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Date : 9-9-2014

UNIVERSITI TEKNOLOGI PETRONAS

AN ENERGY EFFICIENT CROSS-LAYER NETWORK OPERATION MODEL

FOR MOBILE WIRELESS SENSOR NETWORKS.

by

MARWAN IHSAN SHUKUR AL-JEMELI

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AN ENERGY EFFICIENT CROSS-LAYER NETWORK OPERATION MODEL FOR MOBILE WIRELESS SENSOR NETWORKS

by

MARWAN IHSAN SHUKUR AL-JEMELI

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DECLARATION OF THESIS

Title of thesis: AN ENERGY EFFICIENT CROSS-LAYER NETWORK OPERATION MODEL FOR MOBILE WIRELESS SENSOR NETWORKS

I MARWAN IHSAN SHUKUR AL-JEMELI

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Date : 9-9-2014	Date : 9-9-2014

DEDICATION

To my parents, you were the source of this courage that I have to finish this work and to achieve the level that I am in. whatever I do will not be enough to repay for what you did to me through my life. Thank you.

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ABSTRACT

Wireless sensor networks (WSNs) are modern technologies used to sense/control the environment whether indoors or outdoors. Sensor nodes are miniatures that can sense a specific event according to the end user(s) needs. The types of applications where such technology can be utilised and implemented are vast and range from households' low end simple need applications to high end military based applications. WSNs are resource limited. Sensor nodes are expected to work on a limited source of power (e.g., batteries). The connectivity quality and reliability of the nodes is dependent on the quality of the hardware which the nodes are made of. Sensor nodes are envisioned to be either stationary or mobile. Mobility increases the issues of the quality of the operation of the network because it effects directly on the quality of the connections between the nodes.

This research has investigated the field of WSNs and has proposed an operational model that can improve the energy consumption and system throughput of mobile WSNs. The operational model incorporates four major aspects in network operation: Medium Access Control (MAC) protocols, Routing protocols, Mobile node location estimation and Cross-layer operation between network layers. The final outcome of the research is a cross-layer operational model aimed at mobile WSNs. The thesis also includes the following subsidiary outcomes: SEEK-MADP MAC protocol for WSNs, an energy efficient composite routing metric for mobile WSNs and an energy efficient location estimation method for mobile wireless sensor nodes. The operational model has been evaluated using the network simulator 2 (NS2) as the tool of evaluation. The thesis also includes a hardware-based implementation of the proposed location estimation method. The final results have shown that the operational model offers better energy consumption and better system throughput than the standard ZigBee protocol stack, and energy efficient and QoS aware multipath routing (EQSR) cross-layer protocol.

ABSTRAK

Rangkaian pengesan tanpa wayar (WSNs) adalah teknologi moden yang digunakan untuk mengesan / mengawal alam sekitar sama ada di dalam bangunan atau di luar rumah. Pengesan Nod adalah miniatur yang boleh mengesan peristiwa tertentu mengikut kepada keperluan pengguna terakhir. Jenis-jenis aplikasi di mana teknologi tersebut boleh digunakan dan dilaksanakan adalah secara meluas daripada keperluan isi rumah sehingga keperluan berasaskan ketenteraan. Walau bagaimanapun, sumber WSNs adalah terhad. Pengesan nod berfungsi pada sumber kuasa yang terhad (contohnya bateri). Kualiti sambungan dan keboleh percayaan nod bergantung kepada kualiti pembuatan bahan nod. Pengesan nod ini dijangka tetap atau mudah alih. Mobiliti dapat meningkatkan kualiti operasi rangkaian kerana ia mengesan secara langsung kepada kualiti sambungan antara nod-nod.

Kajian ini menyelidik bidang WSNs dan mencadangkan satu model operasi yang boleh meningkatkan penggunaan tenaga dan sistem pemprosesan mudah alih WSN. Model beroperasi menggabungkan empat aspek utama dalam operasi rangkaian: protokol Kawalan Akses Sederhana, Protocol Arah, Anggaran Lokasi Nod Mobile dan Operasi Silang-lapisan di antara lapisan rangkaian. Hasil akhir penyelidikan adalah model operasi silang lapisan bertujuan untuk mudah alih WSNs. Tesis ini juga termasuk hasil kepada bahagian berikut: SEEK-MADP MAC protokol untuk WSNs, rencam cekap tenaga laluan metrik bagi WSNs mudah alih dan kaedah anggaran lokasi tenaga yang cekap untuk mudah alih pengesan nod tanpa wayar. Model operasi dinilai menggunakan simulator rangkaian 2 (NS2) sebagai alat penilaian. Tesis ini juga termasuk pelaksanaan berasaskan perkakas mengikut kaedah cadangan anggaran lokasi. Keputusan akhir menunjukkan bahawa model operasi menawarkan penggunaan tenaga dan sistem pemprosesan yang lebih baik daripada protokol piawai ZigBee dan tenaga yang cekap dan QoS pelbagai arah (EQSR) protokol silang-lapisan.

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CHAPTER 1

INTRODUCTION

Information and communication systems offer wide possibilities of data and knowledge sharing/exchanging between different types of societies. Environment monitoring and controlling is an important operation in the learning process of human societies. Scientists have observed different environmental properties and collected data to deduct a possible pattern or behaviour of the environment under observation. The monitored environmental properties can vary depending on the application and the issue under scope of the observing scientist(s). Monitored property examples are: temperature, humidity, luminance, entity mobility and many more [1].

Communication and computational system development made it possible to construct devices that are small in size, low in energy consumption with communication and data processing capabilities (i.e., small sized computers). Attaching these platforms with sensing capable MEMS creates what can be called a sensor node [1], [2]. To aid scientists in their process of observing and capturing specific environmental events, sensor nodes can be deployed in the required environment to do the required task of monitoring and capturing the required data [3]. Sensor nodes are envisioned to be deployed by the order of several nodes to hundreds and possibly thousands of nodes. With their communication capabilities, it is possible for the deployed nodes to communicate between each other creating groups and networks. The most utilised communication method in sensor networks is wireless communication hence, the term Wireless Sensor Networks (WSNs).

The potential of this technology in terms of applications where it can be utilised is high. Applications can vary in their types for example: controlling an industrial environment [4], household monitoring applications [5], health care applications [6], military based applications [7], social studies applications [7] and the list goes on. The environment where sensor nodes can be deployed is either indoors or outdoors.

All the potential of the applications where WSNs can be utilised and the portability of the sensor nodes come with a price. Sensor nodes are resource constrained, i.e., a sensor node has limited capabilities, such as computational capabilities, communication capabilities and limited power supply choices. The potential life time of the deployed sensor nodes can be in the range of months to a year or two [8]. Table 1.1 below describes the features that typical WSNs have compared to what Wireless Local Area Networks (WLANs) have [6].

Table 1.1: Feature comparison between WLANs and WSNs [6]

Network type	**WLAN**	**WSN**
Density	Sparse	Dense
Data-centric	Address-centric	Data-centric
Large scale	No	Yes
Workloads	Unpredictable	Unpredictable
Error rates	Medium	High
Energy constraints	No	Yes
Hops	Single	Multihop
Infrastructure	Yes	No
Node failure	No	Yes
Deployment	Random	Random

WSNs are considered application dependent technologies because of the limitation in their resources. Application demands can vary between long life operations with high message delays and vice versa. With the dilemma that WSNs have produced, the interest in this field of research has become very high. The range of research interest has varied from hardware-based improvements to application-based interests [9]. According to [8], the research interest in the WSN research field can be observed by the amount of research available in several categories. Some of these categories are listed in Table 1.2 with the estimated levels of interest in each field.

Table 1.2: List of research categories of interest in the WSN field [8]

Research discipline	Literature available
Deployment	Highest
Localisation for WSNs	High
Applications	Medium
Hardware	Medium
MAC protocols for WSNs	Medium
Routing for WSNs	Medium
Mobility	Low
Network models	Low

There are several approaches to improve the lifetime of WSNs by improving the operational and traffic transactions amongst the deployed sensor nodes. Such improvements can be achieved by proposing distributed operational algorithms to deliver the required messages in a balanced fashion. Algorithms for routing protocols, for example, can be optimised to be energy aware to improve the lifetime of the network [10]. MAC protocols aimed for WSNs can be designed to avoid extra charges in terms of controlling the node(s) engaging in the shared medium [11].

Locating the sensor node(s) of interest is considered high priority information for the end user. Therefore, localisation approaches proposed and designed for WSNs need to consider the resource limitations that are incorporated with this technology [12]. Proposals on a variety of aspects are in favour for stationary WSNs because it is easier to predict the overall operation of the network if node deployment is planned and static. On the other hand, mobility in WSNs is an important aspect. Mobility in limited resource WSNs is a challenge that needs to be carefully addressed during the design process of a WSN.

When the nodes are randomly mobile, the topology of the deployed network changes at a random pace. This randomness makes the topography of the deployment unpredictable which then has an effect on the operation of the deployed network on several levels.

For example, a routing protocol in a mobile situation needs to have the ability to choose the best possible route during node(s) mobility. The process needs to be more light weight and easily performed. Whilst MAC protocols are more of a one-to-one relationship in operations, mobility can still have an effect on their operation when engaging the wireless medium. Mobility can create a high number of failed links which then requires the nodes to broadcast control packets at a higher rate than when the nodes are static. Calculating a node’s location in a mobile scenario can become an extensive and exhausting process for the nodes because of the frequent location changes in the network. Mobility is then a challenge with a high effect on many levels of the WSNs’ operations.

From this scope, it has been possible to derive the following points of interest for this research:

- Mobility of the nodes is a challenging issue in sensor networks; the rapid change in the network topology can increase the probability of information loss which requires a fast converging solution to overcome the mobility burden.

- Sensor nodes are envisioned to be deployed in a random number of nodes. A balanced traffic processing is required to avoid congestion and data drop.

- Sensor nodes are energy and Computation constrained. Lifetime is an important issue in WSNs as the nodes are expected to operate for long periods (the order of months).

The major interest of this research has been the mobility challenge in WSNs. Mobile WSNs can increase the types of applications that can be utilised in real life problems. Applications like firefighting, vehicular networks, military tracking, robotic and health care related applications can benefit from the findings and the output product of this research.

1.1 Research problem statements

The problem statement that the research has tried to investigate and provide a possible solution for can be drawn as follows:

Nodes Mobility increases the number of broken connections by increasing the rapid topology changing trend.
Mobility increase the unbalanced traffic flow processing in WSN which is a critical factor that rises up power consumption and information loss that leads to impractical results for the end user.
Localization process can become frequent and therefore a burden on sensor nodes if they were mobile.

The focus of the proposed problem statement has been mobility and its effects on the traffic flow of a sensor network. Mobility can also lead to undesirable energy consumption issues because of the addressed reason. The problem statement has encompassed the following concerns in the WSNs' operations: energy efficient operation, mobility, traffic flow issues and localisation of the mobile nodes.

1.2 Research Hypothesis

The research hypothesis is based on the following general assumptions attributed to WSNs:

- The nodes are mobile and deployed in a random fashion.
- The nodes are homogenous i.e. the nodes share the same computation/communication/power source capabilities.
- A stationary sink node is available in the network.
- The source nodes directs there data to the sink node.

From the general assumptions presented above it is possible to propose the following hypotheses:

- Controlling the transmission power of the node improve the energy consumption of the network.
- Minimizing the number of broadcasted control packets in the network improve the network lifetime and throughput.
- Mobility adaptive MAC protocol can improve the network performance.

- The network throughput improves if the routing protocol is designed for mobile nodes.
- The network energy consumption is improved if the location estimation method is designed for energy efficiency.
- The network operation improves in terms of energy efficiency and throughput if a cross-layer operation model is implemented.

1.3 Research objectives

The research has proposed a possible solution for the given problem statements by accomplishing the following objectives:
The main objective of this research has been to design an energy and throughput efficient network operational model for mobile WSNs. The model encompassed the mentioned problem statements. The proposed operational model composition had the following subsidiary objectives:

- Design a cross-layer operational model for mobile WSNs with transmission power control mechanism.
- Design an energy efficient and high throughput MAC scheme for mobile WSNs.
- Design an energy and throughput efficient routing approach for mobile WSNs.
- Design an energy efficient localisation method that can be utilised in mobile WSNs.
- Design a mechanism to minimize the control packets overhead.

The subsidiary objectives were then integrated into one stack that represented the proposed operational model.

1.4 Research steps

The steps that were followed to start and implement this research are illustrated in Figure 1.1 which represents a flow chart of the steps of the research process. The research was divided into three main branches. Each branch dealt with one of the major concepts mentioned in the research scope. Each concept was developed according to technical facts that served the main goal of the research. The three branches were then merged into one main component which was the proposed operational model. The proposed model was then implemented and evaluated according to comparison criteria: operation lifetime, system throughput, end-to-end delays and location estimation error levels.

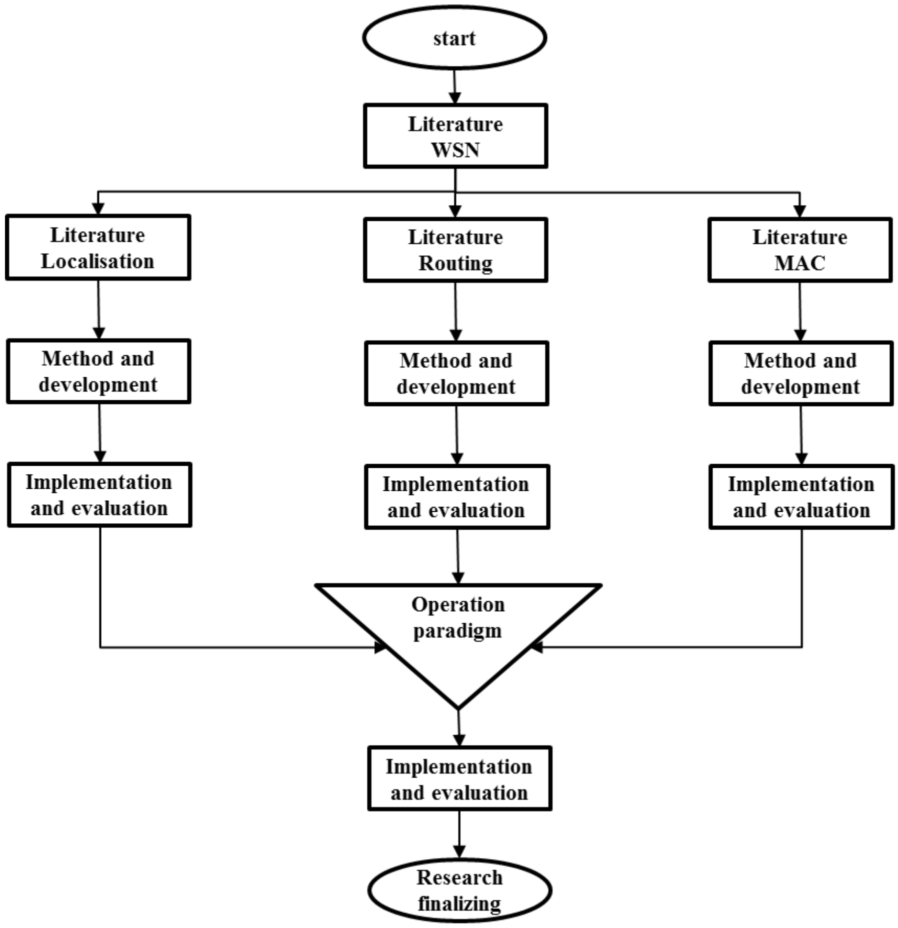


Figure 1.1: Research steps flow chart. The flow chart describes the three major concepts that were then integrated into the operational model.

1.5 Research methodology

The proposed operational model composes the operation and processes of several activities and protocols to achieve the final protocol. First the operational model is detailed in terms of the focus points: MAC protocols, routing protocol, localization, transmission power control and cross-layer operation. For each point the research proposed an alternative method to overcome the state of the art method in mobile WSNs. The proposed MAC protocol is detailed and analysed according to the operation cycle and energy efficiency. The proposed routing method is analysed and formulated according the background study made. The location estimation method proposed in this research is explained accordingly. The cross-layer operation model is then detailed with the inclusion of the MAC, the routing method and the location estimation method with detailed explanation of how each part participate in the operational model. An energy model for the final cross-layer operational model has been presented and validated.

To show the performance of each part, the evaluation process is done as separate procedures: the MAC protocol is evaluated separately than the routing method to highlight the efficiency of the method and its effect on the operation of the network. The same procedure has been done for the routing method and the localization method. The performance metrics were energy efficiency, throughput, end-to-end delays and for the localization method the location estimation error metric is used. After finalizing the evaluation process of each proposed method, they were then integrated into the cross-layer operational model and evaluated against the state of the art models in the field of WSNs.

