it has slightly changed because the bottleneck zone nodes did not effect by the presence of repeater. On the other hand, using both load balancing and topology control will increase the MNL by 5 hours i.e. the time when the first device from nodes 1, 10, 18, 26 and 33 drained its battery.

The network disconnection time was enhanced by 15% (i.e. 6 hours) of operation compared to scheduled sleep, in the case of adopting TC as the nodes would have additional paths to the gateway when the bottleneck zone nodes batteries run out. The SB-WSN disconnected as nodes 1, 10, 18, 26 and 33 consume all their batteries power and the sink became out the range of the rest network nodes. Adopting both topology control and load balancing achieved 23% (i.e. 9 hours) increase in the NDT in comparison to scheduled sleep. This enhancement in network disconnection time obtained as a result of switching nodes 9,17 and 25 operation function to end device and perform low power duty cycle.

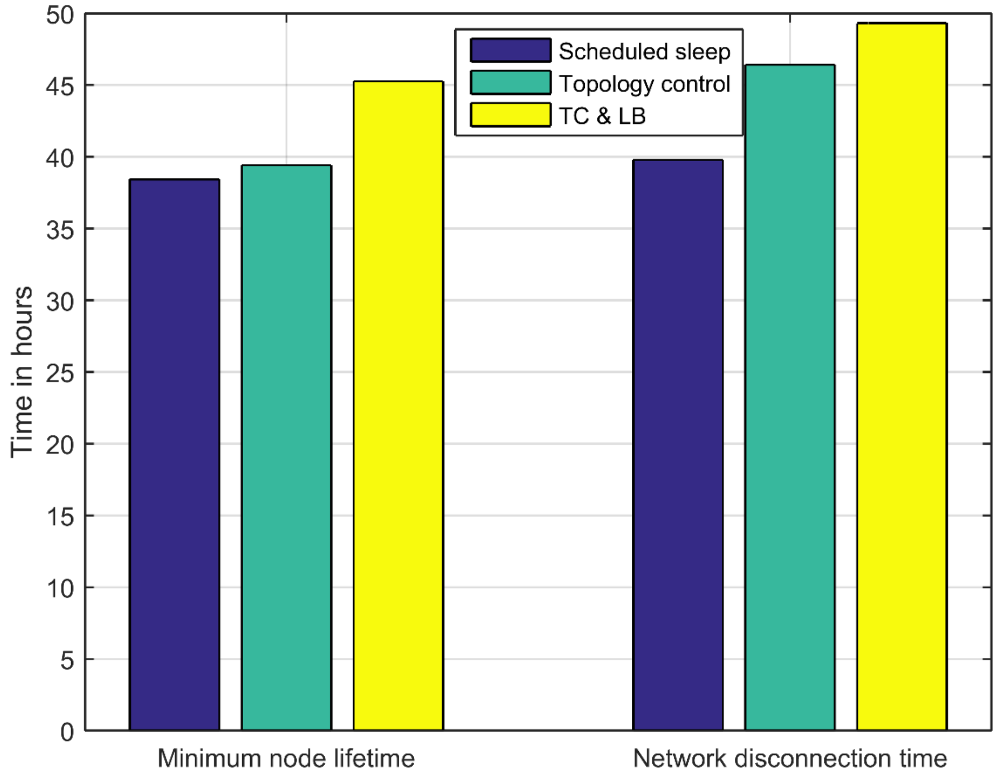


Figure 5.8 Minimum node lifetime and network disconnection time

Figure 5.9 indicates the remaining battery power of SB-WSN nodes at the end of the experiments. It shows the measurement of 40 nodes in scheduled sleep scenario while nodes' battery level of 38 nodes presented in the proposed cases of utilising topology control. The nodes divided in 4 groups according to their battery power level which depends on the node duty cycle. In comparison to schedule sleep method adding topology control mechanism will increase nodes operation time as the paths to the sink were available for a longer period. Therefore, the nodes spent more energy as they were sending more data in constructing and forwarding packets. Consequently, applying topology control resulted in all 38 devices having less than 60% remaining battery power level while 13 devices had battery power level more than 40% at the end of the test.

Also, 14 nodes have 20% - 40% battery power left between and are classified in the second group. The number of nodes had power less than 20% increase to 11 while adopting topology control compared to 8 devices when utilising scheduled sleep due to the additional paths to gateway supplied by the repeaters.

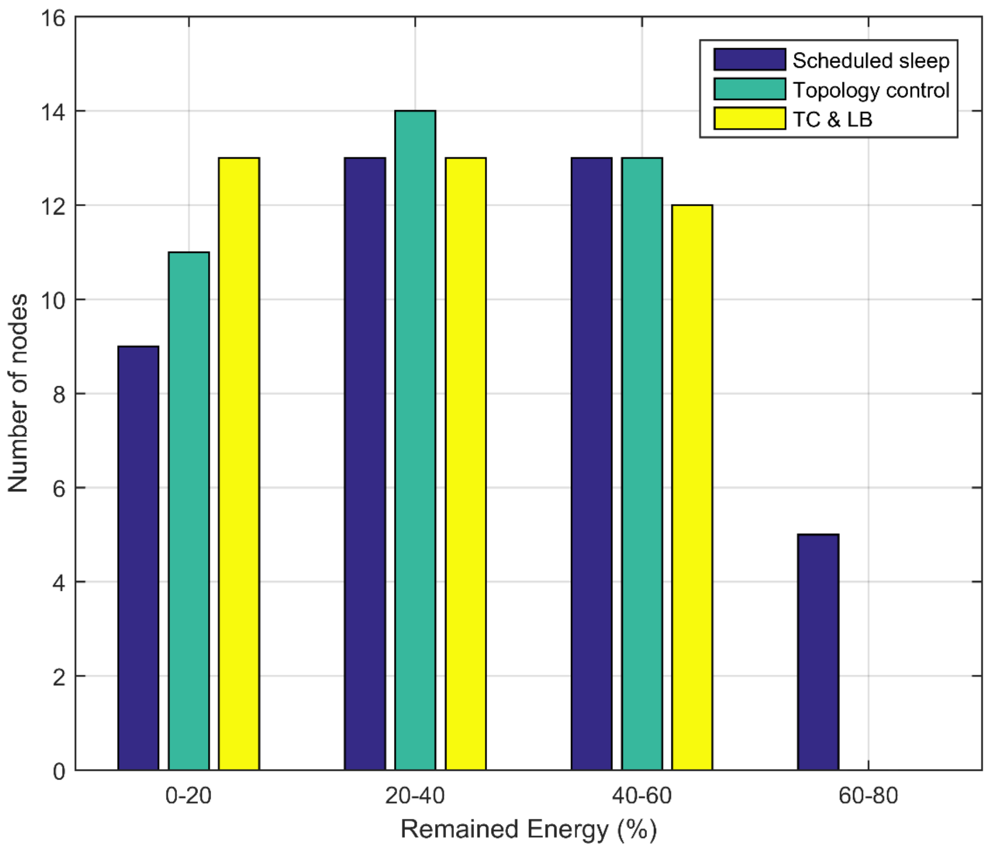


Figure 5.9 Comparison of remaining nodes batteries power level while utilising bottleneck effect reducing techniques

The repeaters required less time to process the packet before forwarding it to the gateway compared to the router nodes. Therefore, less transmission attempts were required to deliver the packet successfully to the sink. In the second test while adopting both TC and LB, nodes 10, 18 and 26 lifetime was slightly longer compared to using TC test because they utilised the repeaters at an earlier time. This allows other network nodes to operate for longer time and spend more energy to create and deliver packets to the sink. In the case of sending the data through the intermediate router, the sender could forward the data and not receive an acknowledgement because the router is busy processing the other packet which means the sender will need to send it again.

Therefore, employing TC and LB resulted in 13 nodes had power less than 20% while 13 nodes having residual batteries less than 40% and 12 nodes were characterised in the third group with power left more than 60%. Nodes' battery power were reduced while applying TC and was reduced compared to scheduled sleep and adopting only topology control.

Provide the repeaters in SB-WSNs near the sink to share the traffic load will increase the network operation time which will enhance the network performance before the network disconnected. At the same time, the increase the network lifetime reduces the node battery power levels at the end of the test.