1.6 Contributions

The list of contributions of this research is as follows:

- A cross-layer network operational model with location based transmission power control and low control packets overhead for mobile WSN.
- An energy efficient MAC protocol for mobile WSN.
- A cross-layer energy efficient and link-aware routing metric for mobile WSN.
- A low power consuming location estimation method for mobile WSNs.

1.7 Scope of research

The scope of the research was in the field of WSNs. The scope of this research focused on the mobility of the sensor nodes as a challenge that has a major effect on the WSNs' operations at several levels and aspects. The scope had been parted into four main concepts in the operation of WSNs; those were: MAC protocols, routing protocols, localisation methods and cross-layered operation. The four concepts were then combined to form a protocol stack that was addressed as the cross-layer model. The work presented is simulation based for the operational model with a hardware based proof-of-concept for the localization method. The application target for the presented operational model is pedestrian based applications.

1.8 Significance and importance of the research

Proposing an operational model for mobile WSNs is a task that requires consideration on many levels of WSNs operation. Providing such an approach can benefit both the scientific society and the end users. The scientific society can utilise the proposed operational model as a starting block of improvements and enhancements on WSN operation for different types of applications where mobility can be utilised as an advantage for the application rather than a challenge. The focus of the proposed operational model can be introduced to other aspects in WSN operations such as: security of data transmission, quality of service, deployment and topology analysis. End users can utilise the proposed operational model in different types of applications and can report back their findings about their applications and the proposed model performance for further developments and enhancements.

1.9 Thesis structure

Chapter two illustrates the literature review that has been carried out for WSNs as a subject in general and highlights the points of interest of this research field. Chapter three describes the methodology of the research and the proposed operational model. Chapter four is divided into four parts: part one presents the evaluation process of the proposed MAC scheme with the implementation and results. Part two illustrates the evaluation process of the composite routing metric. Part three discusses the proposed localisation method. Part four describes the merging of the component to build the cross-layer model and the process of evaluating the final product. Chapter five is the conclusions and future enhancements to the operational model and the recommendations regarding the type of applications where the final product can be used.

CHAPTER 2

LITERATURE AND BACKGROUND

2.1 Introduction: Wireless Sensor Networks

A smart environment is a current and evolving approach to control and maintain a specific environment whether this environment is inhabitable or uninhabitable [13]. The recent advancement in electronic integrated circuits (IC) and System-On-Chip (SOC), has allowed the possibility to build and establish systems that are cheap, reliable and in several applications have the capabilities of a personal computer (e.g. smartphones). Going deeper in the VLSI systems and MEMS, the possibility of covering a wider range of applications becomes enormous [14].

One of the important applications in a smart environment is event sensing [15]. Sensing a specific event/action allows the end user to obtain the required information about the environment under observation. Industrial manufacturing, mobile objects tracking and outdoor environment monitoring are only a few categories that are listed under event sensing [16]. Attaching the sensor module to a computational capable device with a communication interface creates a sensor node.

Deploying several sensor nodes in a known region and setting those nodes to collaborate in terms of an operation creates a sensor network. Sensor networks utilise the wireless medium as their communication systems hence, the term Wireless Sensor Networks (WSNs). However, several industrial applications and indoor-based sensor networks utilise wire lines as their communication medium [11].

WSNs are envisioned to be deployed in an outdoor environment where the nodes depend on their attached energy sources (e.g., Batteries). From this scope, WSNs are usually equipped with limited computational capable hardware to maintain a long operational lifetime (the network lifetime can span from months to years depending on the application [17]).

With limited energy sources and limited operational capabilities, the WSN research field is considered a current topic [18]. This importance comes from the fact that WSNs promise an invaluable number of applications in the field of smart automation and environmental monitoring [19]. The number of involved applications is humongous. It can range from indoor smart home appliances to hazardous and military level environmental monitoring applications [7]. Solutions to overcome the issues that are attached to WSNs' operations were wide ranging from application-based solutions to the hardware-based ones. Some of the fields that the WSN's operation encompasses includes and is not exclusive to: low energy consumption operation, energy efficient routing, energy efficient MAC operation, information security in WSNs, node localisation, event localisation, data aggregation and compression in WSNs, low-latency end-to-end delays, high network information throughput etc.

In various cases, sensor nodes are considered static non-mobile. Mobility increases the scope of applications proposed in WSNs [20]. However, mobility in WSNs increases the difficulty of network operation because of the rapid change of the network topology [21]. The network operation is required to be adaptive to mobile nodes.

This chapter discusses the WSN's general topics and issues. The next section will discuss WSN architecture. Section 2.3 will illustrate the issues attached to the WSN's operation in more detail and several proposed solutions. Section 2.4 will illustrate the system models associated with the WSN operation. Section 2.5 will discuss the types of applications where WSNs can be used.

WSN architecture

In literature, a basic WSN (figure 2.1) is composed of three main layers [6]. Each layer specifies a typical WSN component:

1. Sensor node: it is the hardware device that performs the phenomena’s/event’s physical sensing operation. The sensor part is capable of either sensing a single phenomenon (e.g., Temperature, humidity, luminance etc.) or in some applications the nodes are required to have more than one sensing module. The sensor node in general has five other components: a computational processor unit, transceiver, memory module (information storage device), location estimation module and a power source (Batteries). Figure 2.2 illustrates a block diagramme that describes the sensor node components.

2. End user: or (observer) is the user that implements the network and is responsible for monitoring the data received from the network. The observer can also be responsible for maintaining the network performance if any anomaly appears in the system operation.

3. The phenomena: they are the physical actions that happen in the monitored environment that the sensor modules on the nodes can detect and measure. The application where a WSN is implemented defines the type of sensors and events that are required to be measured.

The basic operation of a WSN can be described by the following: a sensor node detects a specific phenomenon (or target movement) and generates an interest to send this information to the base station. The nearby nodes would provide the possible route for the data from the node of interest to the base station. The base station then receives the data about the event (or the target) and forwards it to the end user. The end user can form a decision about the received data (interest).

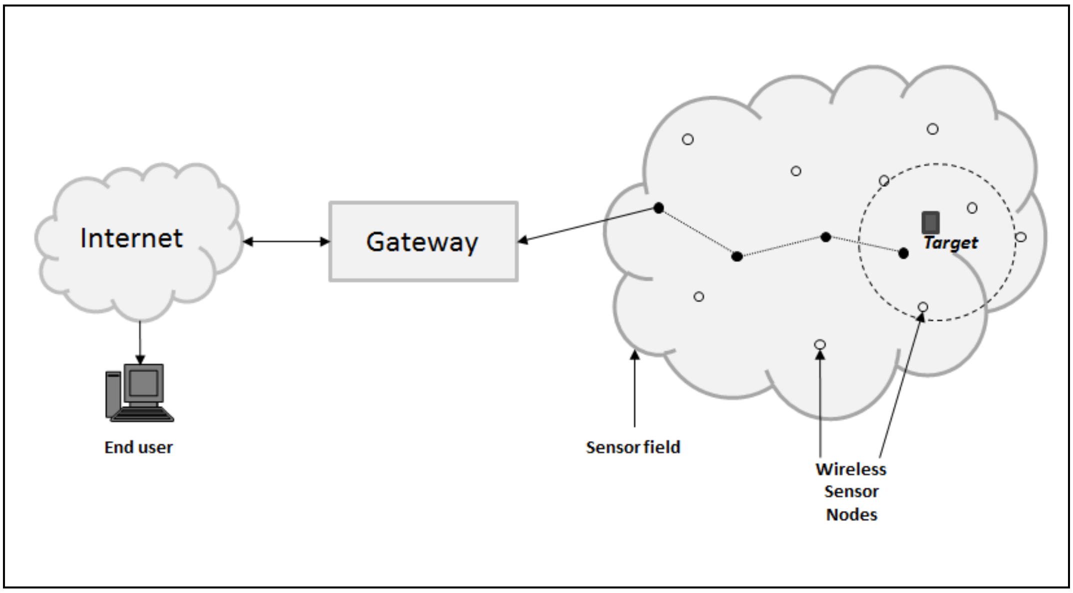


Figure 2.1: A wireless sensor network example

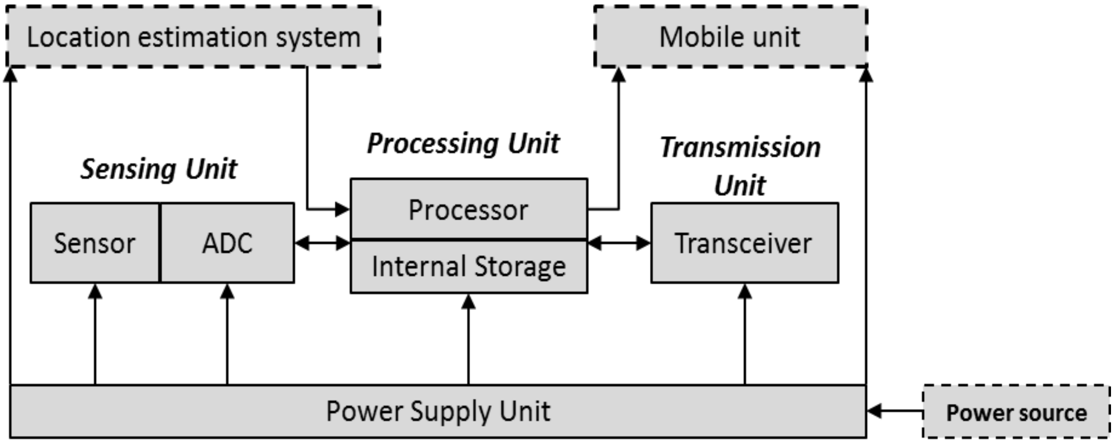


Figure 2.2: Sensor node basic components.

2.2 WSN issues

The versatility of the WSN research field in terms of proposed applications and operational solutions relates back to the WSN operation. WSNs share several characteristics when a specific network design is required [8]. These characteristics are:

2.2.1 Energy limitations

Power consumption in WSNs is a critical issue that has direct effects on the network operation [22]. WSNs are energy limited, i.e., sensor nodes depend on a specific amount of attached energy (e.g., AA battery [23]). Whilst WSNs are required to operate for a period that spans from months to the order of years, the deployed nodes are expected to be unmaintained by the user (indoor WSN applications are more likely to be maintained by the end user [6]). Energy efficient operation in WSNs has claimed the highest amount of research in the field [8], [24]. Lifetime in WSNs is an important measurement that needs to be considered when proposing models and operational protocols. To overcome the energy limitation, several approaches where proposed on different points of operational optimisation. To efficiently consume the energy available in the network, balanced traffic is required to maintain the network information flow in a fashion to achieve the application's required level of energy consumption and lifetime. To mention some of the energy efficient approaches, [25] proposed a cluster-based information collaborative processing in a WSN to minimise the computational overhead on a singular node and distribute the effort on a multi-sensor node. [21] Discusses the impact of the network topology when deploying a WSN to achieve the best possible lifetime from the network. Alternative energy sources were discussed for WSNs, such as solar systems and environmental energy scavenging techniques [18], [26].

2.2.2 Computation & communication limited resources

In WSNs, sensor nodes are expected to be large in number. This leads to the fact that the nodes are expected to be cost effective (cheap) [17]. Therefore, sensor nodes are usually equipped with a limited data processing power that is capable of handling the sensed phenomena data. Then, they either compress and send or send the whole data to the required destination (or next hop) [27]. Cost is an important issue in WSNs. However, one of the main reasons why a sensor node has limited processing power is to maintain low energy consuming modules [28]. Network lifetime is an important issue and the deployed nodes need to be energy efficient to achieve the end user's application needs. In terms of the communication system, sensor nodes are equipped with a wireless communication interface [29]. The wireless interface has limited capabilities in terms of the range of communication with other nodes (ZigBee modules are built to have a maximum range of 100 meters with a maximum bitrate of 250Kb [30]). With a limited communication range, WSNs operate in multi-hop fashion, i.e., the node of interest sends its data to the nearest node in a route decided by an efficient routing protocol [31]. The multi-hop information forwarding keeps on going until the information reaches the required destination.

2.2.3 Scalability

Sensor nodes can be deployed in the order of hundreds of nodes and more. However, after a period of operation, eventually nodes would suffer from lifetime operational issues, such as energy depletion [32]. To regain control of the network and keep monitoring the environment with the remaining nodes, it is possible to deploy new nodes into the network to maintain the operation of the older nodes. Another situation is when the user wants to increase the volume of the network by deploying more nodes to increase the area of monitoring. Scalability is an issue in WSNs because of the application type. The scalability issue is important on the level of the abstract layers of the operation in the network [33] (e.g., MAC and routing). Cluster-based approaches were considered more controllable because the nodes were directed by a cluster-head (Figure 2.3). However, when new nodes are added to the network, the process of the cluster-head election needs to be redone and this process is costly in terms of energy consumption. Scalability is an important consideration when designing a WSN system.

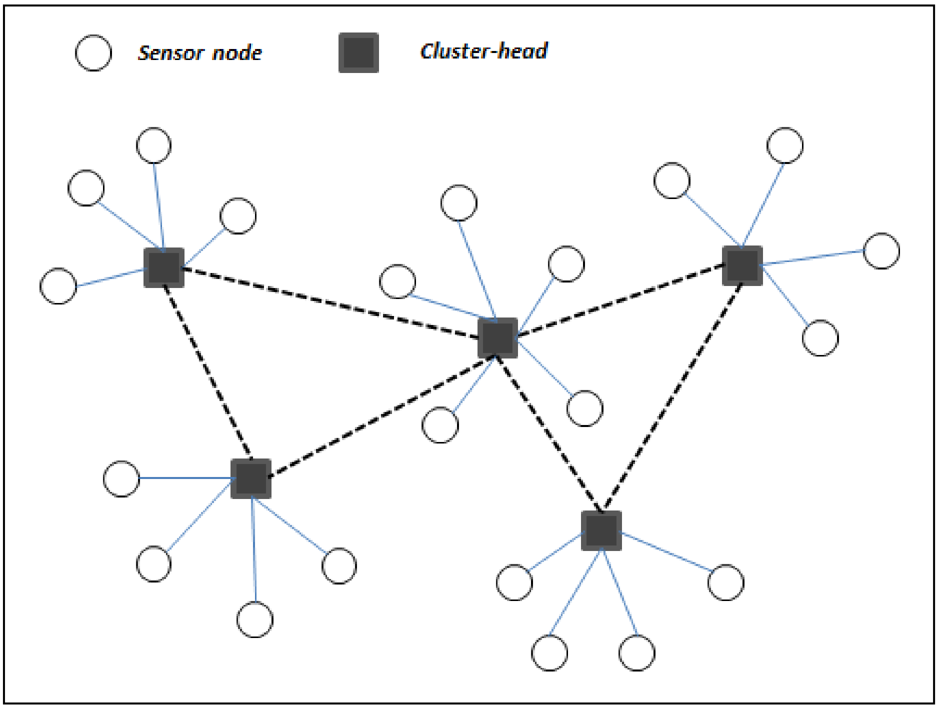


Figure 2.3: Cluster-based sensor network

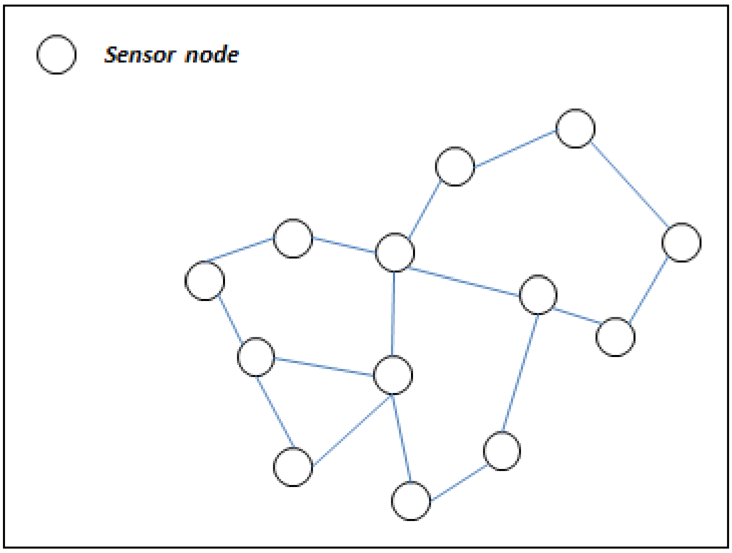


Figure 2.4: Flat sensor network

2.2.4 Location estimation (Localisation)

An important pillar in WSN applications is the location estimation of the phenomena or the sensor node of interest [34]. Localisation is the operation of finding a specific target using a method proposed by the network system designer. Localisation is a fundamental problem in WSNs because sensor nodes are resource limited. The technology development has allowed the possibility to attach the nodes with a Global Positioning System (GPS) [35] to identify the location of the node of interest or a target that is moving through the network. Moreover, GPS modules are cost effective when attached to a sensor node. However, GPS's are also power hungry devices [36] which is improper for WSNs' limited power sources. Different methods have been proposed for localisation that utilises several techniques: Radio frequency (RF) signals, Acoustic signals, Infrared signals and modules, cooperative localisation and more [37]. Some of the works in the field of localisation can be seen in [38], [39]. Localisation is an important aspect in a WSN's system design.

2.2.5 Mobility

In WSNs, mobility enhances the network sensing coverage as the nodes would be able to move and not just settle in one position [40]. Although, a lot of research that has been conducted in WSNs' systems and solutions considers that sensor nodes are stationary in general [41]. Mobility in sensor networks can be limited to collective nodes (mobile base stations). These nodes would roam around the network and collect the data from the static sensor nodes. If sensor nodes are mobile, the network operation would suffer from overhead, such as rapid topology changes. Rapid changes in the network topology have a negative effect on the information traffic flow between the nodes [42]. The routing operation is required to be able to encompass topology changes to insure the best possible route from one source to one destination [43]. Location estimation can also be effected by the mobility of the nodes because the localisation operation would be required frequently depending on the application of the sensor network (e.g., target tracking and monitoring). Mobility increases the range of possible applications for WSNs [44].

Like other wireless networks, WSNs suffer from other common challenges like data delivery Quality-of-service [27], limited bandwidth and error prone channels. Information query in WSNs is an important issue [45]. Query in WSNs is required to be light to insure an energy efficient process. The more complex the query, the more energy cost the process incurs. Operating systems and middle-ware for WSNs have to meet efficient energy consumption requirements because of the computationally limited processing units [46]. Security of the transmitted and received data in WSNs is a challenging consideration in the system design because of the mentioned above issues [24]. A service-centric model described by [47] shows that it is important to identify the type of services that the sensor node can provide to insure the proper operation of the network. Intelligent information processing in WSNs is a wide field that discusses the cooperative information processing between the nodes and to what limits such a model is possible [1], [46], and [48].

2.3 WSNs' system models

WSNs' system models were described in different concepts, such as service centric [47], algorithmic [49], data reliability [27] and other definitions of the models [50]. The reason behind such variety in modelling systems is because of the challenges that the network designer has to consider when planning an application using WSNs. Resource conservative, limited energy, application dependency are only a few examples of such challenges. Models in computer systems are defined as "*abstractions of the functional behaviour of a system or entity, in a form amenable to simulation or analysis*"[51]. Models in general help the network designer to estimate and predict the operation of the network before or whilst testing the system. According to [51], models for WSNs vary in principle and categories. The models mentioned are:

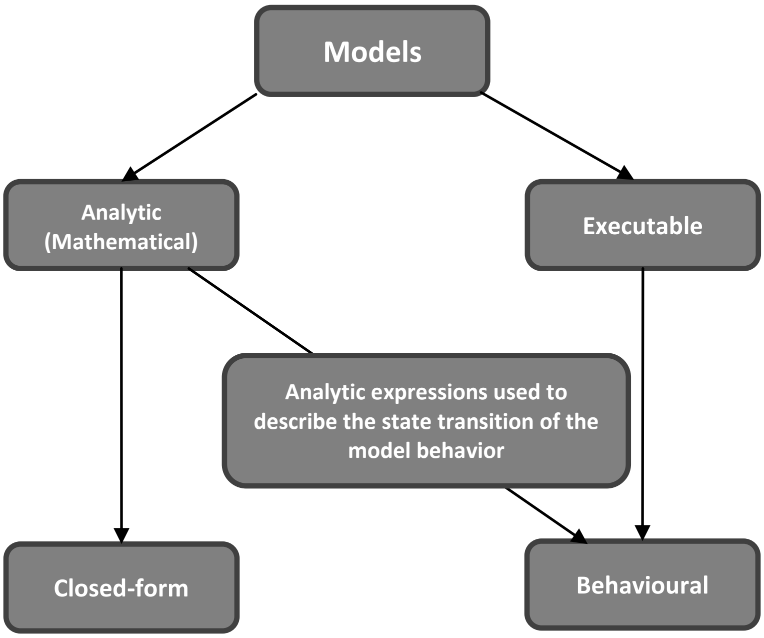


Figure 2.5: Models are derived by either of the two concepts: Executable or Analytic

Analytical versus behavioural models

Analytical (Mathematical) models are represented by a list of operations or equations where it is possible to input some specific data (information) and the proposed model generates the probable response of the modelled system. Analytical models are considered as “Closed-Form” models. Behavioural models are described as executable models where the information is built during the system operation or implementation and based on the system components’ fundamental facts. Figure 2.6 describes the differences between the mentioned model types. The models are classified even deeper into four main dimensions, namely: Application (D), Model structure (S), Construction (C) and the metrics involved (M). Figure 2.6 illustrates the dimensions and there branches.

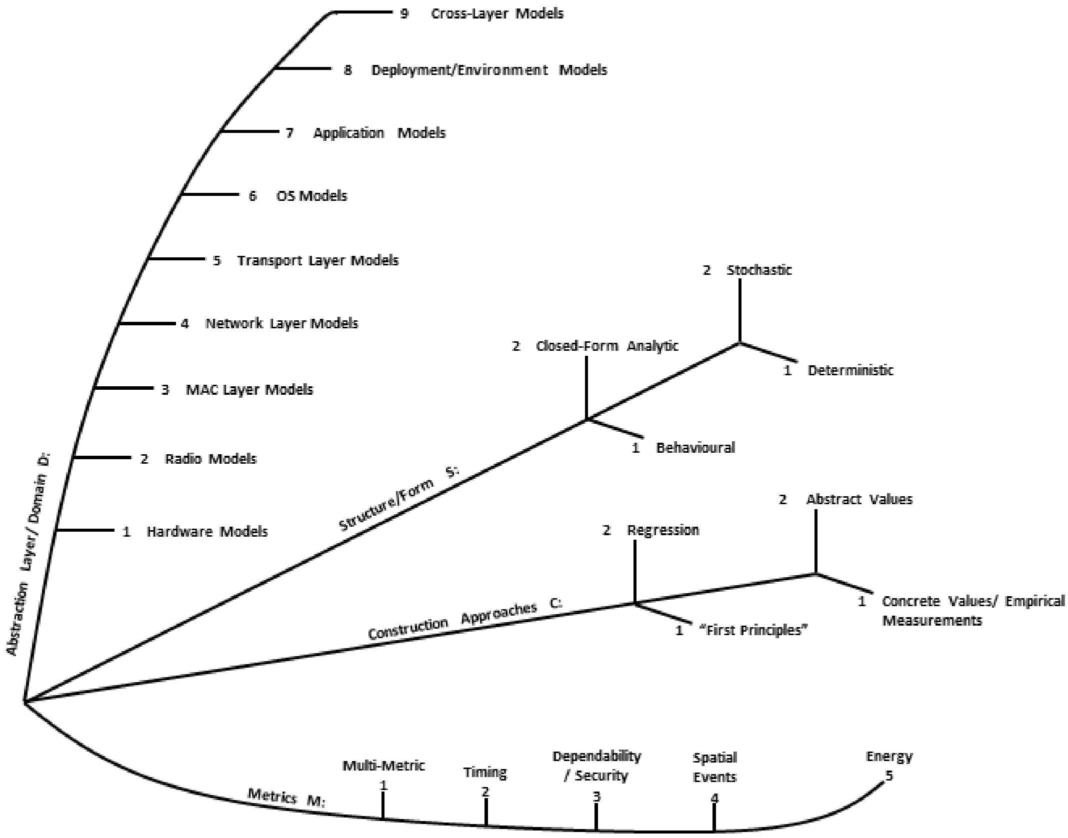


Figure 2.6: The dimensions to develop models proposed by [51].

2.3.1 Node hardware models

The type of hardware implemented in an application design effects directly on the behaviour of the system. The limitations of the hardware are described in the network's general physical capabilities. The metrics that are involved in describing the hardware model include: computational capabilities and energy cost, sensor capabilities, the radio module attached, the power system and the delays and clock drifts of the equipment [52].

2.3.2 Radio and signal propagation models

The radio and signal propagation model describes the environmental effects on the operation of the radio connections and interference in a wireless system. In WSNs, the radio propagation model is of the most important consideration in the network design. The propagation model describes basically how the radio signal will propagate in an environment, for example, the Friss free space propagation model [53] which represents the signal propagation as a power to distance relationship in free space. Another example is the TwoRayGround [53] model which describes the signal propagation as a power to distance relationship; however, a reflection of the signal from the ground is included in the model. Radio propagation models aimed for WSNs are application dependent in general, i.e., the propagation model described for the implemented network is based on the environment that the sensor nodes will be deployed in. For example, if the network is to be deployed in an environment where the space is full of obstacles (urban or modern environments), the free space model is not sufficient because it does not represent the signal attenuation when going through mediums other than air.

2.3.3 Medium Access Control and Link Layer models

The main purpose of MAC protocols is to control the operation of the radio module in terms of using the wireless shared medium between several wireless nodes [11]. MAC protocols in general are software implemented [51]. MAC protocols are one of the main sources of energy consumption in WSNs. The field of research concerning MAC protocols has gained high consideration because they directly control the radio activity and connection of the nodes. MAC protocols have two major categories, Reservation-based (Contention free) and Contention-based protocols. Contention free protocols, such as the TDMA protocol, works on the concept that the connection between two nodes can be conceived if the timing slots of both nodes meet a schedule. The Reservation-based MAC protocol gained popularity because of its scheduled operation and collision free environment. Collisions in a connection can lead to a serious power consumption issue because of the re-transmission of the collided packets. However, Reservation-based MAC protocols limit the network scalability because if new nodes have entered the network, the older ones need to re-schedule their timing slots with the new nodes and this operation itself is power consuming and increases system latency. A Contention-based MAC protocol like CSMA (Carrier Sense Multiple Access) operates by contending for the shared medium. The radio interface has to first sense the wireless medium for whether there is a current transmission happening or not, and if it can engage in a connection with another node. One of the famous examples for Contention-based MAC protocols is the Wi-Fi standard IEEE 802.11 [17]. Contention-based MAC protocols have gained a wider audience than Reservation-based protocols because of their simplicity in basic implementation as the protocols usually do not require a former scheduling for the nodes' communications which improves the network's scalability. Models proposed for MAC protocols for WSNs have been majorly based on the mentioned two categories. A MAC protocol model aimed for WSNs has to cover several elements that are defined basically by the proposed application. Those elements are energy efficient operation, end-to-end delays, collisions, connection overhearing, control packet overhead and finally, the idle/listening operation.

2.3.4 Network and transport layer protocols

Network and transport protocols are responsible for the operation of finding the required destination for the source through the best possible paths. Modelling of the network protocol layer is based on the operational behaviour of the implemented network [51]. The protocol operation in general depends on the state of the network to provide the required decision. Routing protocols are an example of network layer protocols. Models proposed for network protocols are based on the stochastic and statistical analysis of a system implementation. Routing protocols represent the network layer protocols according to the OSI network model [52]. Routing protocols aimed for WSNs have originated from the routing protocols proposed for conventional wireless networks [31]. Categories of routing protocols differ based on the method by which the protocol establishes the link between a source and a destination. Routing protocols proposed for WSNs come from different routing approach families: Cluster-based routing, e.g., LEACH (Low Energy Adaptive

Clustering Hierarchy) [54], Proactive routing, e.g., link-state routing and Reactive routing, e.g., AODV (Ad hoc On-Demand Distance Vector) [55]. Network layer models proposed for WSNs have to consider the scalability of the system deployment, the density of the deployed nodes, channel access probability, node transmission power, end-to-end delays and energy awareness.

2.3.5 Operating system (OS) and runtime system models

An operating system in general is responsible to operate the sensor node hardware to meet the application needs. Tiny OS [56] is an example of an operating system used in sensor network platforms. Models for WSNs include the operating system's performance as a key comparison tool because operating systems vary in their applicable capabilities against their operational efficiency [51]. The code construction of the operating system is important when it comes to the comparisons between platforms. An operating system performs updates to the node's input data and thus performs the required processing to fulfill the job. This frequent update causes energy consumption on the node's level. Energy consumption against provided services is a key aspect when comparing and modelling operating systems for WSNs.

2.3.6 Application models

WSNs are application dependent networks [7]. The network design is based on the type of application that provides the required services to the end user. Models for WSNs have to consider the type of application that the network is to be implemented for. [51] presented the types of applications for sensor networks as below:

- Area mapping (*Spatial mapping*): the main purpose of this type of application(s) is to monitor and define the intensity of a specific phenomenon/event for a given geographic area.

- Target tracking (*Object tracking*): the end goal of this type of application is to make the nodes in the network track a target that can be mobile and not a part of the deployed network.

- Mobile sensor nodes (*Sensor tracking*): as the name suggests, the application is required to identify and track sensor node movement in the network where the nodes can be mobile in a geographical area.

- Data aggregation: the objective of this type of application is to aggregate and collect information from an ad hoc network of nodes. The aggregation process is for the whole network.

Several models that represent applications were based on the behaviour of an actual implementation of mathematical algorithms, e.g., Direct Diffusion data aggregation routing algorithm [57].

2.3.7 Environment, Mobility and Deployment models

Environment models proposed for WSNs are application-based as the model depends and is developed based on the phenomena/event in question. The event includes natural-based physical actions, such as light, humidity, temperature, seismic activity or an intensive density of electro-magnetic activity, in an area generated by a group of transmitter communications [58]. Applications can be monitoring social developments like people's movement in an urban area [51]. Models for WSNs have to study the environment where the nodes are deployed.

Mobility of the sensor nodes in the network can also generate unpredicted patterns of communication between the nodes. Mobility models for WSNs were designed by the developed studies of the mobility issues in wireless ad hoc networks [8], [17]. Mobility can present a challenge in a WSN's operation. Therefore, models proposed for mobile WSNs require the attention of the network designer. The random-way point mobility model [59] is one famous example of the mobility models proposed for mobile ad hoc networks. Deployment of the nodes can have a significant effect on the operation of WSNs [21]. Although the random deployment in several applications is preferred, special nodes like the base station can have a designated location in the network topology to increase the outcome of network information to the end user. The deployment issue of WSNs has gained importance in the literature [50], [51], and [52]. Topologies such as hierarchical (cluster-based) or flat are amongst the types of topologies studied for WSNs. Each topology type has its merits in terms of controllability and scalability. A study carried out by [60] shows the importance of the topology of deployed WSNs on the networks energy efficiency and lifetime.

2.3.8 Standards and protocol stacks

Protocol stacks proposed for wireless sensor networks are diverse according to the goal of the application(s).WiFi is one of the considered protocol suites for WSNs. WiFi bases its communication on physical and MAC layers according to the requirements of the IEEE 802.11 standard. The main issue with WiFi technologies is that they consume relatively high amounts of power. Bluetooth is another example of protocols considered for WSNs. Bluetooth has a short range of operation (10 Meters) and has only one topology of operation: star topology [61]. WirelessHart [62] is a protocol suite aimed at WSNs for industrial applications. WirelessHart adopts the physical layer utilising the IEEE 802.15.4 standard; however, WirelessHart defines a TDMA-based MAC protocol to control the physical medium. The routing operation in WirelessHart is based on graph routing and source routing. WirelessHart operates at the 2.4GHz ISM band with a maximum transfer rate of 250 kbps.

Dash7 is a protocol suite for WSNs [63]. Dash7 operates in a tag fashion manner. The master node asks for the slave nodes’ tag ids. Each slave node then is assigned to a random communication window with a specific period of time. During this period of time, the slave node sends its data to the master node. If a collision occurs during transmission, the nodes choose another random slot to transmit their data over (Slotted ALOHA operation). Dash7’s physical layer operates at the 433MHz ISM band which makes the network free of conflict with WiFi, Bluetooth and ZigBee communication mediums. Dash7 has a transmission rate of 27 kbps with a transmission range that can reach up to 10 kilometres.

ZigBee suite [64] is a protocol stack for wireless personal area networks (WPANs) with low power consumption. ZigBee bases its operation on the IEEE 802.15.4 standard for both physical and MAC operations. The routing operation is performed by utilising the AODV routing protocol. ZigBee network topologies can be organised as star, tree or mesh deployments. The ZigBee stack incorporates 6LoWPAN (IPv6 over Low power Wireless Personal Area Network technology [13] to incorporate the IPv6 network in the deployment. The physical layer operates at the ISM band at 2.4 GHz and has a transmission rate of 250 kbps with a maximum transmission range of 500 meters. The ZigBee stack is the most versatile of the above mentioned stacks that are proposed for low power miniatures. WSNs are one of the applications where the ZigBee stack can be utilised.