5.5 Summary

Employing sleep/wake up schemes will lead to an energy imbalance in the nodes. In this chapter, two methods have been introduced and experimentally evaluated. The objective was to prolong the SB-WSN operation time. Section 4.3.5 shows that the sink stops receiving packets while some nodes still had battery power left. Ideally, the packets should be delivered until the last node's battery run out. This is possible in the star configuration but hard to implement in multi-hops situations, as the nodes near the sink will consume more power forwarding the packets of other nodes to the gateway.

The suggested methods help to reduce energy imbalance at the end of the experiment, use that energy to deliver more packets to the sink, and increase node lifetimes. The future implementation of SB-WSNs can use the topology control approach to enhance system performance in the situation where the nodes near the sink have overlaping sensing coverage. Some of these nodes could be sent to low power sleep status, and then activated to replace the devices that have depleted all their battery power. The time to switch on these nodes to act as repeater can be estimated according to the operation and power consumption of devices they are intended to replace. In addition, the location of the repeater devices is a significant factor in enhancing network performance because incorrect positioning can lead to network being partitioned or congestion which causes more packet loss.

The first test shows that the energy consumption and operation of repeaters devices different from the network node as they awake all the time and could not sense their data. Therefore in the second test, the repeaters were activated early to handle the packet traffic allowing nodes 9, 17 and 25 to switch to low power operation and extend their lifetime. Although both tests utilised 38 nodes to collect data and create packets rather than 40 devices while employing scheduled sleep case, the total number of the delivered packets at the sink increased because the 38 nodes remain connected to the gateway for a longer period.

6 Utilisation of Transmission Power Control and the Use of Multiple Sinks in SB-WSN

6.1 Introduction

This chapter presents experimental measurements of the impact of Transmission Power Control (TPC) on node power preservation and overall network performance. The investigation was extended to cover the influence of multiple-sink on SB-WSN energy behaviour.

6.2 Implementing Load Balance by Adopting TPC

The load balancing introduced in Section 5.3 was done by controlling the topology. In this experiment TPC will be used to distribute the data traffic between nodes near the sink. TPC also to enable thed SB-WSN to implement cooperative transmission for the nodes located near the sink.

6.1.1 Experiment Arrangements

The investigation was undertaken at Bruntingthorpe field-site, and the SB-WSN introduced in Section 4.1.3 was used. The XBee Pro chip can transmit data at five different values of transmission power. In the previous experiments, nodes in the first row send their data with highest transmission power (i.e. 18 dBm the reason behind this is discussed in Section 4.3.1) while rest nodes in the network operate with the lowest transmission level (i.e. 10 dBm).

The situation where only nodes near the sink have the ability to perform TPC is considered in this test. The nodes located in rows 1, 2 and 3 of the network were programmed to utilise TPC. The aim was to enhance lifetime of near sink nodes, which will lead to increased network operation time. In order to enable the nodes of two rows to share the packet traffic load, one node should split the traffic between two nodes that they will cooperatively share packets forwarding to the sink. Nodes in row 3 were named “divider nodes” because they will divide the data between nodes rows 2 and 1. They were set to communicate with row 1 nodes with highest transmission power and with row 2 nodes using lowest transmission power. Cooperative transmission was established by allowing nodes in both rows 1 and 2 to communicate with the gateway through setting their XBee to transmit with a higher power.

The Waspmote antenna and ground plane is designed to radiate signal that follows the free space propagation loss (see Section 3.2.3). The free space path loss is given by Equation 6.1. The Waspmote has two setting in TPC: either low transmitting power, allowing it only to communicate with its first tier neighbours or high transmitting power enabling it to send data to the further node as shown in Figure 6.1.

$$FSPL = 20\log_{10}(\frac{4\pi d}{\lambda}) \tag{6.1}$$

where *FSPL* represent the Free Space Path Loss in dB, *d* = distance between transmitter and receiver in meters and λ = 0.1249 m at 2.4 GHz. According to Equation 6.1, if the distance between nodes is set to 15 meters then *FSPL* = 63.6 dB, while if the distance increases to 30 meters, the *FSPL* will increase to 69.6 dB. In order to enable the node to extend its range to second tier neighbours, 6 dB more is needed. The Waspmote was considered to have only two steps of TPC because the difference between the maximum and the minmum transmission power of XBee pro is 8 dB,

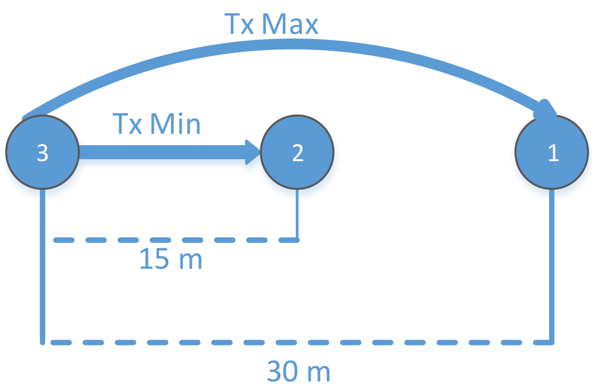


Figure 6.1 Extending node range via using TPC

An experiment including two nodes has been undertaken to observe the power consumption of the nodes while transmitting using high and low TPC settings. At the end of the test, it was found that both of the nodes have the same lifetime because sending in higher power increased the power consumption of the XBee very little. This difference is negligible in comparison to the high energy expenditure in the long active period that is required for coordination, retransmission and to perform CSMA/CA mechanism.

In this chapter, the assumption is that the hopping process will cost more overall network power than using the high-level TPC to communicate with next hop. Also, the link between the nodes in row 1 and the sink is assumed to be established by utilising low transmitting power as the gateway was close by in their first tier neighbours. The SB-WSN nodes were programmed to have an extra active period when they used a high level of TPC to emulate sending with a higher power energy cost. Further, the added active time was set to be less than the time required for the intermediate node to receive and retransmit packets (i.e. the 3 seconds proposed in Section 4.3.5). Estimation of the added active period was based on the operation of divider nodes (i.e. row 3 nodes). In the suggested configuration of SB-WSN and according to the short path Dijkstra deployed routing method algorithm, node 3 forwards the information to node 2 using a low power level while in the next duty cycle, it is required to send data to the sink through node 1, utilising high transmission power. Equation 6.2 was used to calculate the added extra active time:

$$Time\ period\ to\ hop\ packet > \big((\ no.of\ packets\ divider\ sends\ in\ high\ \ TCP) \times added\ time\big)$$

$$3 > 6\ \times\ added\ time,\quad then\ added\ time < 0.5\ second \qquad (6.2)$$

For this experiment, the added time was selected to be 0.333 seconds.

6.1.2 Measurements Analysis and Results

The node lifetimes mapped into node position are shown in Figure 6.2. Using TPC has increased the nodes' ranges which led to row 2 nodes having the ability to communicate with the sink. The cooperative transmission was implemented in the test to balance the traffic among nodes located near the sink. The divider selects the next hop which was a node located either in row 1 or row 2 to forward the data through to the sink. In such situation, the nodes in rows 1 and 2 had two different duty cycles: busy duty cycle when it is required to act as an intermediate node, and low activity one which used to send only the node's own sensed data. Consequently, it's sleeping period will increase which will lead to enhancing its energy performance. However, row 3 node power efficiency decrease in compared to the energy efficiency obtained by adopting only scheduled sleep scheme since it spent extra power utilising high-level TPC. Therefore, nodes of row 3 consume their battery power first and their average lifetimes is 49.45 ± 0.5 hours while other nodes batteries have some energy left at that point, but the experiment ended due to energy gap appearing in row 3.

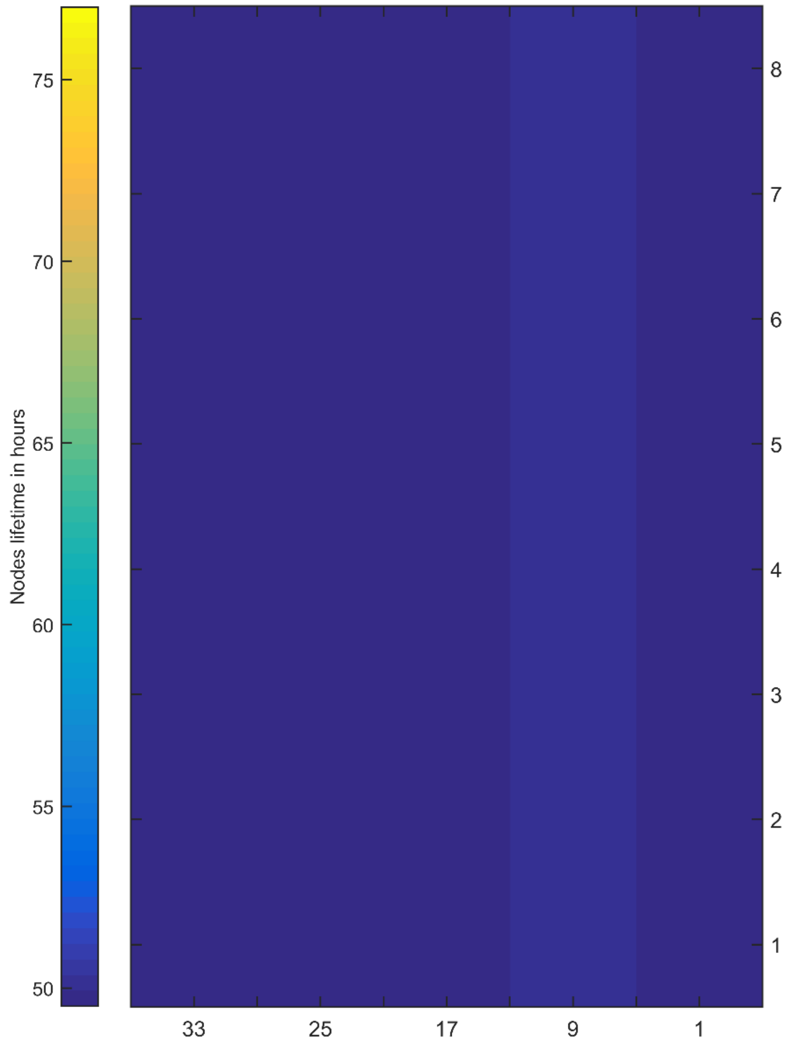


Figure 6.2 SB-WSN node lifetimes adopting TPC and cooperative transmission

Packet loss ratio was plotted in Figure 6.3 while Table 6.1 presents the average packet loss ratio of the nodes in rows. Distributing the traffic between two different destinations required changing the address of next hop at each duty cycle and the coordination to ensure that the destination was awake before forwarding the packets toward it. Also, the route length depends on node's location and having a long path of several hops increases the chance of dropped packets. For these reasons, row 8 nodes had the highest average packet loss. While nodes in rows, 1 and 2 which had a direct link to the sink, have a lower average packet.

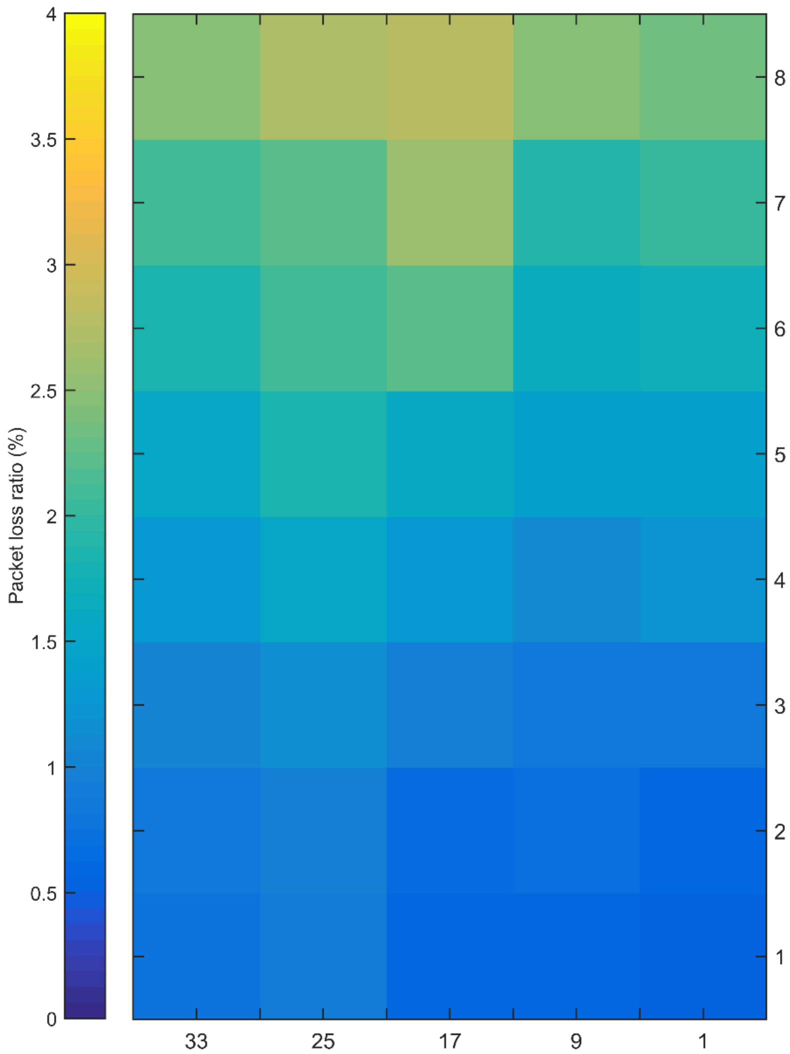


Figure 6.3 Nodes packet loss applying TPC and cooperative transmission

Table 6.1 Average packet loss ratio of nodes in rows using TPC and cooperative transmission

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	0.67 ± 0.1	0.76 ± 0.2	0.97 ± 0.1	1.27 ± 0.1	1.55 ± 0.2	1.91 ± 0.2	2.18 ± 0.3	2.55 ± 0.2

6.3 TPC Usage Effects in SB-WSN Performance

The power behaviour of the nodes was investigated in this experiment where all nodes in the SB-WSN have the ability to perform TPC. Further, the neighbour's lists of nodes were extended as the node transmission range increased from 15 to 30 meters. The procedure presented in Section 4.3.5 was adopted, and additional modifications used to ensure load balancing as some nodes, such as node 19, had more than one possible route to the sink (i.e. nodes 17, 18, 10 or 26). A time slot was set for the setup phase of odd rows (i.e. rows 1, 3, 5 and 7) while nodes in even rows were in sleep status. The procedure was repeated but in the second time slot, activating the nodes in even rows and seting odd rows to inactive mode.

Figure 6.4 shows the node lifetimes obtained by applying TPC. Row 1 nodes had a mean lifetime of 67.88 ± 0.8 hours which represent the odd rows of SB-WSN nodes operation. On the other hand, even rows nodes had a service time average of 68.36 ± 0.9 hours when row 2 nodes' batteries run out. Increasing Waspmotes range led to reducing the number of hops along the route. For instance, node 8 route passes through only nodes 6, 4 and reach the sink through node 2 while without TPC its path includes all nodes from 7 to 1. SB-WSN node lifetimes increased since the sleep period expanded as nodes would have a less active duty cycle. Near sink nodes (i.e. rows 1 and 2) consumed more battery power rather than the other rows nodes because they had a busy extended period of their duty cycle. Hence they needed to retransmit packets of other nodes to sink which led to using higher TPC level more frequently.