The discussed models and concepts for WSNs cover in general several aspects that reflect the limits in resources. However, WSNs are envisioned also as a service provider [47], [51]. The fact that WSNs are mission-oriented means that it is very convenient to map the network as a service provider and each sensor as a service agent. A service centric model proposed by [47] defines sets of layers that depicts the service provided by the network at each level: *Mission, Network, Region, Sensor* and *Capability*. Each level has four planes of functional sets: *communication, management, application* and *generational learning*. The composition of the layer with their functional sets gives a service model description of a WSN (Figure 2.7).

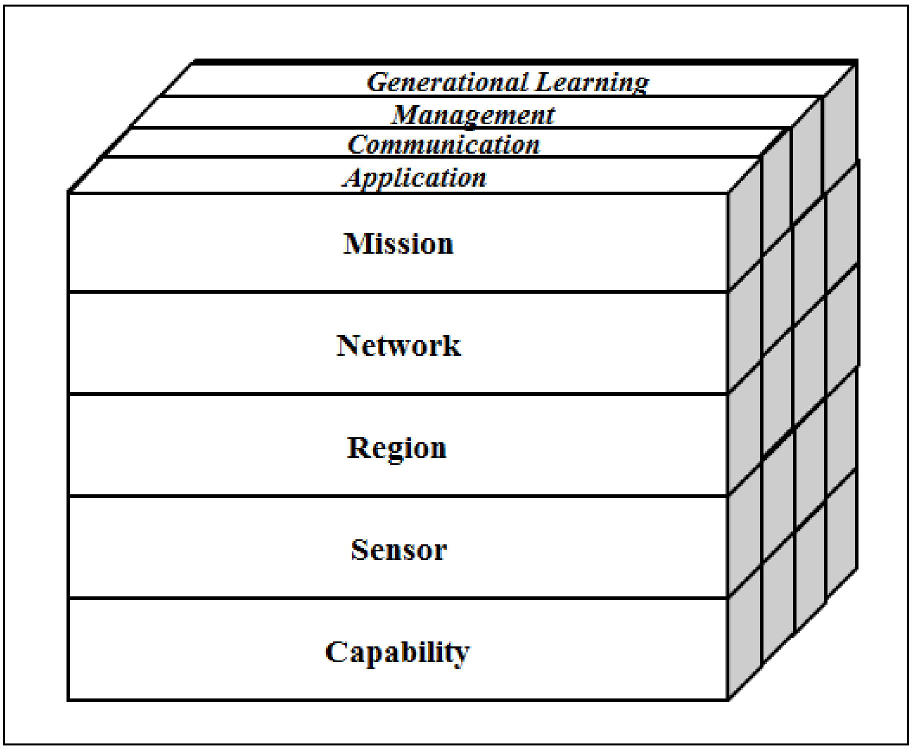


Figure 2.7: Service centric-based model proposed for WSNs [47]

Like conventional computer networks, WSNs can be depicted as graph networks. The distributed nodes with their communication capabilities can then be modelled as a random deployed graph (G) with the deployed nodes as the vertices (X) and the communication links as the edges $(E), G = (X, E)$. Algorithmic models proposed for WSNs based on graph theories were discussed in [49]. The study has introduced the network connectivity structure as a graph network whilst the interference model has been described as a Signal-to-Interference plus Noise Ratio (SINR).

A survey study performed by [52] shows the potential of modelling WSN operation based on the network traffic analysis. The distributed behaviour of the network implies that the network traffic is unbalanced in several cases and can be optimised by load balancing the traffic of the network. The study discussed energy efficient MAC and routing approaches in general and their importance in modelling WSNs. In-network processing is one of the fields that was a subject of interest in the aforementioned study.

An example of an environment and network deployment-based model is the work carried out by [32]. The author proposed a cluster WSN model based on Log-distance path loss. The study tried to achieve the optimum number of cluster-heads in the network to reduce the energy dissipation at the cluster-heads. Another example of a deployment-based model is the work carried out by [28]; the Deployment-aware Energy Model for Operator placement in Sensor Networks. The study defines the related issues of in-network query and how to deploy "*operators*" to enhance the query process in the network based on the lifetime of the network as the deployment metric.

Data reliability in WSNs is a practical issue and requires attention in network behaviour analysis. Model-based techniques for data reliability in WSNs have been presented by [24]. The study provides a method that uses the sensor's properties to enable reliable data collection.

The author of [50] provides a survey of modelling techniques for WSNs; however, the survey encompasses hardware platform representation models for the sensor nodes in the network and their capabilities. Models like High-level

Specification and Description Language (HL-SDL), SensorML and SystemC-AMS were some of the models discussed in the survey.

Packet traffic is an important source of anomaly detection and system modelling for WSNs as pointed out by [27]. The study concludes that the traffic in WSNs is simpler and lighter than on conventional networks (e.g., the internet). It is, therefore, possible to build a precise and more accurate model for the packet traffic of the network. Based on the development of the network operation, any critical change in the traffic behaviour can be a result of a high risk occurrence and can, therefore, be monitored and isolated. Such anomalies can be due to malicious (attacking) nodes that interfere with the system. The next section illustrates several applications implemented using WSNs.

2.4 WSN applications

2.4.1 Military based applications:

Military applications are probably the most related applications of WSNs. There is also an uncertainty of whether sensor nodes "Motes" were first developed to fulfill the requirement of the air defense needs or if they were developed separately and were integrated into army services [7]. Back to military applications, the subject can extend from information collection in general to enemy target tracking, battlefield monitoring or target classifying [65], [66]. The classification process methods can utilise, for instance, input data that are retrieved from a seismic or an acoustic signal activity. For example, explosive mines are considered dangerous and outdated and can be replaced by thousands of distributed sensor nodes that are able to detect a hostile activity or penetration units. The intrusion response system "Defense system" will act according to the level of intrusion. The University of Virginia has proposed and demonstrated such an application [67]. Another application described in [68] targets multi-vehicle tracking in the form of a "pursuit-evasion" game. The application contains two main contenders: the pursuers and the evaders. A third party involved is a sensor network which aids the pursuers to locate their opponents. The sensor network acts as an information aid which informs the pursuers with required information about the enemy units' movements and locations. Sensor nodes then strengthen the "vision" of the pursuer team and uncover their opponents. Ohio State University showcased a military application with the name "A line in the Sand" [69]. The application works by deploying ninety sensor nodes with the capability of detecting metal objects and materials. The main objective is to track and classify the mobile objects with a significant amount of metallic content "vehicles and armed soldiers". Other objects (e.g., civilians) are neglected by the system.

2.4.2 Environmental monitoring

2.4.2.1 Indoor environmental monitoring and emergency services

The possibility of sensing physical actions, such as light, temperature, frame states (windows and doors), steam and indoor air pollution levels, makes it possible to utilise this information to control the monitored environment [70]. Additionally, energy wastage can happen through unattained and uncontrolled heating or cooling of a room in an establishment [4], [5]. Sensor nodes can control the environment by utilising heaters, fans or other equipment in an economic fashion, resulting in a healthier condition and comfortable level for the establishment residents. Fire and smoke detectors are common equipment in building and establishments in a lot of countries (some countries enforce it in their laws). Exit indicators in buildings are also becoming mandatory. The two systems, however, are not connected and do not cooperate in case of an event (e.g., fire). The installation of a sensor network integrates both systems. The sensor nodes functionality would be to guide the trapped residents to the safest area and away from fire routes to the nearest exit and save them from imminent danger.

2.4.2.2 Outdoor Monitoring Application to Ecology

Outdoor monitoring is considered as a wide area of possible applications for sensor networks. The Great Duck Island project (GDI) [71] is an example of this type of application. The project consisted of deploying 32 nodes on the island. The deployed network was aimed at habitat monitoring. The deployed sensors had the capabilities to sense temperature, humidity and barometric pressure. The nodes were also equipped with passive infrared sensors and photo-resistors. The goal of the project was to observe the natural environment of the storm petrel (a bird species) and how it behaves when there is a change in the surrounding climate. Therefore, some sensor nodes were attached inside the birds' "burrows" to allocate the birds' availability. The other nodes were deployed in the surrounding area. Data were collected by the sensor nodes and then passed to a gateway node. The gateway purpose was to pass the data to a local base station through a higher-level network. The data of the base station can be accessed via the internet and is then duplicated to another location for safety purposes. This application is an example of WSN monitoring applications using a heterogeneous, hierarchical levelled network.

Another application presented by North Carolina State University that had the purpose of studying the red wolf, which is an endangered species [7]. The basic concept was to attach a node to each animal to monitor its state and behaviour and to record the required data. However, sensor nodes are incapable of transmitting in a long range of distances and are energy constrained devices which means that it is not applicable to keep the nodes online all the time. To overcome this issue, the suggestion was to use two types of nodes in the network: static and mobile nodes. The mobile nodes collected the required data whilst the animal roamed until it reached the range of a static node. The static node initiated the connection with the mobile node and finally started uploading the recorded data.

An application that is inclusive to outdoor observation and concerns environmental monitoring in general is weather forecasting. ALERT (Automated Local Evaluation in Real Time) [72] is a system developed by the national weather service in the 1970s was only a depicted application of sensor networks. ALERT is a predecessor and can be considered a pioneer of the current WSNs. The application was used to monitor the rainfall prediction in California and Arizona. The system was equipped with several types of sensors; Temperature, water level and wind sensors. However, the sensors were used in this system and not per se in the current referred sensor nodes as the nodes did not have processing capabilities. The collected data were raw data and were then processed through GUIs.

2.4.2.3 Outdoor monitoring Applications for agriculture

Agriculture has gained an interest in the field of sensor networks. The system is used to enhance the efficiency of "growth cultivations". With cooperation between Intel and Intel Berkeley labs, they studied the case of installing and deploying a sensor network in a vineyard [73], [74]. The original goal was to survey and monitor the "microclimates" to enhance productivity and aid the farmers.

Accenture Technology labs were also interested in vineyards as an area of sensor network applications. Their R&D team installed a sensor network system in a test field in "Pickberry Vineyard" [75]. An area of 30 acres was covered by sensors to measure humidity, wind, water, soil and air temperature. Millennial Net's sensor nodes "motes" were the nodes installed for this application.

Irrigation is a field of interest in sensor networks. Water management can be achieved in an efficient and economical way by monitoring the soil, air humidity and weather forecasting. Other applications are "frost" detection, warning systems, disease detection and "pesticide" applications.

The scope of applying sensor network technology to the agriculture field includes crop management, cost efficient operation and product quality enhancement.

2.4.2.4 Support for logistics

An application field for sensor networks is inventory control. This is an important issue for large companies. Managing various assets (machinery, different products and equipment) can be a dilemma. The issue in general is rather scattered because such companies are basically all around the world for example, oil companies or food chain companies. Tracking the distributed assets and relieving the issue is by using various technologies for example, RF ID tagging and WSNs. British Petroleum (BP) in participation with the CoBIs program and Accenture Technology Labs performed a cooperative research in this application area.

BP proposed “smart surrogates”. The application is aimed to control the warehouses and storage of barrels. The main concept behind the application is to install sensor nodes on barrels. The nodes are capable of detecting and locating close objects (other barrels). The nodes have, in their storage, the object information (e.g., the material inside). When different barrels are close to each other the nodes then detect each barrel’s stored material so in case of incompatibility (that leads to a serious issue) the system can then alert the end user about the issue. Other applications for the node can be monitoring the age of the container. Such a system can improve safety and increase product quality[7].

Researches from UC Berkeley have proposed an application for firefighters based on wearable sensors “wearable motes”. Integrating motes into the firemen’s suits helps in coordinating the fire extinguishing process more effectively and can also work as an added safety measurement by locating each fireman. In case of an accident that can happen to firemen’s crew, the rescue team can then work more efficiently [7].

2.4.3 Human-centric applications

The health sector has gained an incremented interest in the field of WSNs. An example is the research concerns of senior citizens and their problems as performed by Intel [7]. “Cognitive Disorders” a medical case that perhaps can lead to Alzheimer’s, is possible to be observed in its early stages using WSNs. Intel in Portland and Las Vegas has carried out such an experiment (Proactive Health Research). Sensor nodes were able to record the patient’s recent activity (e.g., taking medication, latest visitor etc.) and were able to work as a reminder for the patient, monitor his/her real behaviour or detect a probable problem. A related research implemented by Intel and the University of Washington, used RFID tags attached to several objects surrounding the patient to monitor the behaviour of the person according to the pattern of touching specific objects [7]. The data from the applied sensors were then transferred to a display that aided the "caregiver" to monitor and extract the required information about the patients discreetly to avoid hurting their feelings. Sensor nodes were also used to study the behaviour of children [76]. The main concept of the study was to analyse the children's activities by observing the data recorded by the sensor nodes attached inside their toys.

Other categories of applications related to the health sector includes the monitoring and tracking of doctors and patients and tracking the drug level usage in hospitals [76].

2.4.4 Applications to robotics

Applications proposed to couple between sensor nodes and robots have been proposed vastly. An example is "Robomote" a small scaled (tiny) robot developed at the USC Center for Robotics and Embedded Systems promoted the research of large-scale mobile WSNs were robots can play a role [77]. The implemented application such as the one in [78] is an example of such coupling. The application discussed has an objective to detect the level sets of scalar fields (e.g., isothermal and isobar curves) by utilising mobile sensor networks and imitate the function of "bacteria" in seeking "dissipative and gradient sources" [79]. The target was to track a light source using simplified algorithms. The "coverage problem" was investigated with a proposed solution by [80] using robots and sensor nodes. The concept was to try and perform dense measurement across a "wide area". Static sensor nodes and a mobile sensor node collaborated together through the usage of mobile robots. The mobile robot deployed sensor nodes "motes" as beacons and from that the motes would aid the robot in defining its directions. Swarm based robot sensors are also considered as a future application in sensor networks [81].

Robotics aimed at health sector applications have also embraced sensor networks. An example is "the virtual keyboard" developed by U.C. Berkeley. The virtual keyboard is a device that contains wearable sensors to sense acceleration. Six sensors are attached to a glove, each finger has a sensor and the last one is attached at the wrist. The main goal of the application is to record and understand the movements of fingers and recognise the gestures performed [82]. Applications derived from such a system can be a wireless wearable mouse or keyboard, a pointing device, disabled aid recognition systems and others.

2.5 Mobility challenges

In WSNs, mobility can have a profound effect on the network operation [83]. This effect is diverse according to several parameters that include: application diversity, network topography (topology), network connectivity and deployed node(s) or sensed event(s) location estimation. Sensor node mobility can be divided into two categories: limited mobility where there are specific nodes that roam around the network to perform an exclusive task (e.g., mobile sink nodes) and random mobility where the nodes (sensor nodes) roam around the area of deployment to collect the data needed for the application. Mobility as an issue has either an advantageous effect or a disadvantageous one.

2.5.1 Mobility advantages to the network operation

Advantages of introducing mobility to the network can be listed as below:

1. Applications: introducing mobility to the network can enlarge the scope of applications can implement WSNs. Applications such as: social activity monitoring, cattle monitoring, swarm bots actuated networks and more [83].

2. Topography and network connectivity: since WSNs transfer their data in a multi-hop fashion, mobility can enhance the network operation by changing the location of the nodes leading to fresher links to the destination required.

3. If mobility is limited to special nodes, e.g., sink node(s), the stationary nodes can then be relieved in terms of links generated to the destination node. The sink node(s) can roam around through stationary nodes and gather the information sensed by sensor nodes. A mobile sink node can also enhance the network connectivity by minimising the congestion that can happen during network traffic flow [84].

2.5.2 Mobility disadvantages to the network operation

Mobility can introduce a critical challenge to the operation of the deployed network:

1. If mobility is limited to special nodes, then those nodes can suffer from a bottle-neck problem. A considerable number plans and calculations are required to estimate the optimum number and paths for the special nodes to cover the deployed network [85].

2. If mobility is random, i.e., sensor nodes are also mobile in the network, the effect is greater as the network topology change becomes rapid and that has an effect on the connectivity of the nodes. Topology changes have effects on the routing operation as the links need to be rebuilt frequently; therefore, there is an increased energy consumption of the nodes. Mobility has effects on the MAC protocol operation because the connectivity can suffer from cut connections because of the transmission range of the wireless interface. Location of the sensor node(s) in random mobility is of importance because the sensed event is attached to the location of the sensor node. In the mobile scenario, the localisation mechanism becomes a frequent operation leading to an increment in node energy consumption [86].

As aforementioned, mobility is a serious issue in WSN operation. It has its advantages and disadvantages on diverse levels of network operation. The focus of this research has been on random mobility of the deployed sensor nodes and how it affects the network operation in terms of the connectivity and location estimation of the nodes. The connectivity issue has been dealt with by routing protocols and MAC protocols as both layers have the responsibility of insuring an available connection between one hop and another. The location information is an application layer attachment; however, it requires a specific mechanism to estimate the location of the mobile node(s).

2.5.3 Mobility affect on network connectivity

2.5.3.1 MAC protocols for WSN

The MAC protocol’s objective is to synchronise the send and receive operations of the network interface of the node. Manipulating and optimising the operation of a MAC protocol can improve the protocol efficiency in terms of energy consumption and packet delivery delays [87].

Different MAC protocol proposals have been defined for WSNs because of the application dependency issue. The proposed protocols have to compensate between power consumption efficiency and the system throughput to improve the system’s dependability [87], [88].

The wireless medium has a major characteristic that it is a shared medium. Therefore, MAC protocols need to operate efficiently when utilising the medium to ensure proper connections between the nodes. Designing MAC protocols for WSNs has to include an important consideration, which is energy efficiency. Conventional MAC protocols optimise delays and throughput. When it comes to WSNs, energy is an important issue that needs to be addressed [17]. MAC protocols can improve the energy efficiency of the system by improving the scheduling of the channel access. Sleep scheduling is a common way to improve channel access on a long time scale. Sleep scheduling is like the CPU’s shutdown techniques. The sleep scheduling explores energy against response time compensations in wireless communications. The response time is translated into system throughput or transmission delay [89].

The mobility affect on the operation of the MAC protocol is related directly to the transmission range. When a mobile node leaves the transmission range of the nodes in the vicinity, the process of regaining the connection becomes frequent which is a burden for the nodes involved. The research field of MAC protocols for WSNs is wide and active. MAC protocols proposed for WSNs can be categorised into two major categories [90]:

1. Contention-Based MAC Protocols (CSMA carrier sense multiple access). The wireless nodes contend to enter the medium of connectivity (which is the wireless medium in the case of WSNs) and the winner node reserves the medium for itself until it finishes its operation. Examples of this kind of protocol are: IEEE 802.11, S-MAC [91], T-MAC [92], R-MAC [93] and others.

2. TDMA-(time division multiple access) Based MAC Protocols. The medium is divided into time slots. Each node knows its time slot and when to enter the medium and perform its operation. One popular TDMA-based MAC protocol for WSNs is ALOHA [94].

Contention-based MAC protocols are more scalable in operation than TDMA-based protocols. TDMA-based protocols have to slot the connection time into periods for nodes in the vicinity. The slotting process can decrease scalability efficiency when deploying a large number of nodes. Below are some of the works in the field of Contention-based MAC protocols for WSNs:

IEEE 802.11 is a popular Contention-based MAC protocol for wireless communication systems. It is the current standard for Wi-Fi network interfaces and WLAN applications. IEEE 802.11 has been tested as a MAC protocol for WSNs. However, the MAC protocol was considered unsuitable for such applications because of the idle/listening operation states. The idle state was found to consume energy as much as the receiving energy; therefore, it was pointed out as an unfeasible solution for WSNs [91].

Ye et al. [91] proposed S-MAC (Sensor-MAC), a MAC protocol designed explicitly for WSNs. The main objective of this design is to reduce sensor node energy consumption. The protocol is scalable because it is based on the CSMA/CA operation. The protocol also has a collision avoidance capability. Efficient energy consumption is obtained by utilising a scheduling process of listening and sleeping states. The protocol can synchronise its sleep schedule with a number of nodes to form virtual clusters. The protocol utilises the same mechanism to avoid overhearing and hidden channel problems that is used in the IEEE 802.11. S-MAC, however, suffers from latency issues because of the periodic sleep and listen scheme. The periodic scheme is dependent on the operation's duty cycle (Figure 2.8).

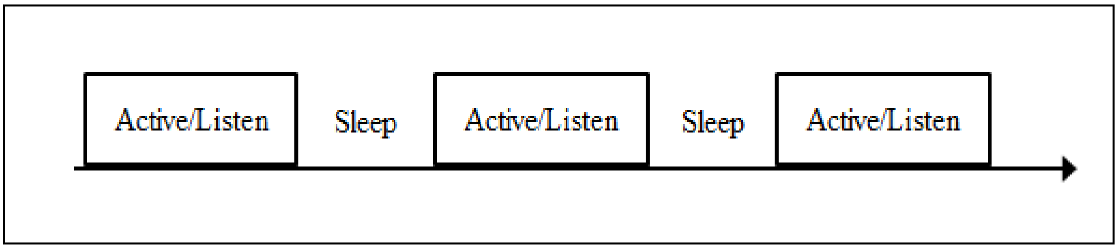


Figure 2.8: S-MAC periodic Listen/Sleep operation

S-MAC operates in the following manner: The source node of interest synchronises its sleeping periods with the receiving node to avoid retransmission of data packets because of the absence of a connection. When the source node has its interest available and wants to send data, it sends an RTS (Request To Send) packet to the receiver node to check whether the receiver node is not busy with another connection. The receiver node then replies to the sender node using a CTS (Clear To Send) packet to inform the sender of the receiver's availability. The sender node then initiates sending data packets to the receiver node. After the completion of the data packet transmission, the receiver node sends back to the sender node an acknowledgment packet (ACK) to inform of full reception of the data packet(s). Such a relationship is described in Figure 2.9.

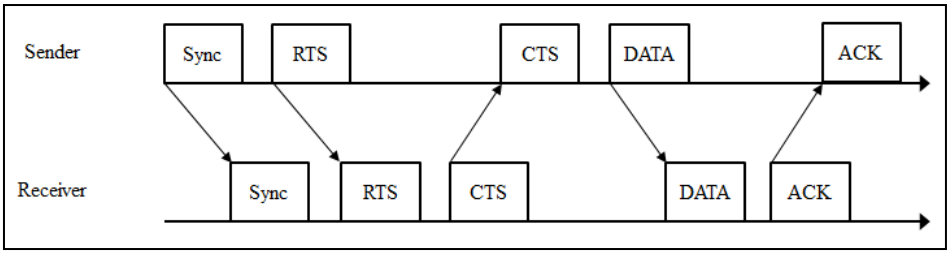


Figure 2.9: S-MAC operation between a sender node and a receiver node

WSN applications share some unique properties in operation. Properties such as: low message rate and insensitivity to latency [95]. These properties can be exploited and utilised to reduce the energy consumption using, for example, active/sleep schemes. Timeout MAC proposed by [92] can handle an adaptive duty cycle by dynamically ending the active part of it. This reduces the amount of energy wasted on idle listening, in which nodes wait for potentially incoming messages whilst still maintaining a reasonable throughput. T-MAC uses TA (timeout) packet to end the active part when there is no data to send/receive on the node. The protocol balances between energy efficient consumption and latency efficient throughput due to the scheme of burst data sending which is more effective in terms of energy consumption.

The authors in [96] explored the periodic listen and sleep scheme. As a result, they proposed TEEM (Traffic aware, Energy efficient MAC) a MAC protocol based on S-MAC protocol. The protocol provides energy efficient operation by utilising the 'traffic information' of each sensor node. They show that the nodes can be put to sleep earlier by anticipating the medium for a possible data traffic occurrence. To achieve these results, S-MAC had to undergo two important modifications: the first was to make the node turn off when there was no data or traffic expected, and the second was eliminating communication of a separate RTS (Request To Send) control packet even if data transmission was likely to occur. TEEM, however, lacks on packet delay efficiency to save energy.

A cross-layer solution was investigated and explored by [97]. TA-MAC, which stands for Task Aware MAC protocol, was the proposed solution. The protocol determines the channel access by monitoring the traffic loads of the two nodes involved in the connection. In this approach, the TA-MAC protocol can reduce energy consumption and improve the throughput by eliminating unnecessary collisions. The TA-MAC theory can be applied or integrated to other MAC protocols (e.g., S-MAC).

The authors in [93] have also explored the cross-layer approach and presented the Routing-enhanced MAC protocol (RMAC). The MAC protocol utilises the routing information in order to insure low energy consumption and guaranteed delays. RMAC is capable of delivering a packet through multi-hops in one duty cycle. In RMAC, during the sleep period, the relay node is activated only if the upstream node has the data packet ready to transmit. When the relay node receives the packet, it can also forward this packet to next downstream node. The control packet that informs the nodes of the transmission state is called Pioneer. The Pioneer packet is transmitted to the nodes in the downstream to synch their sleeping periods and their duty cycles to receive the data packet efficiently.

The authors in [98] developed on the S-MAC protocol and proposed SEA-MAC which is aimed at efficient energy consumption operations for habitat monitoring. The protocol design assigns the synchronisation schedule to the base station only. Sensor nodes are awake if there is an interest (event sensed) and, therefore, preserve the system’s energy. The duty cycles can be optimised to meet the requirement of the sensed event period. The packet which is responsible for initiating important data delivery in SEA-MAC is called the TONE packet which has a shorter period than the SYNC packet in S-MAC.

Whilst TDMA scheduling has its merits in terms of insuring connections, the literature shows that such a scheduling method is unfeasible for WSN applications because of the overhead of time slotting. The time slotting process can lead to improper results especially when the sensor node deployment becomes large scaled. The authors in [99] proposed the Energy and Rate (ER) MAC protocol. The main advantages of ER-MAC are: packet loss because of collision is less (or absent) because when two nodes engage in transmission, each one of them has its own schedule for transmission. However, packet loss can happen because of other reasons, such as link quality, interference, loss of signal etc. Time slots insure that there is no need for contention mechanism to engage in the wireless medium. Therefore, no control packets are required to control the contention process.

ER-MAC utilises the concept of periodic listen and sleep; however, it differs in operation from the one used, for example, in S-MAC. The sensor node goes to sleep mode only when the time slot is its own and has nothing to transmit. The radio interface needs to be awake during the neighbour node's time slot to receive packets even if the neighbour node has nothing to transmit.

Another example of TDMA-based MAC protocols is Real-Time MAC proposed by [100]. TDMA-based MAC protocols suffer from latency caused by the assigning of time slots which takes up a lot of time because of the number of sensor nodes deployed. RT-MAC overcomes this problem by reutilising the connection channel between two successive channel accesses of a sensor node. RT-MAC also allows sensors to go to sleep which preserves energy. Although it provides delay guarantee, the RT-MAC protocol requires a lot of computation that exhausts the sensor node itself in some cases like clock drifting problems. There are other works on the design of the MAC protocol-based on the TDMA scheme [101], [102]; they all share the same complexity in time slot assigning.

MAC protocols aimed at mobility scenarios have been introduced in the literature [103]. The mobility-aware MAC protocol for sensor networks (MS-MAC) [104] is a mobility aware extension scheme for S-MAC protocol. The MAC protocol utilises the duty-cycle operation to schedule the neighbouring nodes. The sender node tries to estimate the mobility of the neighbour node through the changes in the RSSI values. The values are captured through the transmission of SYNC packets. The node then adjusts its duty cycle to have an adaptive operation with neighbour nodes with mobility changes. MS-MAC consumes high energy as the synchronisation mechanism becomes frequent if the mobility in the network is high.

A mobility extension to the TRAMA MAC protocol [105] called MMAC has been introduced by [106]. The MAC employs the same procedure of TRAMA MAC protocol; however, the protocol utilises a flexible time frame that makes the protocol adaptive to node mobility. The mobility of the nodes is estimated using the AR-1 mobility estimation model. The main disadvantage of MMAC is that it inherits the computationally intensive operation by the TRAMA mechanism.

M-TDMA is another mobility extension scheme proposed by [107] based on TDMA mechanism. M-TDMA creates non-overlapping clusters by using the FLOC algorithm [108]. Each cluster elects a head and each node attached to the head has its own unique id. The protocol splits the round operation into two parts: the control part which handles the mobility adaptiveness and the data part which handles the data transmission process. The assumptions that are made for the operation of M-TDMA are strict. The nodes are expected to always hear from the cluster-heads in one round of operation. The second assumption is that the nodes are assumed to leave the cluster for two consecutive rounds.

MobiSense [109] is a cross-layer MAC protocol that utilises the routing layer information to achieve an energy efficient operation in mobility situations. MobiSense segments the network into clusters. The cluster–heads are stationary and placed in a planned manner with the mobile nodes roaming around the clusters. This is to simplify the management of the network operation. MobiSense's disadvantage is being dependent on planned static nodes and the multi-channel operating adjacent clusters which is expensive since it requires managing channel resources and a multi-channel compatible receiver design.

A current survey of MAC protocols for WSNs was carried out by [11]. The survey investigated more on the issues of each category of MAC protocols and showed the challenges that arise in industrial applications. Another extensive survey of MAC protocols was performed by [95]. The survey focused on general mechanisms applied on MAC protocols' major operation categories, CSMA and TDMA, and their derivatives.

To summarise the investigated literature, the authors of this present work devised a table that illustrates the categories of the MAC protocols proposed for WSNs, showing their advantages and disadvantages. Refer to Table 2.1:

Table 2.1: MAC protocols for WSNs

MAC Protocol	Category	Main Advantage	Main Disadvantage	Mobility
IEEE 802.11[91]	CSMA/CA	The Highest system throughput	Inefficient energy consumption	MANETS and mobile WSNs
S-MAC [91]	CSMA/CA	Scalable, energy efficient due to the sleep/listen scheme	Suffers from latency issues	Aimed mainly at stationary WSNs, however, has been used in mobile WSNs.
S-MAC Adaptive listening [91]	CSMA/CA	Energy efficient, adaptive listening period to improve throughput	The adaptive listening is effective for when the data packet is larger than the duty-cycle.	Stationary WSNs
IEEE 802.15.4 [64]	Slotted CSMA/CA	Energy efficient. Versatile in terms of possible applications to use for.	The delivery ratio degrades when the network scalability increases.	Stationary WSNs.

2.5.3.2 Routing in WSNs

An extensive survey of routing protocols for WSNs has been carried out by [110]. The routing protocols were categorised into four main branches:

1. Proactive routing: routing protocols from this category operates by exchanging routing table information periodically (e.g., Link-state routing). WSNs are energy limited networks. Therefore, the periodic exchange of the routing tables puts weight on the routing process which leads to undesirable results. If the network deployed is mobile, the problem becomes more sever for the network to handle because of the rapid topology change. An example of a proactive routing protocol is Optimised Link-State Routing (OLSR) [110].

2. Reactive routing: this category of routing protocol operates on source node demand. The node of interest starts the routing operation by sending and

broadcasting route request messages to the neighbour nodes [111]. The destination node then replies to the received route request messages to build the path. This type of routing process has its advantages when implementing it in a mobile node network. The nodes are not required to exchange routing table information. An example of reactive routing protocols is the Ad hoc On-demand Distance Vector (AODV) routing protocol [112], [113].

3. Hybrid routing: hybrid routing protocols combine the features of different routing approaches. DSR [110] is a reactive hybrid routing process. The source node initiates the routing process on-demand like AODV. However, the nodes are required to exchange extra routing information, such as a routing table (link state routing) to keep the routes updated.

4. Cluster-based routing: the process of routing requires the election of a cluster-head by a group of nodes in the deployed network. Cluster-heads can then communicate between each other to form a multi-level network (Hierarchical). Cluster-based routing is a bottleneck in the operation when the network deployed is mobile. The nodes are then required to re-elect cluster-heads depending on the mobility rapidness. An example of a cluster-based routing protocol is the Low Energy Adaptive Clustering Hierarchy (LEACH) routing protocol [110].

Routing protocols for WSNs are mainly based on routing protocol algorithms proposed for ad hoc networks. Protocols like AODV, DSR and their extensions are examples of such proposals. Other data centric-based routing protocols were also proposed for WSNs like the Direct Diffusion (DD) routing protocol [57]. With DD, all nodes are application aware which makes the protocol suitable for light monitoring applications. The geographic routing protocol [114] and rumor-based protocols also fall under the DD routing class.

A cluster-based routing derivative called Mobility-Based Clustering (MBC) proposed by [58] utilises a two-tier of information routing represented by a cluster-head and the connected nodes. The protocol operation exploits the TDMA strategy that assigns the information transmission and reception between a cluster-head and child node (connected node). The protocol has been proposed for controlling mobile WSNs. The TDMA strategy has its advantages in terms of guaranteed connection slot reservation. However, mobility has an effect on the network topology, therefore, an effect on the slotting process that is required by the TDMA strategy. This slot process can exhaust the nodes deployed if mobility is rapid and results in undesirable energy consumption. The multi-sink strategy has also been utilised in routing protocols proposed for WSNs. MUSTER [115], is an example of multi-sink routing protocols. The protocol is aimed at stationary WSNs which enhances the network routing operation by having more than one sink node (or base station) in a deployed network. The proposal improves the lifetime of the system; however, for stationary applications, it operates as a tree-based routing process.

Machine learning-reinforced routing protocols [116] have been discussed for WSNs. Given the limited constraints that WSNs have, routing protocols are required to be more intelligent in choosing the best path. However, the processing power in WSNs is another obstacle in performing such an approach unless the nodes are stationary to decrease the issue of environmental parameters changing.

The field of routing protocols for WSNs is presented by an extensive survey carried out by [117]. An experiment was implemented by [60] which identified the maximum number of links required to be considered by a node to provide an efficient operation. This was an important investigation which elevated some issues regarding the feasibility in cutting routes to provide better energy consumption for the network.