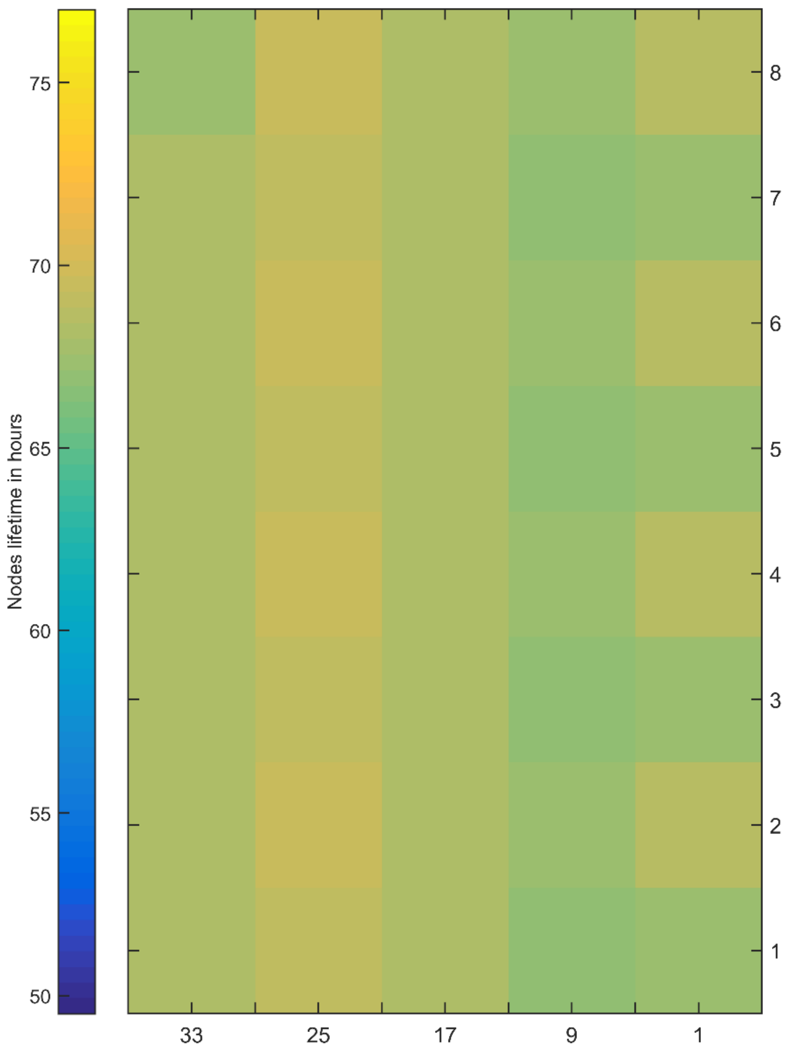


Figure 6.4 SB-WSN node lifetimes adopting TPC

Figure 6.5 presents SB-WSN packet loss utilising TPC while Table 6.2 shows the mean packet loss values of by row. Packet loss increased gradually moving from the sink towards the end of the network. Nodes located in rows 8 and 7 have the highest packet loss of 2.97% and 2.88%, respectively (see Table 6.2). Hence, their routes toward the sink consisted of more intermediate nodes than other rows' nodes. The mean packet loss values for nodes in row 5 nearly the sameand that in row 6 because they had the same number of hops along their paths.

Although, in this experiment, all nodes in rows 1 and 2 had a direct link to the sink, the average packet loss in rows 1 and 2 had 0.33% extra packets drop in comparison to measurements from Section 6.2. This additional packet loss occurs because of the simultaneous transmission from both rows to the gateway while using a higher transmission power to extend the range. It has been stated before that the nodes routing tables configuration was constructed in a separate time duration, but after the setup period ended, the packets forwarding process started which was carried out through some overlapping period.

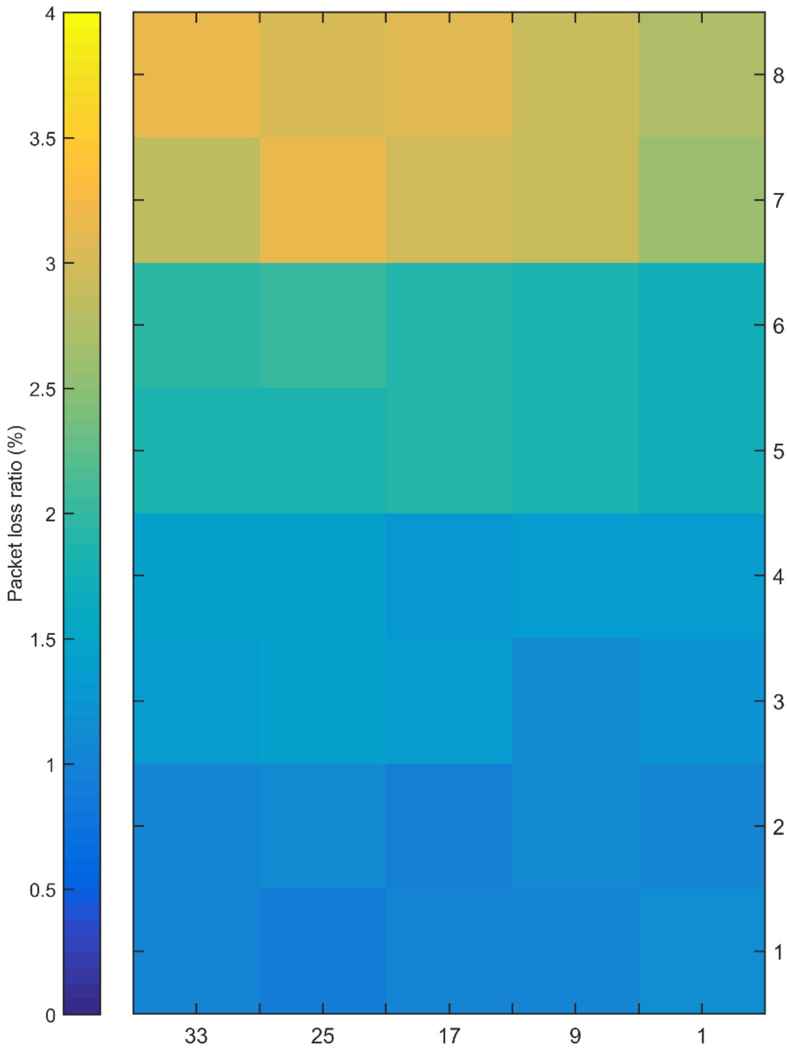


Figure 6.5 Nodes packet loss using TPC

Table 6.2 Average packet loss ratio of nodes in rows utilising TPC

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	1.03 ± 0.09	1.05 ± 0.05	1.27 ± 0.1	1.35 ± 0.05	1.83 ± 0.07	1.89 ± 0.1	2.88 ± 0.2	2.97 ± 0.2

6.4 Investigation of the Effect of Multiple Sinks on SB-WSN Power Performance

The effect of adding an extra sink (S2) to the SB-WSN configuration was experimentally investigated. The second gateway location was selected at the far end of the network as shown in Figure 6.6. Also, its radiation pattern was modified by adopting the as the other nodes structure, in order to reduce its range and prevent remote nodes (i.e. rows 7 nodes) communicating with it directly, so that a multi-hop situation was established and observed. S2 was installed 10 meters from node 24, so that it was out of range of node 23, while it was located 18 meters from nodes 32 and 16, so their XBee transmission power was set to level 2. On the other hand, nodes 40 and 8 transmitted their packets using higher transmission level since S2 was positioned at a distance of 31 meters.

The data collected at S2 was forwarded through a repeater (R1) to the main sink at the hut where the packets were recorded on the computer. R1 was programmed to work as pipe-line using the same coding presented in Section 5.2.1. Also, it was operated without antenna modification because it was defined only to S2 since its position was not included in the nodes location information that stored in each node memory. Further, R1 was installed 1 meter from the ground and equipped with 5 dBi antenna, so it had the sufficient transmission range to establish a direct link to the main sink. Nodes selected their path according to their distance from the sinks, as they had previous knowledge about both sink positions.

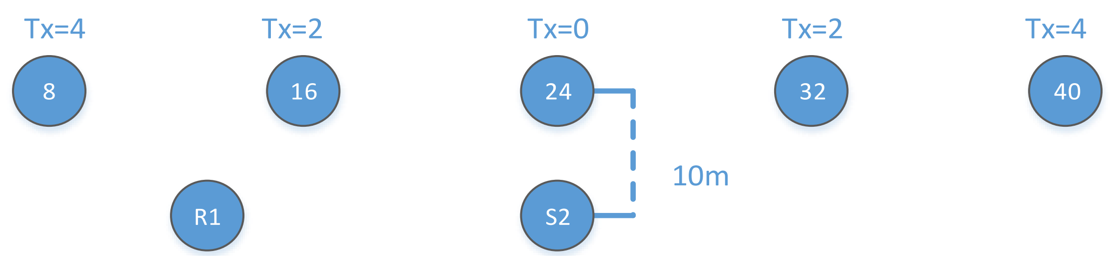


Figure 6.6 a Transmission power of row 8 nodes

Figure 6.6 b On field SB-WSN nodes distribution

Figure 6.6 a and b. Second sink and router location

Figure 6.7 shows the SB-WSN nodes' lifetime in the presence of S2 and indicates that the nodes had an operation time about 75 hours. The existence of two sinks partitioned the network into two sections. For instance, node 8 sent its data directly to gateway rather than sending it through a multi hop path. Accordingly, nodes had more inactive time in their duty cycle which led to longer lifetime. S2 stopped collecting data after nodes in row 8 consumed their batteries after 75.38 ± 0.9 hours. Similarly, row 1 nodes' batteries run out at 75.35 ± 1 hours causing network disconnection for nodes in rows 2, 3 and 4. Including multiple sinks to the SB-WSN reduces the total power required to transfer and deliver the packet to the central gateway that leads to 10.3% increment in network lifetime in comparison to adopting TPC introduced in Section 6.3. In contrast, implementing load balance by utilising TPC, 25.5 hours more of network service were obtained.