2.5.3.2.1 Routing metrics for wireless sensor networks

Routing metrics are quantities or values that determine the reliability level of the path between a specific source node and a destination node. These values aide the routing process by defining the best route to be chosen by the routing protocol. Proposing a routing metric is a cumbersome issue and requires substantial efforts. Routing metrics can have an effect entirely on the operation of the routing process that either enhances and improves the process or can drastically deteriorate the network operation in general [118]. Routing metrics represent different types of information about the link quality or level of worthiness of the next hop. In WSNs, the energy constraints elevate the consideration in proposing a proper metric to represent the optimal path chosen by the routing protocol. Mobility of the nodes brings up another issue represented by how easy it is to acquire and calculate the metric value and how the choice of the metric affects the operation of the routing protocol in a rapid changing network topology. According to [119], it is possible to classify routing metrics into two major classes:

1. Hardware metrics: Examples like Signal to noise ratio (SNR), Received Signal Strength indicator (RSSI) and Link quality indicator (LQI) [119].

2. Software metrics: Examples like Expected Transmission Count (ETX), Requested Number of Packets (RNP) and Four Bit (4Bit) [120].

Hardware metrics are based on measurements and values determined by exploiting the information of the wireless hardware interface. Hardware metrics are easy to collect or calculate. They are also easier in implementation, which is their major advantage over software-based metrics. Software metrics can depict better information about the estimated link quality. Software metrics are considered more accurate than hardware-based metrics. However, software metrics requires calculations that might have an effect on the operation if the calculation process is extensive. These extensive calculations can degrade the reliability of the routing protocol operation. If the nodes deployed are mobile, software metrics with their calculations can pose serious problems during operation.

Hop-count is one of the most widely used routing metrics in routing protocols for wireless networks whether stationary networks or mobile ones [121]. A study was performed by [121]to compare routing metrics for static wireless networks. The study included three routing metrics to compare against a hop-count metric: (1) ETX metric, which is based on calculating and measuring the rate of losing broadcast packets between two neighbour nodes; (2) per-hop Round Trip Time (RTT), which is based on the round trip delay observed between neighbouring nodes and the third metric was per-hop Packet Pair Delay (PktPair), which is based on the delay between a pair of back-to-back messages to a neighbour node. The result showed that ETX outperformed all of the other metrics in a stationary network whilst the minimum hop-count performed best in a scenario where the source node was mobile. Extensive studies and more recent ones of the above routing metrics can be found in [121] and [122].

A modification of the ETX metric has been proposed by [123] which utilises a heuristic approach combined with the remaining capacity in the area of saturated nodes and ultimately would relieve the network from possible interference and congestion in information processing. The method proposed by [123] is aimed at a stationary WSN or a WSN where the nodes would be mobile only for a period of time when the nodes are setting the network topology, and stay static through their whole lifetime.

Energy awareness is an important concept in the WSNs' routing operation. Following this concept, [124] introduced Gain per Energy Metric (GEM), a routing metric aimed at WSNs to increase the lifetime of the network considering the energy dissipated by a successful transmission with respect to the information gained from the transmission established. GEM is aimed at a stationary WSN's situation because it is possible to increase the effort in calculation on the node if the network topology does not change rapidly.

Ad hoc networks share several similarities with WSNs in terms of the ad hoc operation of both types of networks [117]. [125] proposed the usage of different types of modulation techniques utilised in the physical layer mixed with information of the packet fragmentation size to provide the least energy consuming route. The proposed metric was implemented on the AODV routing protocol and compared against the AODV original operation configurations. However, the proposed metric requires a search process for the best level of SNR to fit the fragmentation packet size. The latter process can lead to inefficient energy consumption on the sensor node.

SNR information has been exploited as a routing metric to enhance the route choice process of the routing protocol. Qianyu Ye [126] investigated the utilisation of the local SNR as the metric of choice for a cluster-based routing protocol. The proposed routing process is aimed at stationary WSN implementation where the nodes with the highest local SNR level would initiate sending their data. SNR information was also an interest in the proposal of [127] to enhance the operation of the DSR routing protocol. The proposal was compared against the ETX metric and simple minimum-hop selection process. The results of [127] illustrated that SNR performed better than the ETX metric performance. SNR was also investigated by [128] as a routing metric for the routing process of mesh networks. When implemented on the OLSR routing protocol, SNR showed significant results in terms of end-to-end delay and network throughput.

Routing metrics with combined types of information to estimate the link quality of service was also investigated thoroughly. The triangle metric [129] is an example of the type of metric mentioned. The triangle metric is aimed at a mobile WSN which combines the information of SNR, Packet Reception Rate (PRR) and LQI to result in a robust decision about the estimated link during the process of building the route required. The triangle metric performs better in stationary networks than in mobile ones.

Energy Efficient and QoS-based Routing (EQSR) [130] is another example of combined link information to provide a routing metric in a routing protocol. The protocol utilises SNR, residual energy and the node’s available buffer size to achieve its goal in estimating and providing an optimal path of data transmission between a source node and a destination node. A routing metric based on fuzzy linguistics was proposed by [131] called Fuzzy Link Quality Estimator (F-LQE). The proposal is built on four link quality properties: packet delivery, asymmetry, stability and channel quality. F-LQE performs well in a stationary WSN scenario where the time requirement is more relaxed than in a mobile scenario to estimate the four link properties mentioned. A holistic approach proposed by [119] as a routing metric combines four different link characteristics: short and long-term quality, link variation and an indicator of current trends. The Holistic Packet Statistics (HoPS) is proposed for static WSNs given the requirement of monitoring the link’s four characteristics periodically and is aimed at the tree-based routing protocol. Table 2.3 shows a summary of several routing metrics proposed for WSNs with their class, advantages and disadvantages.

The proposed methods mentioned in Table 2.3 were aimed majorly at stationary WSNs or if mobility is considered it would be limited to specialist nodes (e.g., base station nodes). Mobility increases the randomness in the connection fluctuation between one source and one destination as the relay nodes can change position rapidly. Inevitably, utilising a routing metric in a mobile WSN routing process is a must and has to maintain ease in collection and calculation with energy awareness as a vital object in WSNs.

Table 2.2: Routing metrics for WSNs

Metric	**HW/SW**	**Mobility**	**Advantage**	**Disadvantage**
SNR [119], [126], [127], [128]	HW	For MANETs, stationary WSN	Easy to implement as the information is hardware obtained	The quality of information is dependent on the noise model for the environment.
RSSI [119]	HW	For MANETs, Ad Hoc nets, Stationary WSN	Easy to implement	RSSI is dependent on the hardware quality of the wireless interface.
ETX [120], [123]	SW	Stationary WSN, MANETs	Efficiency in static networks	A rapid changing network topology effects on the calculations required for the estimation of the link.
EQSR (Energy, SNR and Buffer) [130]	Mixed metric	Stationary WSN, MANETs.	Energy aware, load balancing,	Multipath mechanism introduces overhead if applied in rapidly changing network topology.

2.5.3.3 Localisation in WSNs

Location information in WSNs is an important block in the information retrieved for the deployed sensor nodes [132], [133]. The sensor node's task is to sense a specific environmental effect like humidity or pressure. The information collected from the network usually contains the information regarding the sensed event and the sensor node that initiated the sensing activity in the network [21], [39], and [134]. The location information of the sensed phenomena is of great importance to the end user because it uncovers the behaviour of the environment being monitored and how the sensed event has an effect on that environment. Location information is important also to apprehend a source of an undesirable activity [86] (e.g., fire protection systems).

Location information can be exploited to improve the operation of other layers in the network operational stack like routing protocols [135], [136], [113], and [137]. Amongst the resource constraints the WSNs share, network lifetime is an important aspect and needs to be covered in the development of WSN operation [132], [138]. Mobility in WSNs can have an effect on the power consumption of the network in general because of the rapid change of the nodes' locations. Location estimation of the mobile nodes can become a frequent process and consumes power. Therefore, a location estimation method for mobile WSNs has to be power efficient.

2.5.3.3.1 Location estimation methods for WSNs

Location estimation methods proposed for WSNs range from additive modules to the nodes like GPS modules [135], and to the utilisation of mathematical trigonometry and distance measurements to find the location of the sensor node required (e.g., Trilateration and Triangulation). RF signals can be utilised to estimate the distances required in the localisation method through their Received Signal Strength Indicator (RSSI); because the nodes use wireless interfaces, it makes it possible to measure the RSSI of the connection signals. Other types of signals used to estimate the required distances includes but is not exclusive to: acoustic waves, light waves or any other alternatives to RF based signals.

Location estimation for WSNs is a vital area of research and has gained a major interest by researchers [33], [139], [140], and [141]. It is possible to list some of the major methods of localisation for WSNs as follows:

1. Global Positioning System (GPS): GPS receiver modules are attached to sensor nodes as a location estimation tool by utilising their satellite

coordinates [142], [143], and [144]. GPS systems are currently found on many electronic appliances and are used for urban localisation purposes. The major disadvantages with attaching sensor nodes with GPS modules is that they are rather expensive and cost a high amount of energy to operate when used in WSNs. They are also not appropriate for indoor applications.

2. Time-Of-Arrival (TOA): To apply the TOA method, sensor nodes are required to be equipped with two different types of signal source transmitters (acoustic waves, RF transmitter or infrared signals). The nodes can then transmit the required signals between each other and by calculating the time differences of both signals' arrival it is then possible to estimate the required location [145], [146]. The advantage of such an approach is the relatively low cost of the equipment as opposed to GPS systems. However, the accuracy of the signal estimation is rather low as the method requires a complex calculation to estimate the location required.

3. Angle-Of-Arrival (AOA): Like the TOA operation, the receiving node would calculate its location according to the received signal's angle of arrival [147], [34]. The signal type can be RF based. The nodes need to be attached with an array of directional antennae and by that the angle of the signal's arrival can be estimated and then the location calculated. Like TOA, AOA has difficulties of accuracy when calculating the angle of arrival and requires extra equipment to be added to the node(s).

4. Trilateration: Trilateration is the method of estimating a point of intersection of three circles (or three spheres if 3D geometry is applied). Location estimation using a trilateration method requires the availability of three beacon nodes (Beacon nodes are wired or wireless nodes that know their location whether by GPS or built-in by the user) [20], [148]. These nodes are placed around the sensor node(s) to estimate the location by determining the distance of a sensor node from each beacon node. With this information it is possible to estimate the location of the requested node. Trilateration is one of the widely used GPS free location estimation methods in wireless systems as it requires

the distance estimation of three beacon points using one type of signal, usually an RF signal is produced by the wireless interface modules.

5. Triangulation: Like trilateration, triangulation requires the presence of beacon nodes. However, only two can be sufficient [35], [36], [37], [149] and [150] compared to the three required by trilateration. Sensor nodes are required to have a directional antenna in their design to determine the angle of the signal's arrival and the distance of the beacon nodes from the requested sensor node. This forms a triangle and by trigonometric algebra, the location can be estimated. The directional antenna can sense the direction of the transmission unlike an Omni directional antenna which senses the signals on wide ranges of directions. With this disadvantage, the nodes are required to be equipped with an array of directional antennae (like the AOA method).

Following the trend by the methods proposed for locating a sensor node, there are three important variables to consider when implementing a location estimation method. The first is the node distance from the beacon node, the signal angle of arrival from a beacon node and the location of the beacon node [44]. The most used type of signal in estimating the distance is the RF signal because it is already available by the network interface of the wireless nodes [151]. This fact has given RF signals a great number of advocates as a distance estimation tool [152].

Usually, RF signals can be translated to their relative RSSI and from the latter it is possible to calculate the required distance. Other systems have proposed the usage of other types of signals like laser-beam signals or acoustic waves signals [132] because the equipment that produces such signals consumes less power than GPS modules. A study on joint RSS-based estimation of unknown location coordinates was performed by [153]. The results of the study show the possible errors of distance calculation if the RF value is dependent on RSSI. An extended work performed by Xinrong Li [154] investigated the usage of RSSI in a collaborative localisation method which merges the operation of two localisation algorithms called the multidimensional scaling (MDS) and maximum-likelihood estimator (MLE). The result is an algorithm of a collaborative approach that has the strength of both methods to avoid the inherent signal-modelling error in the MDS method. The method is suitable for stationary

WSN deployment. Cooperative localisation examples can be followed by the following proposed methods in [154], [155] and [156].

Guoqiang et al. [157] also indicated the ease of using and implementing RSSI as a distance estimator with precautions as the error produced by the estimation is dependent on the propagation model used in the calculations. The field of RF estimation has a tremendous number of proposals because of their greater availability in implementation (e.g., the wireless interface of the node) than other types of signals [158], [159].

Acoustic waves were proposed as an alternative for RF signals and an example of using these signals was implemented by Kim and Choi [159]. They implemented an indoor localisation system that utilises acoustic waves as distance estimators of the nodes from the beacon point. The system is aided by a digital compass to determine the direction of the mobile object. Because the environment is indoors, the system implements a band-pass filter to avoid the noisy effect that the acoustic waves can produce in indoor locations.

Zheng Sun et al. [160] proposed Cortina, an indoor localisation system that utilises both RSSI and Rtof-based (Round-trip Time-of-Flight) techniques to estimate the required distances. Various algorithms have been applied to override the multi-path problem; the complex calculation can result in high power consumption for the wireless node. Indoor location estimation caught high interest in the field of indoor sensor networks because of the challenges that come with such an environment. A proposal to improve the RSS estimation by [161] implementing two methods to achieve accurate signal propagation was made. The two methods were regression-based and correlation-based. The proposed methods have been aimed at indoor environments.

SpiderBat [162] is a location estimation system proposed for a WSN which includes the information of both distance and the angle of the sensor node by using an ultrasound-based transmitter and receivers in all compass directions. The node is also equipped with a digital compass to indicate the direction of the node. By collecting the information from both sources, it is possible to calculate the location of the required node. The system requires one anchor node to operate. It also requires the nodes to be equipped with two types of modules: the ultrasound transmitters and the digital compass. The node can consume a high amount of power depending on how frequently the location information is required. Chia-Ho Ou [163] proposed a localisation method for a WSN using mobile anchor nodes. Each anchor node is equipped with four directional antennae, digital compass and a GPS module. The anchor node roams around the deployed stationary sensors and through sending beacon messages, the receiving node would be able to determine their coordinates according the sender antenna of the anchor node. The method aims to be efficient in the power consumption of the nodes and possess a low location estimation error. The directional antenna-based mobile or stationary anchor localisation scheme is highly proposed in this research area as several works have been described by [44], [148] and [163]. The number of deployed anchor nodes in the network also affects the performance of the localisation process of the network [141], [164].

Mobility in a WSN increases the problem of localisation as the nodes tend to change their location rapidly which requires the localisation process to be called every time the network topology changes, Unlike stationary WSNs where the localisation can be achieved at the initialisation process of the network [165], [166].

Isaac Amundson et al. [147] proposed a localisation approach for a mobile WSN where the sensor nodes are equipped with a digital compass to maintain the position of the mobile node during mobility. The proposed method requires the anchor nodes to have an array of nodes: one is the primary node and two more assisting nodes are combined together to make one anchor node. The mobile node performs regular localisation using triangulation. The rapid change in the mobile node position increases the calling for the triangulation location estimation process which leads to high power consumption on the sensor node’s behalf. The speeds of mobility in the performed simulations were between 100mm/s and 400mm/s.

Localisation systems proposed for WSNs are mainly focused on providing the location of the sensor node(s) in the network (mainly stationary nodes). The importance of the location is dependent on the application type applied. However, sensor networks are energy constrained systems. If the nodes were to be mobile in the network and the location was required rapidly, the localisation process is would be initiated rapidly. The localisation process can be computationally exhausting which would then reflected on the node’s power consumption. Energy efficiency has to be a priority in designing a suitable localisation method for mobile WSNs.

Table 2.3: localisation estimation methods.

Localisation method	**Advantage**	**Disadvantage**
Trilateration, Triangulation [20]	Easy to implement as the information is hardware obtained	The quality of information is dependent on the wireless interface hardware of the node. The mobile node energy consumption increases as the method requires frequent usage of the wireless interface.
Isaac Amundson et al. [147]	Mobile node location estimation method.	Requires an array of antennas to operate. The mobility of the tests were between 0.1-0.4 m/s. The location estimation error is at 0.95 meters at the tests mobility speed.

2.5.3.4 Cross-layer protocols in WSNs

The authors in [167] introduced a cross-layer operational mechanism that considers the routing, MAC and physical layers to maximise the network lifetime. The model assumes the network problem as convex where $G(P, h(n_i))$ is the network graph and P is the set of nodes deployed and $h(n_i)$ is the amount of data from node i that is needed to represent the sensed event in the deployment area. The nodes deployed are static. The model has not been tested for WSNs with mobility characteristics.