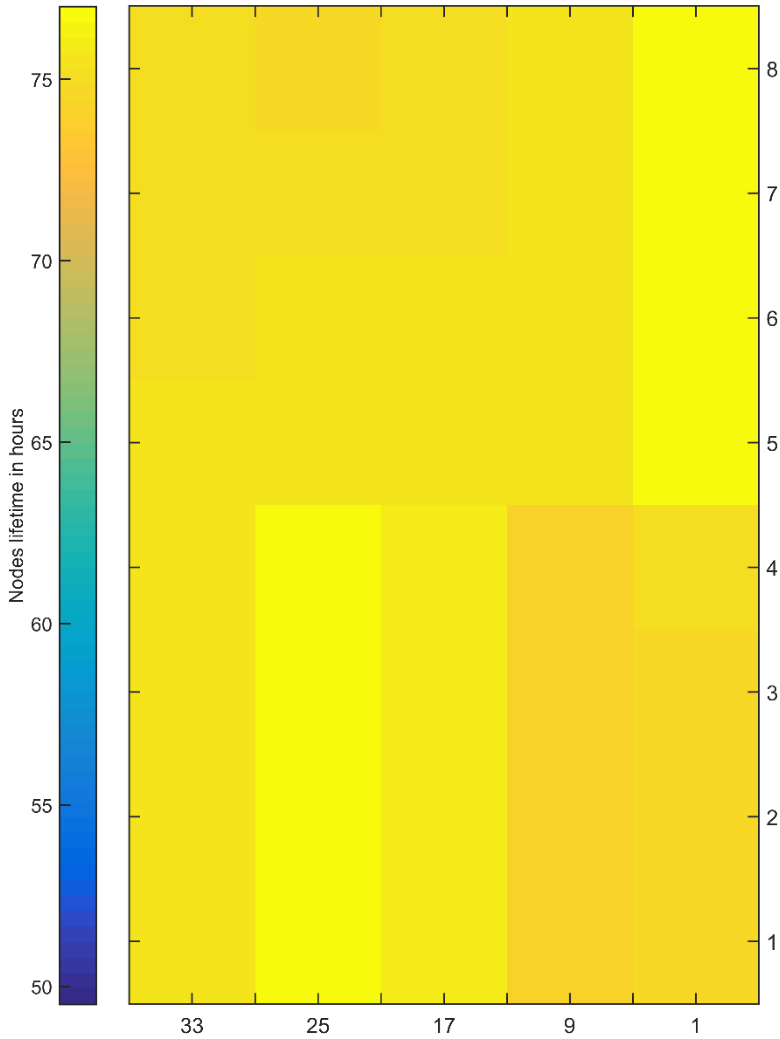


Figure 6.7 SB-WSN node lifetimes applying multiple-sinks

Figure 6.8 presents nodes, packet loss while adding S2 and it indicates that packet loss increased gradually with the distance of the nodes from the sinks. Table 6.3 shows the rows' mean packet loss values, and it signposts that highest packet loss takes place in nodes located in rows 4 and 5 with average packet loss about $2.71\% \pm 0.1\%$ and $2.96\% \pm 0.2\%$ respectively because they had the longest path in the network. The mean packet loss for rows 1and 2 are similar since they both had a direct link to the gateway. The reason that the repeater forwards the data collected at S2 to the main gateway at the hut causing packet collision as 5 other nodes sending their information to the gateway at the same time.

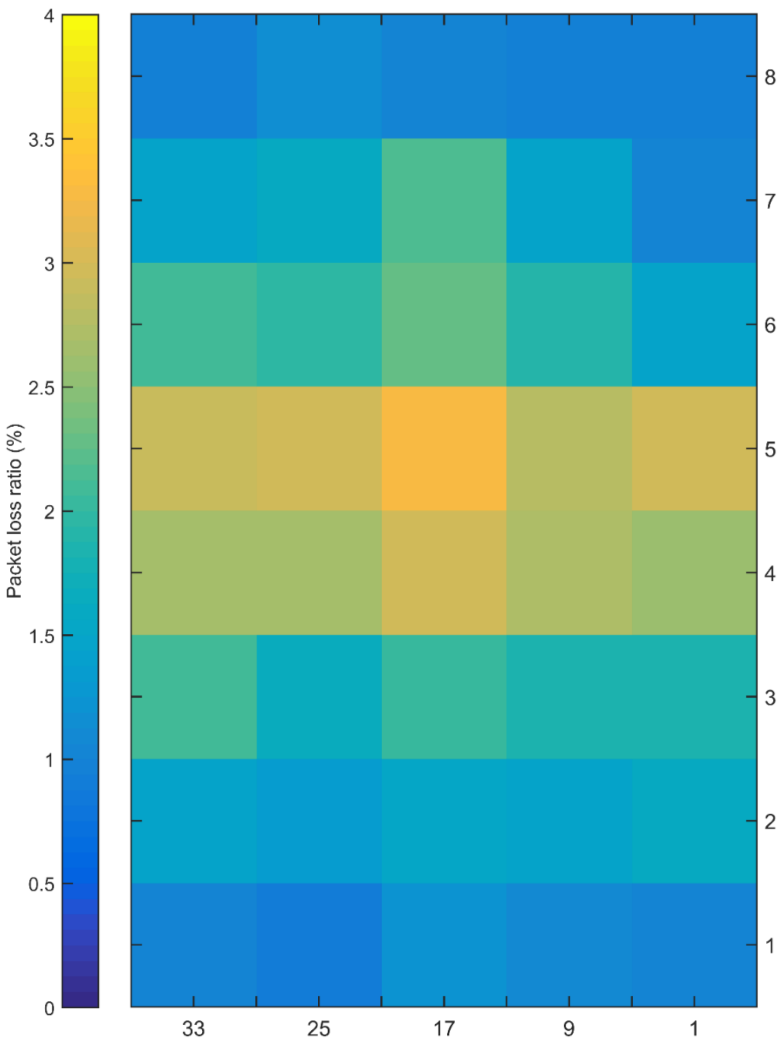


Figure 6.8 Nodes packet loss implementing multi-sinks

Table 6.3 Average packet loss ratio of nodes in rows employing the second sink

Rows number	1	2	3	4	5	6	7	8
Average packet loss ratio (%)	1.05 ± 0.1	1.49 ± 0.08	1.91 ± 0.2	2.71 ± 0.1	2.96 ± 0.2	1.94 ± 0.3	1.54 ± 0.4	1.01 ± 0.07

6.5 Measurements Comparison and Results Discussion

Figure 6.9 indicates the total number of delivered packets at the main sink from the scheduled sleeping technique (see Section 4.3.5) and all the proposed methods to reduce power consumption presented in this Chapter. In comparison to the outcomes from the scheduled sleeping scheme, balancing the traffic using TPC (i.e. LB & TPC) obtained 25% increase in the total gathered packets at the sink. In the case where all SB-WSN nodes utilised TPC, the network achieved 72% more packets collected by the gateway. While using dual sink offered 90% more packets at the central gateway because the SB-WSN divided in two sub-networks that minimise the power required to transfer the packet from its source to the destination. Although, the approach suggested applying TPC in SB-WSN split the network into two groups, it delivers 10% fewer packets compared to dual sink mechanism due to the energy cost of using higher transmission power. Minimising the nodes energy expenditure led to extended network operation which increases the amount of delivered information.

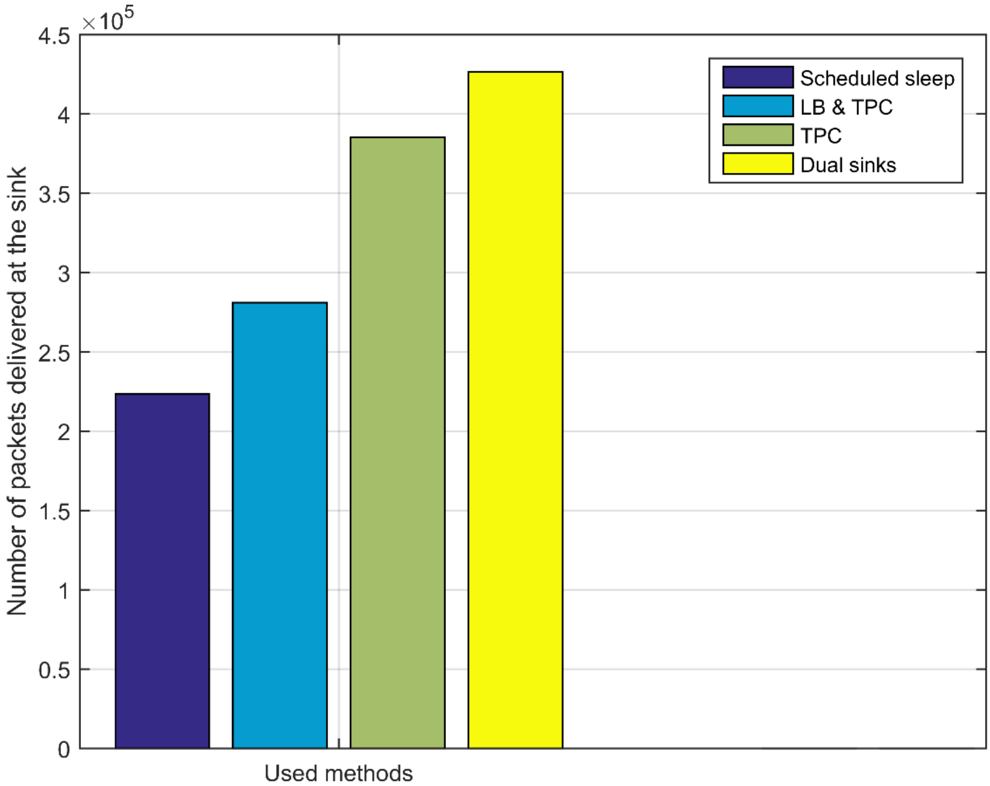


Figure 6.9 Total number of packets received by the primary sink for the various techniques implemented

Figure 6.10 shows a comparison of the time in the experiment when the first node's battery run out, and the last time the sink received any packets. In comparison to scheduled sleep method, adding a second sink to the SB-WSN extended the network disconnection time by 37 hours because the nodes had a shorter active interval in their duty cycle period. In contrast, utilising TPC technique improved the network disconnection time by 30 hours due to increasing the node range which reduces the number of hops along the paths. While adopting TPC to determined near sink load balancing (i.e. LB & TPC) achieved extra 10 hours of network operation.

Nodes in rows 1 and 8 have shared the transmission to the gateway in the dual sink test. While nodes in row 1 and 2 act as the last hops before the gateway in the scenario of applying TPC. Since nodes in these rows had the busiest duty cycle, so one of them is usually the first node to deplete its battery power, and the network will disconnect when all of them have consumed all their batteries energy. Figure 6.10 shows that the minimum node lifetime values for the dual sink and TPC were 74 hours and 66.7 hours respectively. On the contrary, the network disconnection for the dual sink was 77 hours and 69.7 hours in the case of using TPC. The difference between MNL and NDT was 3 hours which occur because of the inequality in batteries fully charged level at the beginning of the experiments of that 10 nodes. On the other hand, the number of high traffic load nodes reduced to either row 1 nodes while utilising scheduled sleep or row 3 nodes in the case of adopting TPC to provide load balance. From Figure 6.10 MNL and NDT were 38 hours and 40 hours respectively in the first scenario, whereas they were 48 hours and 50 hours for adopting TPC and LB, so the difference between parameters was 2 hours.

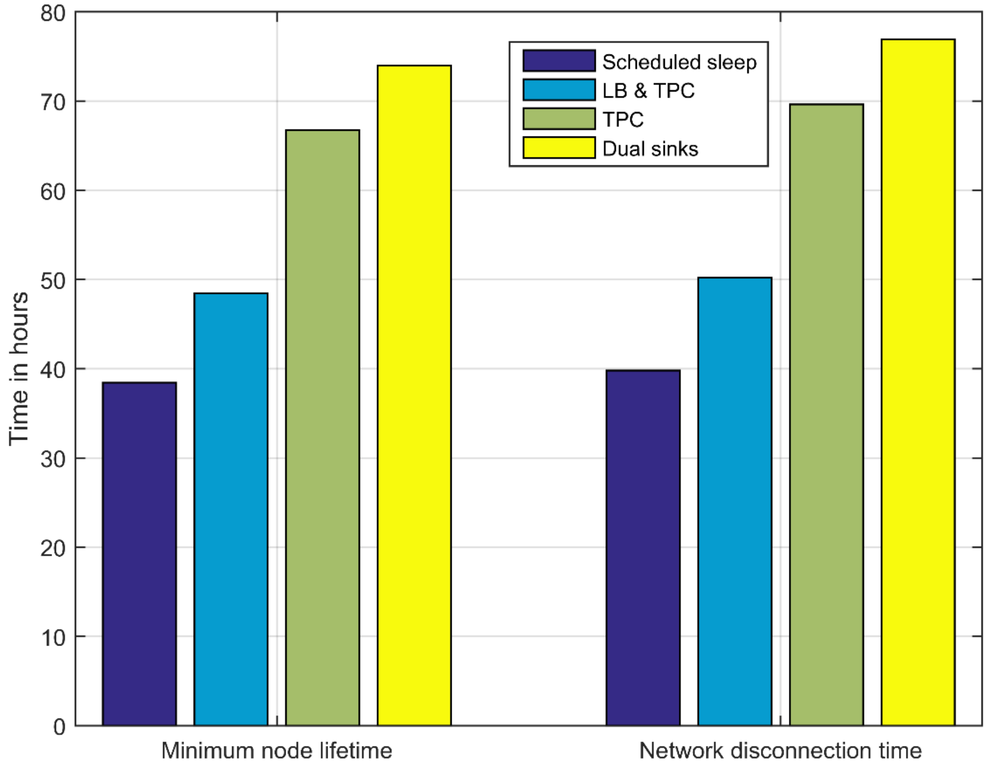


Figure 6.10 Minimum node lifetime and network disconnection time

Figure 6.11 shows the remaining SB-WSN nodes' battery levels after the network disconnected in the experiments. Nodes are classified into four groups according to their residual energy. The proposed scheduled sleep method improves the SB-WSN but creates energy imbalance between the nodes. These values had changed when the network was applying dual sinks due to increasing the network operation time, which makes 19 of SB-WSN nodes batteries power less than 40% and at the end of the experiment. In contrast to 21 nodes in the same group results adopting TPC and LB or TPC only. Meanwhile, the percentage of nodes in the first group reduced in comparison to scheduled sleep to 5 nodes when TPC and LB ware utilised because most of the traffic load concentrated in one row only (i.e. row 3). In addition, enabling more nodes to be able to communicate directly to the sink (or sinks in the dual sink case), increased the number of possible paths, but made these nodes consume all their power before the end of the experiment. Therefore, 10 nodes had power level less than 20% at the end of tests using dual sink and TPC.