The XLP protocol is a cross-layer protocol that employs the concept of initiative determination. Introduced by [168], the protocol represents one of the first models to introduce a tight coupled cross-layer operation into one module.

The service oriented cross-layer operational model has been introduced by [169]. The protocol aims to prolong the network lifetime by maintaining the number of nodes required to achieve the application requirement. The application-based operation tracks the duty-cycles of nodes so that the network is maintained for the sensed services that are available.

SAMAC [170] is a cross-layer model that combines the slotted operation of the MAC protocol with the direction of the attached sectored directional antennae. The communication interferences between the nodes are lowered because the communication is between the directional antennae as Omni-based antennae can infer higher interference. The zones of the connections are directionally related to the directional antennae. The MAC mechanism starts by the CSMA/CA operation to converge the network and when the network is fully converged, the nodes then start transmission using the TDMA operation.

The authors of [171] proposed Breath. It is a cross-layer model for industrial applications. The protocol investigates the coupling of the routing, medium access control and the node's duty-cycle to achieve a longer lifetime. Breath adapts to traffic variation and channel conditions. The environment of deployment is industrial facilities where the nodes are stationary and deployed in a planned setting.

Transmission power control is introduced in a cross-layer operation as in [172]. The proposed operation utilises a TDMA-based MAC mechanism with a clustering routing algorithm. The transmission power control is achieved based on the path-loss characteristic of one hop between to connected nodes. If the nodes are mobile, the transmission recalibration operation of the whole network has to be performed in a frequent manner. Since the approach assumes that the transmission power control is performed for every packet type, the recalibration process becomes energy expensive.

A cross-layer operational model has also been investigated to improve the operation of one layer such as [173]. The method proposes a solution for the hidden terminal problem that the IEEE 802.15.4 MAC protocol suffers from. The solution investigates the over hearing of the hidden nodes and based on their overlapping signals in the physical layer, the protocol addresses the hidden nodes.

A cross-layer geographic-(location-based) based routing with mobile sink nodes has been proposed by [137]. The protocol utilises the mobile sink node's location broadcasting to the neighbouring nodes. The location information then reaches the sink using those neighbour nodes' overhearing of the location to deviate the data transmission accordingly.

The authors of [174] proposed the ZigBee-based mobility enhanced topology configuration approach for MWSNs. The model utilises the nodes' locations and their probabilistic behaviour to be near the routing path. The final model improves the delivery ratio of the network by forcing the nodes to gather near the network tree root. The scope of this paper has been the cross-layer operation's enhancements for MWSNs.

Routing-focused cross-layer mechanisms have been introduced for MWSNs [84]. A mobility-based clustering routing protocol (MBC) for wireless sensor networks has been proposed by [58]. The protocol incorporates the node mobility direction and cluster-head residual energy to create a metric for time slotting the connection between the nodes using the TDMA mechanism. The protocol utilises the transmission power control between the cluster-head and non-cluster head nodes. The cluster-heads are assumed stationary and some of the deployed nodes are mobile.

Location enhanced routing has also been introduced by [175] for the MWSN. Location aware and fault tolerant clustering routing protocol [175] is an example of such approaches. The protocol improves the clustering mechanism by assuming that the cluster-heads are chosen if there mobility indicator is the lowest and there residual energy is above the threshold value. However, the mechanism also assumes that the cluster-heads when chosen, are to be stationary or remain in the same cluster for the whole operational period. This limits the network's general operational flexibility.

An Energy Efficient and QoS aware multipath routing protocol (EQSR) has been proposed by [130] for WSNs. The protocol utilises multipath routes to find the best path from the source to the destination. The protocol cross-layers its routing paths choice criteria based on the physical layer elements of the next hop. Those elements are the node's(s') residual energy, interface buffer availability and the connection signal-to-noise ratio (SNR) between two neighbour nodes. The protocol is an example of a tight cross-layer of information between the physical-layer and the network layer (routing protocol).

Table 2.4: Cross-layer operation model for WSNs.

Cross-layer model	**Advantage**	**Disadvantage**
EQSR [130]	Multipath routing operation with physical layer cross-layer operation. Two layers crossed together.	In mobility multi-paths can be hard to establish since the network topology changes rapidly therefore effecting the network throughput.
L. Shi and A. Fapojuwo model [172].	Energy efficient as the model utilises transmission power control and cluster based routing	The model is not suitable for mobile operation as the transmission power control method is assumed to be operative to all the packets transmitted from the nodes whether they are control packets or data packets.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The objective of this research has been to propose and develop a network operational model for mobile WSNs. The cross-layer operation utilises information calculated and processes performed at the following layers:

1. Data-link layer MAC protocol and transmission power control.
2. Network layer routing protocol.
3. Application layer-based information represented by the sensor node's estimated location.
4. Control packet overhead reduction mechanism.

This chapter discusses the proposed network model. The next section describes the model operation in a brief form. Section 3.3 describes the MAC protocol proposed for the model. Section 3.4 discusses the proposed routing operation for the proposed network model. Section 3.5 illustrates the location estimation method. Section 3.6 details the operation of the network model with a description of the cross-layer operation in the model.

3.2 Cross-layer network operational model

The concept of cross-layer involves the utilisation of different layers' information and passes it between the layers' processes or operations to achieve a specific task. The main objective has been to propose a cross-layer network operational model for mobile WSNs. Figure 3.1 describes where each component of focus had an effect on the proposed operational model.

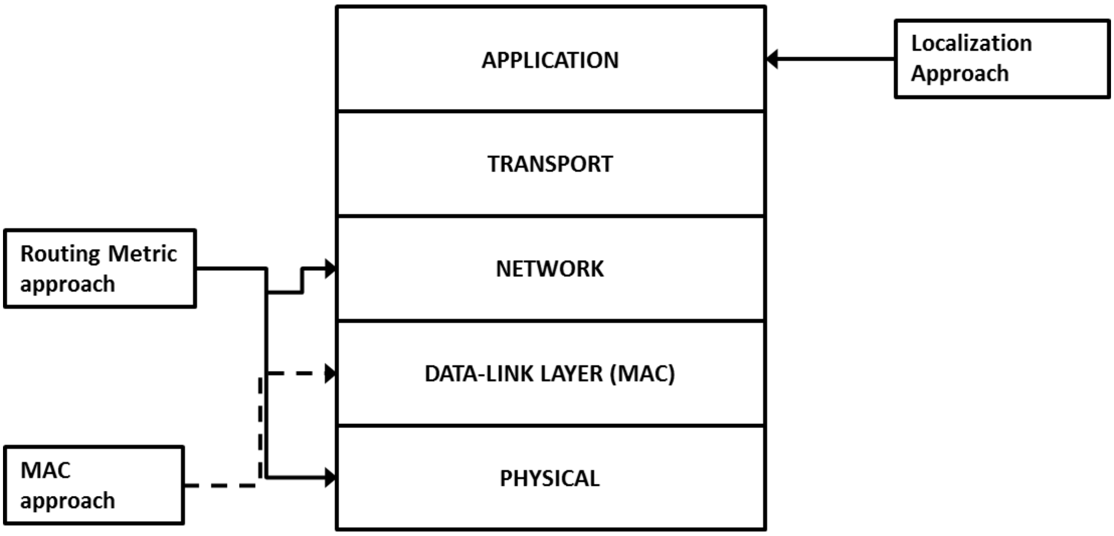


Figure 3.1: The components of focus' affects on the proposed operational model

The localisation method provides application important information which is the location of the mobile node with an energy efficient operation (hardware property). The routing metric is a cross-layered approach that utilises information from the physical layer to aid the routing operation. The MAC approach serves the MAC layer of the system. The proposed operational model is cross-layer in operation by implementing the following concepts:

1. After initialising the network, the nodes will have the ability to access their location information. This information will be embedded in the RREP control packet of the routing protocol.

2. The routing can maintain the next hop of transmission in a route and because of already performing the information exchange (which includes the location of the next hop), it is then possible for the sending node to calculate the distance to the next hop.

3. The distance information is then passed to the MAC layer operation where it has the ability to control the transmission power required to send a packet.

This approach yields less power consumption when the sender nodes are trying to send packets to their next hop(s) in the route. Figure (3.2) describes the cross-layer approach implemented on the proposed operational model. This approach represents a three layer cross-layer operation.

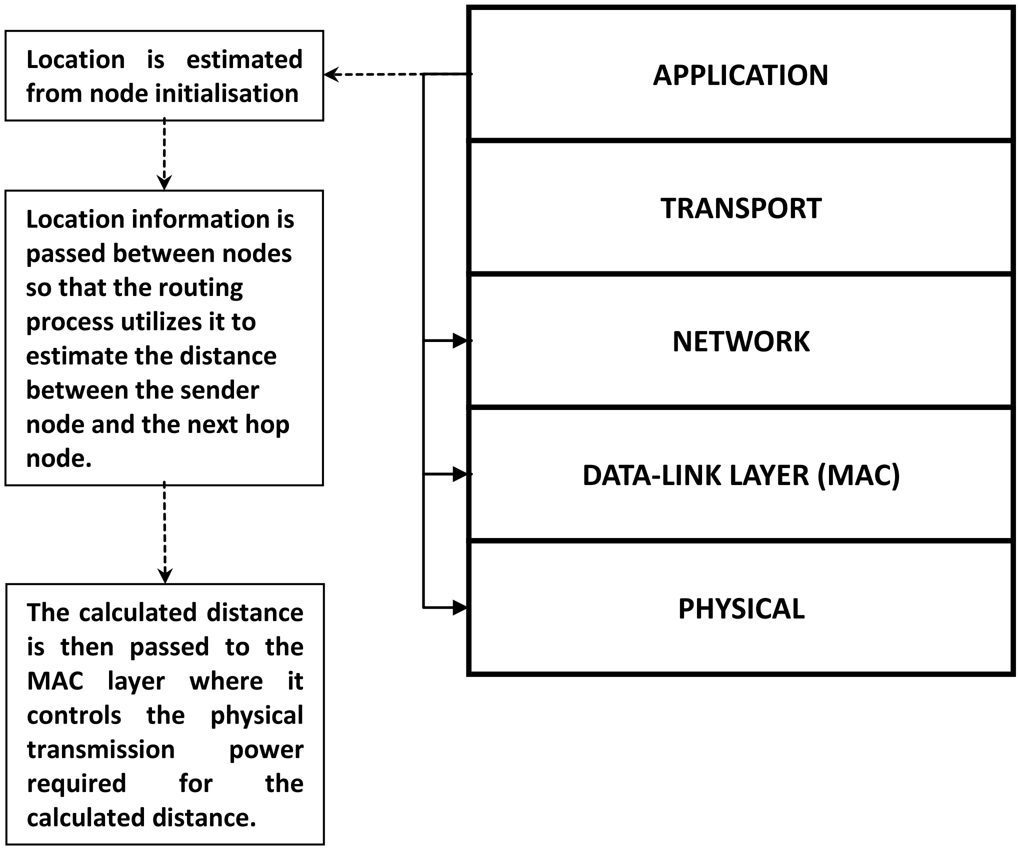


Figure 3.2: Three layer Cross-layer approach using the proposed operational model

The abstract representation in Figure 3.2 shows a brief overview of the proposed model operation. The model design goes deeper. Mobility has an effect on a sensor node's connections and this is the main challenge that this research has tried to overcome. In mobility, node connections are frequently involved in the re-association process in the MAC layer. Therefore, a MAC protocol needs to be designed for mobility. The routing process is required to be adaptive and reliable in a mobility scenario. Sensor node locations change according to their mobility. The localisation process has to become mobile friendly, i.e., the method has to be light and energy efficient for the nodes to process. Section 3.3 discusses the proposed MAC protocol for the operational model with analysis for energy consumption and message delay.

Section 3.4 discusses the optimisation method proposed for the routing protocol to meet the requirements for a mobile environment. Section 3.5 illustrates the proposed location estimation method. Section 3.6 details the cross-layer operation of the proposed network model.

3.3 The proposed MAC approach

This section discusses the proposed MAC approach, SEEK Mobile ADaptive Protocol (SEEK-MADP), solution for the operational model. The next section describes the protocol operation and provides analysis of the energy consumption and delay of the data packet delivery.

3.3.1 SEEK-MADP protocol operation

The MAC protocol proposed is based on S-MAC protocol. The proposed MAC implements the control packet operation in a different fashion to provide better operation in terms of energy consumption and packet delivery delays. The proposed protocol operates in the following manner:

A short neighbour discovery (ND) broadcast packet is broadcast between the nodes at the network initialisation for neighbour discovery. The ND packet is a very short packet and has only a source node address. After establishing the neighbour's table(s), a control packet that combines the functionality of a SYNC packet with an RTS packet is sent to the next hop. This combination eliminates the need of sending two packets and decreases control packet overhead. This packet from now on will be referred to as SEEK.

The nodes in the network are mobile; therefore, the data sending period is made adaptive by dividing it into four periods. The adaptive operation is implemented to minimise the possibility of data loss at the nodes that are prone to be out of connection range. The choice of the data period is chosen when the nodes transmit and receive the SEEK and CTS packets. Both packets have a mobility category ($MobCat$) indicator field represented by two bits (Table 3.1).

Table 3.1: Mobility category and data period mapping

Bit configuration	Mobility category (**$MobCat$**)	Data period
00	Stationary	Full
01	0 > Speed <= 1/3 Max. Mobility Speed	3/4 Data period
10	1 > Speed < Max. Mobility Speed	1/2 Data period
11	Speed = Max. mobility Speed	1/4 Data period

When a node in the stream receives a SEEK or CTS packet, the recipient node checks the mobility indicator field as explained in Table 3.1. The node then chooses the data period according to the category with the highest speed. The nodes engaged in the connection will then have the same data transmission period. This approach improves the data transmission process by minimising the data period if the nodes are moving at high speed.

To increase the throughput of the system, the (SEEK) packet will be sent all the way to the downstream nodes before sending the CTS packet to the upstream node (Figure 3.3). This will open the way for the data packet to move through the stream of nodes until it reaches the base station node (or the required destination node). This mechanism will generate a long idle delay period on the downstream node when waiting for the data packet(s) to be transmitted. This idle period can be represented by the following equation:

$$Period_{idle} = \sum_{i=0}^{\{m\}} t_{idle(i)} \quad \text{……(1)}$$

where $t_{idle(i)}$ represents the idle period generated after the SEEK reception at node i, i is the node id, and $\{m\}$ is the set of relay nodes in the data stream. To minimise the effect of the incremented idle period, the SEEK recipient node will check the clock time of the receiving data from the upper node ($T_{sendData}$).

$$T_{sendData} = t_{CTS} + t_{data}(MobCat) + t_{ACK} \quad \text{……(2)}$$

If the data clock time is greater than double the time required to generate a SEEK and CTS packet, consecutively, the node will put itself in sleep mode for a period equal to the time stamp of receiving the SEEK packet plus the difference of the data's expected reception time to the time stamp (Figure 3.4).

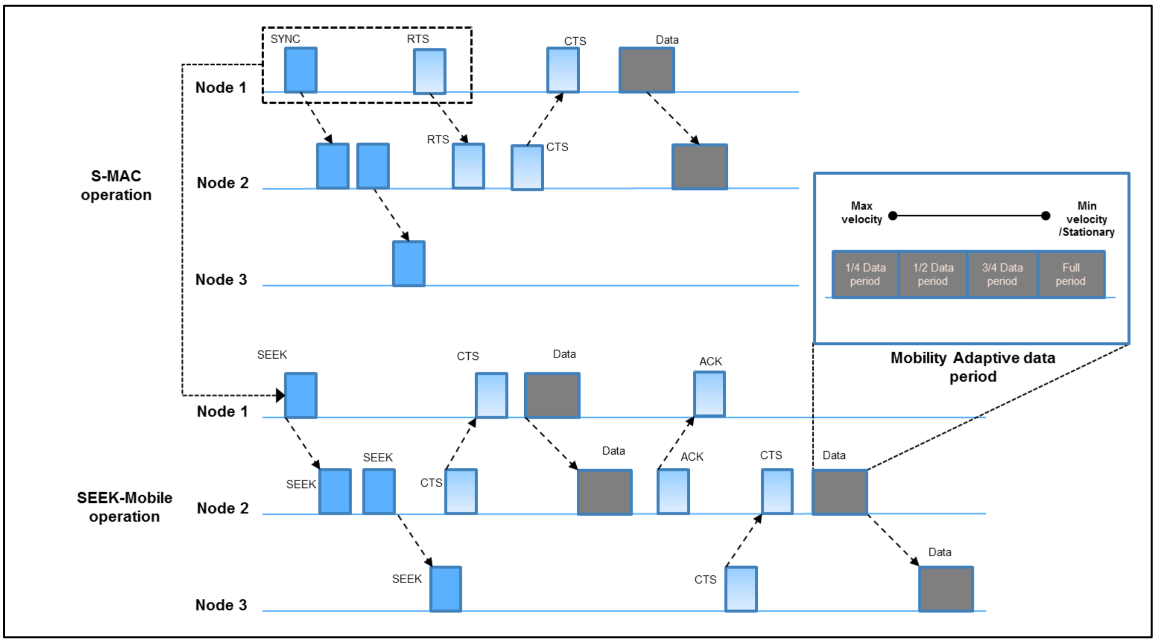


Figure 3.3: SEEK control packet operation between source node (Node 1) and destination node (Node 3)

```
Idle period time check algorithm
Line1: Node relay recv SEEK
Line2: Ts = time stamp of SEEK packet
Line3: Td = expected time of sending data packet
Line4: Tseek = Time required to generate SEEK packet
Line5: Tcts = Time required to generate CTS packet
Line6: Tsleep = Sleep period
Line7: If (Td > (2 * Tseek + Tcts))
Line8: Then Tsleep = Td-(Ts+Tcts)
Line9: Go to Sleep
```

Figure 3.4: Idle period avoidance algorithm

3.3.2 Energy consumption analysis

To analyse the energy consumption for the SEEK MAC protocol, a basic three node scenario (Figure 3.5) has been proposed to investigate the relationship between the nodes when the MAC protocol is in operation. The following assumptions were given for analysis purposes:

1. All nodes in the way are by all means available for any packet transmission.
2. The packet delivery direction is from node 1 to node 3.
3. Node 3 cannot overhear node1.
4. No collision happens between nodes (assuming that Carrier Sense is successful in each transmission start).
5. DATA packet could be transmitted in one hop.
6. All control packets are fixed in size.
7. Data period is a function of the node's(s') mobility speed. The highest the mobility speed has the shortest data period. The lower the speed, the higher the allocated data period.
8. If the next node in the way is in sleep mode, SEEK works as the signal that wakes up the node.