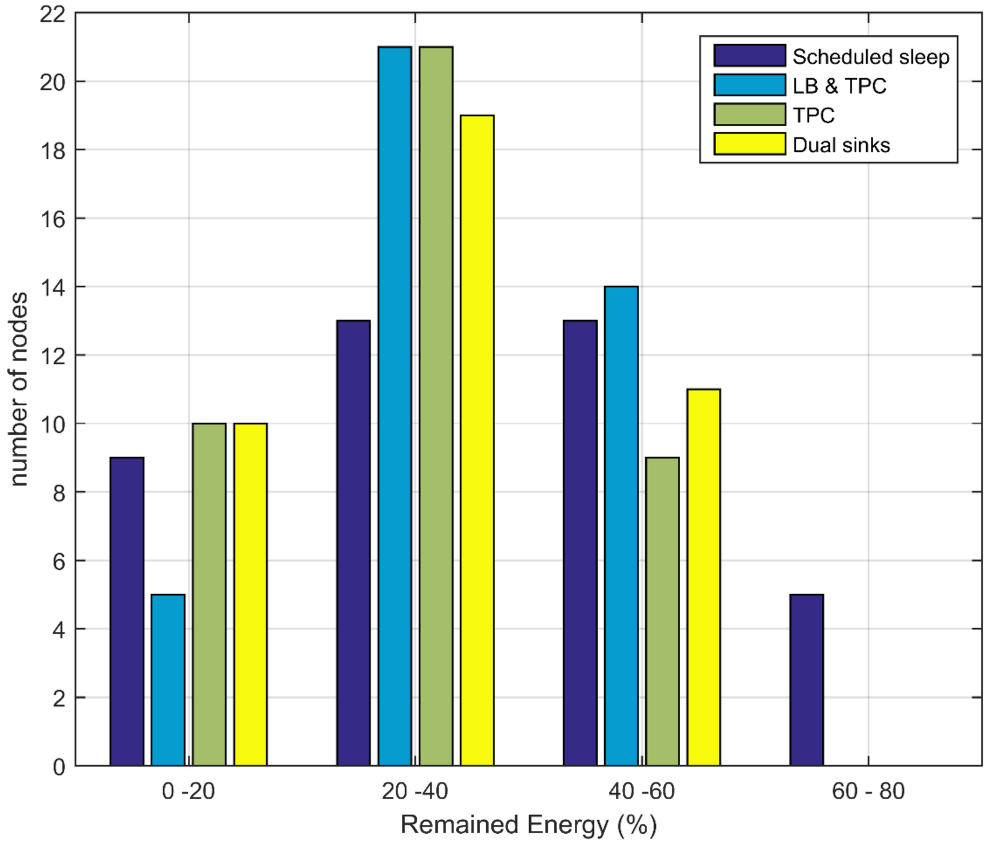


Figure 6.11 Comparison of nodes remained batteries power level at the end of the tests

Adopting TPC in SB-WSN required the nodes to spend more power when using the high setting that reflects on nodes' battery power level at the end of the experiment. For this reason, 21 and 9 nodes categorised in second and third groups respectively, while dual sink had 19 and 11 nodes in the same groups, so more nodes had better battery power level in the second case.

6.6 Summary

In this chapter, several techniques have been investigated to achieve better power performance for SB-WSN. Firstly, TPC was used to establish load balance between near sink nodes (i.e. rows 1 and 2), so they utilised cooperative transmission to reduce bottleneck effects. Also, Equation 6.2 proposed to estimate the extra active time to emulate power cost of employing higher TPC setting in Waspmote. This equation can be utilised to determine whether applying TPC and LB will enhance network lifetime by replacing the power cost instead of the time period needed. The second test investigated the situation where all nodes are adopting TPC. Node lifetimes was increased because the number of hops along the routes has been reduced. The results reveal that employing TPC to reduce energy consumption is a limited in WSN having multiple intermediate routers in paths. The nodes that perform TPC required extra power while using higher TPC setting which will accumulate causing the nodes consume their power rapidly leading to reduced network disconnection time. Accordingly, using TPC to obtain better power performance will depend on two factors; the number of hops along the path and energy cost of utilising higher TPC to extend communication range. Space WSNs can benefit from the TPC by obtaining better performance while the network is disconnected and when required to find an alternative route via increase node transmission range. Also, minimise the congestion by reducing the number of hops in routes. Further, using TPC in WSNs will increase the direct links towards the sink which will enhance network reliability.

The third experiment investigated the effects of providing multiple sinks on the SB-WSN power behaviour. Adding a second sink to the network configuration increased its lifetime and the amount of delivered data. As the network was divided into two subnetworks, the cost of delivering packets from sources to destinations decreased. The implementation of multiple sinks in WSNs requires extra hardware, and a continuous power supply should be available along the networks' lifetime. The SB-WSN will need extra energy which will increase the overall system power budget. In addition, the location of the second sink can affect the power performance of the network. The adopted SB-WSN choice the location of the primary sink to located at the edge of the network in order to investigate the longer paths with up to 7 hops. In addition, the results from Section 4.3.5 shows that at the end of the test the highest nodes' batteries power left were in row 8 nodes because they only needed to send their data and back to sleep. Therefore, the extra sink installed near row 8 nodes. The configuration of planned future space WSNs will control the positions of the gateway, and the location of the added sinks. They could work in master and slave scenario like the implemented SB-WSN in Section 6.4 or all of them act as the primary gateway then the packets collision reduced but extra hardware needed to collect and store the sensed data.

7 Conclusions and Discussions

The current technologies for WSNs mainly rely on simulators to develop an understanding of the network behaviour. A complete idea about WSNs is operation requires in situ measurement where all node parts (processing board, communication module and sensors) are considered. The space application sector of WSNs still less explored and studying the performance of such networks on the ground can provide the network designer with crucial information about the nodes' lifetime and the amount of delivered data. Further examination of the network operating under the situation where all nodes have data to send and some of them need to deliver their packets via multiple hops can help in addressing the deployment issues and reduce the cost. In this thesis, the power performance of SB-WSNs were experimentally investigated. The motivation behind this work was to develop a novel sleep/wake up scheme for space application to enhance the network performance and extend lifetime. The power consumption when communicating is usually the most significant factor that reduces lifetime. Turning the radio communication off while it is not in use can preserve the nodes' power. The optimisation between nodes' inactive period and their network duty as a router is a major challenge that was investigated through experiments in this work.

7.1 Summary and Evaluation of the Results

This work presents several novel aspects:

- Design and testing of a SB-WSN testbed
- Investigate the nodes power performance under various sleep/wake up schemes
- Proposed novel scheduled sleep scheme
- Study the impact of topology control
- Transmission power control utilisation for power minimisation
- Multi-sink implementation

Space-based applications require the design of a robust and reliable system that should be tested and validated before deployment since the system will be far away with no or limited access. Developing a testbed system to investigate the SB-WSN communication on the ground required a modification in these devices antenna radiation pattern to match the channel characterisation to space. Chapter 3 introduces the design of a SB-WSN that builds on one of the Commercial Off The Shelf (COTS) motes. Many research projects demonstrated the utility of these motes in SB-WSNs applications (reviewed in Section 2.1). The antenna modification was implemented by adopting the concept of the monopole antenna. Since it was infeasible to install the antennas on the ground to have infinite size reflector, different reflector size was simulated, and experimentally validated. The results show that using a 1 × 1 m ground plane will reduce the ground reflected energy and establish a system that its radiated signal will follow the free space propagation model while travelling through the channel.

The SB-WSN deployment configuration can vary between star, tree or grid depending on the application requirement. In this research, a grid network configuration was adopted because it represents a general performance of the situation where many nodes try to reach the main gateway through many routes that can relay the data to the ground station. The experiments investigated the scenario where all the nodes are identical, and all of them equipped with sensors and have data to send, in order to make the most efficient use of them. Since even with the introduction of small satellite networks their cost is still high, beside the extra cost of launching and placing them in their positions. The network had 8 rows and 5 columns to study the effect of multi-hop techniques in the node and network performance by implementing maximally achievable hops on the path with the available number of nodes. In addition, it has 5 nodes connected to the gateway to investigate the efficiency of CSMA/CA mechanism in coordinate packet delivery.

The power performance of a network deployed in grid configuration under various sleep/wake mechanisms was studied in Chapter 4. Firstly the scenario of the nodes operational and their communication module always on was investigated. The nodes were programmed to report every 25 seconds while adopting the DigiMesh technique to handle route configuration. The results show that the packet loss increases as the number of hops in the path increased and the last nodes' batteries are exhausted after 31.8 ± 0.4 hours. The packet loss increases proportionally to the reporting rate as attempts to access the channel for transmission will increase and vice-versa. Furthermore, the nodes' lifetime depends on the power budget of the sensors, processor and the communication radio. Decreasing the reporting rate will reduce the power needed for transmission while the energy consumption will stay high due to the power supplied to keep the radio on. This scheme can be adopted in the situation where the nodes have an external energy source such as a solar cell in the space-based applications or the network had a critical event and required to send the data with less latency. Also, to achieve less than 6.6 ± 2% average packet loss, the path should be less than 3 hops from the sink.

The effect of asynchronous sleep was investigated in Chapter 4. The nodes sleep for 20% of their duty cycles asynchronously from their neighbours. The experiments study the case where each node has no more than 4 neighbours. The results indicate that the packet loss will increase compared to the first scenario, as the probability of establishing a path decreases since the nodes will switch off their radio and enter low power mode. Also, the lifetime of nodes up to the third row increased as they can grant a path quickly to the gateway, send their data and enter sleep mode. The packet delivery ratio could be improved by reducing the inactive period part in the duty cycle or increasing the number of neighbours which could be possible in the deployment of a WSN where the sensing range is less than the communication range. Furthermore, the network can utilise asynchronous sleep and add relays with higher transmission range and better power capability that can work as an umbrella, but this solution will add extra cost.

Some applications require a lower reporting rate of the sensed data, so the time between two successive measurements is relatively high. It will be infeasible to keep the nodes on all the time or send them to sleep asynchronously as the overlapping working period will be lower. Therefore, sending the nodes to sleep and synchronously activating all the devices in the network together will achieve better performance. However, setting all the nodes to send their data at the same time will increase the chance of packet collisions, and only nodes near the sink will successfully transmit their data. One possible solution is to activate the nodes at the same time but organise their transmission in the awake period. This technique was investigated in the third scenario (Chapter 4) where the nodes are activated at the same time but are assigned different sending times within the awake interval, depending on their position in the network. The mechanism can be considered as a data gathering scheme which is presented in the literature (see Section 2.5.2), but the synchronous scheme was studied under the situation while all nodes send data. In order to examine the performance of the network while adopting the synchronise sleep/wake up method, the nodes program to activate periodically for 20 seconds and enter sleep mode for 10 seconds then the duty cycle is repeated. The nodes' awake period was set the same as in second scenario to compare the results and answer the question of how will the packet loss percentage change if the sleep interval is increased. Also, an extra node was used to act as a coordinator that was sending the sleep/wake information to the nodes. The results indicate that the lifetime of all the nodes increased because they sleep for a longer period and the packet loss is reduced which is still high (up to 13.5 ± 2% in the fourth-row nodes). The performance of the network can be improved while applying sleep/wake up scheme by increasing the active period and the gap between two sequential nodes transmissions. The estimation of the best time difference can be used depending on the time delay required to accomplished the receiving and retransmission process.

Both synchronous and asynchronous sleep/wake up mechanisms set up all the nodes in the network to switch off their radio for the same duration. A novel sleep/wake scheme was investigated in the fourth scenario (Chapter 4) which suggest a schedules the nodes sleep according to devices position in the network. The Dijkstra algorithm is used to configure the paths from sources to the gateway since each node knows its position and the location of other devices in the network. The proposed scheduled sleep scheme allows the nodes to develop a previous knowledge about how long they need to stay active based on their assigned network task.

To reduce the packet collisions, each node duty cycle consists of an active period where it helps the other devices in forwarding their packets then transmitted the device itself sensed information and enter sleep interval. The result shows that a significant improvement in the packet delivery ratio even in the path with 7 hops, and increases nodes operation time by 8 hours. Scheduled sleep scheme can be considered as a hybrid of the synchronous and on-demand sleep methods. It can support the application with low data reporting rate by extending the sleep period and duty cycle interval. It is applicable for the network with more than 7 hops or with a larger packet size. In that case and to ensure low packet loss, the nodes' duty cycle (DT) should be modified according to the used system capabilities so that DT > (the maximum number of hops × the time needed to receive and to retransmit a single packet).

Hence the nodes near the gateway will consume their battery power faster than other nodes because they stay awake for a longer period since they relay more packets to the gateway. A bottleneck problem will arise as the node near the gateway dies sooner than other nodes in the network. The effect of topology control in improving network performance was investigated in Chapter 5. The network configuration was modified, and the number of nodes near the sink increased. Some of them switched off as they were not needed at the beginning of the experiment and they were activated before the first node in the network consumed all its battery power. The results show 5 hours improvement compared with scheduled sleep scheme in network disconnection time which allows the network to deliver more data to the sink. Also, it indicates that the power consumption of the repeater nodes was higher than normal devices because they were active all the time.

The repeaters were programmed as a pipeline that allows relaying the packet faster but at the same time restricted their ability to create their own data. Therefore, part of the sensed data was lost because some nodes depleted all their battery power and stopped working. An experiment was undertaken to investigate the network performance when the nodes in the last hop switch to low power operation by sending only their data and enter sleep mode once their batteries power were depleted to a predefined level (10%). Consequently, the nodes in the network reconfigured their path and forwarded the packets to the sink through the repeaters. The results indicate a 2.5% increase in the total amount of delivered packets, in comparison to utilising only scheduled sleep. The topology control technique can enhance the network efficiency in the application where the deployment method can provide additional nodes in the area close to the sink. Also, it can improve the network power performance when the nodes had overlapping sensing coverage so some of them can be sent to sleep and activate when needed.

The impact of utilising Transmission Power Control (TPC) is studied in Chapter 6. Some of COTS motes can send their packet with different transmission power to increase the communication range. The usage of TPC in WSN with nodes have paths with multi-hops can achieve lower battery power consumption if and only if the power budget required to increase the transmission range and communicate with second tier neighbours, is less than the energy cost in hopping process. The SB-WSN power behaviour using TPC technique was tested. Firstly, this mechanism was employed to cope with the near sink bottleneck effect. The result shows that the nodes operation time increased by 10 hours in contrast to scheduled sleep the nodes packet loss was with a maximum average of 2.5% ± 0.1%. A further improvement in nodes' lifetime can be obtained if the used motes are designed to consume less power while utilising TPC.

Secondly, the influence of all nodes employing higher transmission power to reduce the number of hops in the path was experimentally investigated. The nodes extend their communication range and neighbours list. They selected the next hop according to which is located closest to the gateway. The result indicates an improvement in node lifetimes as the power budget required to deliver a packet from its source to destination reduced. Also, the nodes operation was enhanced to an average of 67.88 ± 0.8 hours while the packet loss has a highest average value of 2.9% ± 0.1%. The TPC technique is an attractive solution to reduce nodes power consumption, but increasing number of neighbours list will need an additional process to select the next best neighbours, which is solved by dividing nodes into groups and assigning different time slots for the setup phase. Further, this technique will create overlapping in nodes' communication range which will arise interference and packets collision problem.

The second part of Chapter 6, addresses the impact of providing multiple sinks on SB-WSN power behaviour. The network was reconfigured, and an additional sink was added to the system. The result shows that the node lifetimes increased to 75 hours since the routes from nodes to their final destinations were reduced. This mechanism improves node performance, but it increases the overall network power cost, since supplying extra sink to the network requires more hardware and power as that sink needs to stay on all the network operation period. It can be an appropriate solution in a situation where a network is deployed to monitor an area between two spacecraft.

7.2 Future work

There are several areas that could benefit from further investigation. The proposed scheduled sleep assumes that the nodes have the previous knowledge about their locations. This information can be developed using a localisation algorithm and shared that data between nodes using message flooding technique.

The measurements study the situation that all the node in the network identical and have the same battery power at the beginning of the experiment. In the case that nodes have different battery capacity at the start of the network operation, the scheduled sleep can be extended by adding a condition to avoid the nodes with lower battery power in route creation.

Node failure effect on network power behaviour is a great potential for further work, from detection of node failure to finding an alternative path to forward the traffic through. But the biggest potential is in optimising between the packet delivery and traffic balance which can produce better network performance.

The investigated SB-WSN assumes that the nodes are relatively static to each other but in some LEO applications, the satellites suffer from deorbiting and are separated eventually. Therefore, adding node movement to the system can provide better network lifetime estimation.

The concept of experimentally examining the network power behaviour can be extended from the two-dimensional node distribution to three-dimensional node deployment. A simulator which support the access to all level in the OSI layers can be used to provide more tests before the real implementation. Several simulators were checked for their suitability in simulating the tested configurations, but each of them lack some concepts of the experiments which make the results deviate from reality. Table 7.1 offers a comparison of the simulator features.

Table 7.1 Simulators supported features comparison

	Supported features				
Simulators	Duty cycle	Node sleep	Individual node TPC	Routing Protocol	Individual node programming
NS2 (Issariyakul and Hossain, 2011)	Yes	Yes	No	Yes	No
CupCarbon (Bounceur, 2016)	Yes	Yes	Yes	No	Yes
NetSim (Tetcos, 2017)	Yes	No	Yes	Yes	No
OMNet++ (Varga and Hornig, 2008)	Yes	No	No	Yes	No

None of these simulators consider the power consumption of the control board or the sensors. Also, they calculate the power budget per transmission not per packet length, so the energy need for acknowledgement packet is the same of the complete packet with header and payload which is not realistic. Therefore, a computer-based investigation would require bespoke software to be written.

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