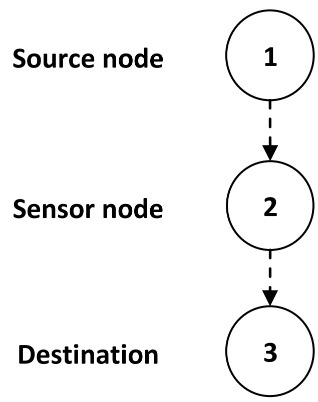


Figure 3.5: Analysis Scenario. Node 1 was the source node which had the data of interest and intended on sending them to destination Node 3.

The analysis started by separating each node's energy consumption analysis during operation for the given scenario, starting with node 1 (as the sender node):

$$E_{Node1} = E_{SEEK}(t_S) + E_{CTS}(t_{CTS}) + E_{DATA}(t_{DATA}(MobCat)) + E_{rcvACK}(t_{ACK}) \;\ldots\ldots\ldots\; (3)$$

The variables utilised in the equation above have been listed as, t_{SEEK} representing the time required to transmit the SEEK packet, t_{CTS} as the CTS packet time length, $t_{DATA}(MobCat)$ DATA packet time length function which was a function of the node's(s') movement speed. $MobCat$ stood for the mobility speed category of the node(s). Following the same trend in node 1, node 2's energy consumption trend can be illustrated as in equation (4):

$$E_{Node2} = E_{rcvSEEK}(t_{SEEK}) + E_{SEEK}(t_{SEEK}) + E_{CTS}(t_{CTS}) + E_{rcvDATA}\big(t_{DATA}(MobCat)\big) + E_{ACK}(t_{ACK}) \;\ldots\ldots\ldots\; (4)$$

Node 3's energy consumption trend can be described in equation (5):

$$E_{Node3} = E_{rcvSEEK}(t_{SEEK}) + E_{CTS}(t_{CTS}) + E_{rcvDATA}\big(t_{DATA}(MobCat)\big) + E_{ACK}(t_{ACK}) \;..(5)$$

Finally, the equations that represented the energy consumption of each node in the analysis could have been combined into one equation that represented the trend of the energy consumption of the system (Equation (6)).

$$E_s = E_{Node1} + E_{Node2} + E_{Node3} \;\ldots\ldots\ldots\; (6)$$

where E_s represented the energy consumed by the analysis system when the SEEK MAC protocol was in operation. The S-MAC energy consumption of each node could have been represented by the following equation:

$$E_{SMAC} = E_{SYNC}(t_{SYNC}) + E_{RTS}(t_{RTS}) + E_{CTS}(t_{CTS}) + E_{DATA}(t_{DATA}) + E_{ACK}(t_{ACK}) \;\ldots\ldots(7)$$

Applying equation (7) to the scenario in Figure 3.5, the system energy consumption equation was represented as follows:

$$E_s = \sum_{i=0}^{N} E_{SMAC}(i) \;\ldots\ldots\ldots(8)$$

where N was the number of nodes in the data stream and i was the node id.

3.4 Routing protocol proposed optimisation method

The routing protocol operation development focuses on proposing an energy aware and link aware routing metric. The design process is divided into two parts: the first is to establish the base routing protocol and the second is the routing metric.

3.4.1 The base routing protocol

Choosing a base routing protocol for the proposed metric was an important task. The aim was at a mobile WSN. With mobility, there are several issues that have to be maintained to achieve the required performance. The required routing protocol has to encompass the following properties:

1. Energy limitations in WSNs require the operation to be classified as phenomena driven networks. The nodes start communication only when there is an interest of sending data from one particular source to one particular destination.

2. Because of mobility, the protocol has to have the ability to rapidly maintain the topology of the deployed network. This is achieved by maintaining the list of neighbours around a node.

3. WSNs are expected to be large in deployment. The chosen protocol has to have the ability to maintain a heavy load of exchanged information.

The above points describe vastly how the routing protocol needs to operate for the proposed metric to succeed. The above points narrowed down the choice of the routing protocol to two on-demand routing protocols, namely: AODV and DSR routing protocols [110], [112]. Both protocols, AODV and DSR, share three similar main points of operation:

1. AODV and DSR are on-demand based routing. Which means that the path calculation is established only when the node of interest needs to send some particular data. This meets the proposed metric's requirement for point 1 above in the properties required for the chosen routing protocol.

2. Both protocols maintain their network topology by periodically sending *Hello Packets* between the nodes to maintain their neighbour's lists. This meets point 2 of the above requirements.

3. Both protocols are aimed at mobile wireless networks with a large number of deployed nodes. This meets the third point of the above properties.

With such similarities [176], the protocols claimed the highest level of consideration in Mobile Ad Hoc Networks' (MANETS) researches regarding their operation and their applications to be used in. According to a study performed by [112], both protocols handle wireless networks differently when it comes to mobility and the number of nodes deployed in the network. DSR outperformed AODV in terms of end-to-end delay when the network scenario had a low number of nodes and low level of mobility. DSR uses source routing to calculate the paths required for one source to one destination. AODV utilises table driven path calculation which can maintain a single link at a time.

The study also showed that AODV outperformed DSR in terms of system end-to-end delay and throughput when the scenario had a high number of nodes and high level of mobility. DSR lacks the mechanism to avoid stale route problems which cause inaccuracy and packet drops when the number of nodes deployed is high. AODV deploys a fresh sequence number with every route calculation to prevent stale routes from being involved in the route establishment and to provide loop free operation. According to the study results, the DSR operation deteriorated when the number of nodes deployed increased and when the mobility requirements were high. Motivated by the above findings, AODV was chosen as the base routing protocol because it met all of the important requirements as a base protocol aimed at mobile WSNs.

3.4.2 The composite metric

The proposed metric utilised two physical values from the nearest neighbour node namely, the node's residual energy and the RSSI of the link. The metric was then embedded in the operation of the AODV protocol.

Consider the following network graph $G(N, E)$ where N represents a set of nodes deployed in an area and E represents the edge (connection) that connects the set N to the other nodes. Figure 3.6 describes an evaluation scenario for the AODV protocol using the hop-count metric. Assume node 1 is the source node and node 7 is the destination.

Node 1 had data that needed to be sent to node 7. Node 1 started broadcasting route request packets (RREQ) to the neighbour nodes. During the operation of the RREQ broadcasting, a counter started to count the number of hops that the RREQ packet(s) had passed (hop-count). RREQ messages were attached with a sequence number. The sequence number function was to avoid broadcast storms that could happen from receiving the same request from several nodes. The node that received the RREQ message checked the sequence number attached. If the node received two RREQ (or RREP) that had the same sequence number, the receiving node chose the packet with the lowest hop-count. If the sequence numbers received were different, the highest number was chosen as it represented a fresh link. The neighbour nodes forwarded the RREQ packets through the network until they reached node 7. According to the hop-count metric, node 7 chose the reverse neighbour node with the least number of hops to send a unicast route reply packet (RREP).

RREP was then sent through the network until it reached node 1 and a route was established for data transmission. From the scenario above, it is possible to see a specific issue that could occur during the route building process. There were multi-routes with the same number of hops; these were: 1↔3↔5↔7 and 1↔3↔6↔7. This issue raises an inconsistency in the operation of the routing protocol when using the hop-count metric. The composite metric can evade this inconsistent occurrence by utilising the RSSI and the residual energy level of the chosen neighbour node. The values of both the RSSI and energy level(s) are dependent on the hardware specifications and the network interface of the node (Figure 3.7). The proposed composite routing metric gave priority to the residual energy level of the neighbour node. The second priority was for the RSSI value. The established route according to the values in Figure 3.7 was: 1↔3↔5↔7. The composite metric followed the algorithms described in Figure 3.8 and Figure 3.9.

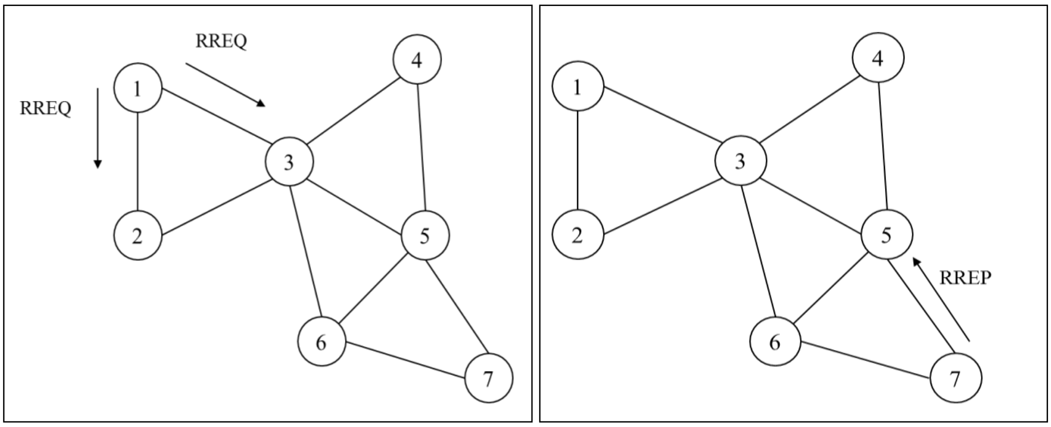


Figure 3.6: (a) Broadcasting process of the RREQ messages (b) RREP unicast message

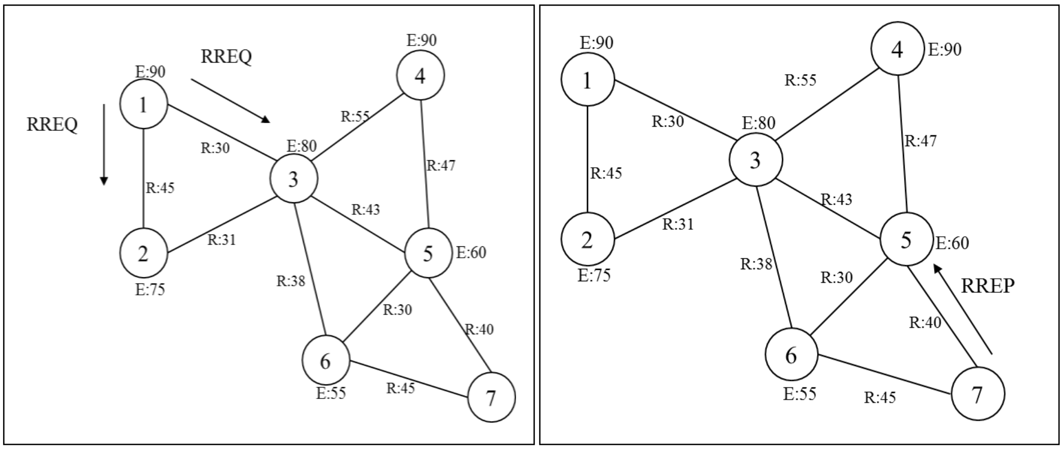


Figure 3.7: (a) Broadcasting process of the RREQ messages (b) RREP unicast message: E and R labels stand for energy and RSSI, consecutively

```
Algorithm 1: Receive RREQ message handling
Line1: Seq ← Sequence no. RREQ
Line2: Energy ← EnergyRREQ
Line3: RSSI ← RSSI RREQ
Line4:  if(seq>=Seq_table)&&( Energy >Energy_table)) ||
       ((Seq >= Seq_table)&& ( Energy = Energy_table)&& (
       RSSI > RSSI_table))
Line5: then Update route entry (current_node)
Line6: Update Energy_RREQ = Energy_current_node
Line7: if(current_node == destination),
Line8: then Send RREP
Line9: else forward RREQ
```

Figure 3.8: RREQ message handling function

```
Algorithm 2: Receive RREP by source node
Line1: Seq  ← Sequence no. RREP
Line2: Energy ← Energy_RREP
Line3: RSSI ← RSSI_RREP
Line4:  if(seq>=Seq_table)&&(  Energy  >Energy_table))  ||
       ((Seq >= Seq_table)&& ( Energy = Energy_table)&& (
       RSSI > RSSI_table))
Line5: then { Update route entry (node x)
     Send data }
```

Figure 3.9: RREP message handling function

The control packet structures for the modified AODV version are depicted in Figure 3.10. The composite metric values were embedded in the control packets as follows: the residual energy was embedded in the reserved section of the RREQ and RREP packets as a 7-bit value (ranging to 128 values). The residual energy was first mapped to its percentage values and then to the equivalent of the percentage in the decimal range. The RSSI values were replaced by the hop count as a 7-bit value (ranging to 128 values). The range of values was enough as the lowest value that can be sensed by the wireless interface was -92 dB [177].

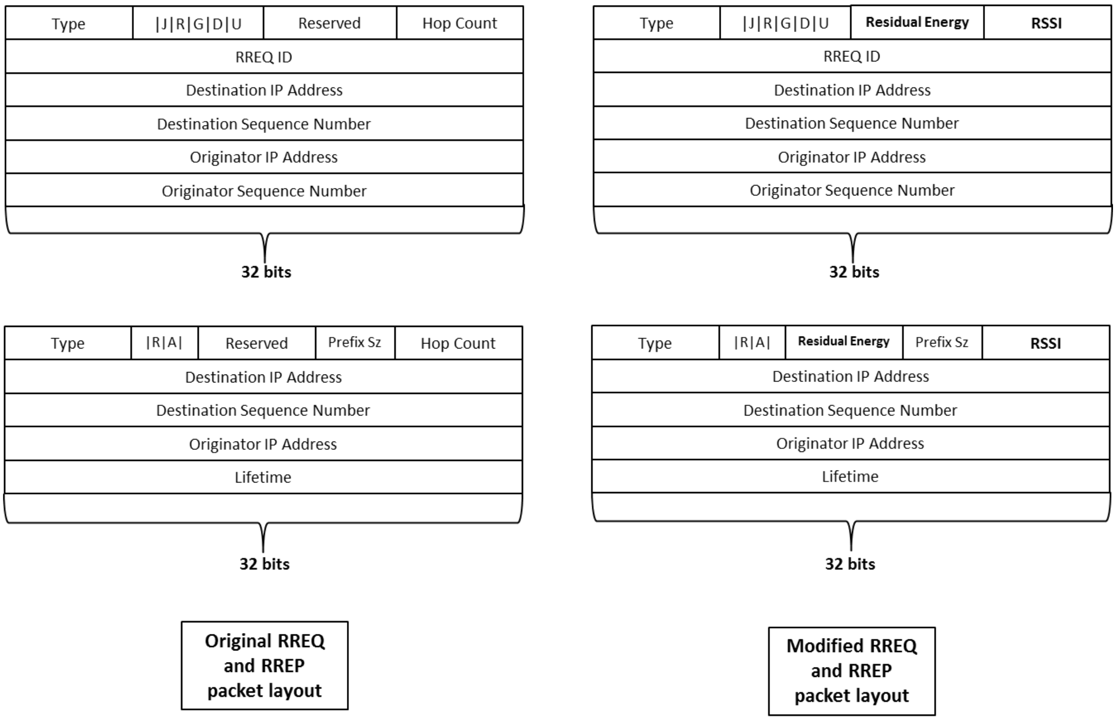


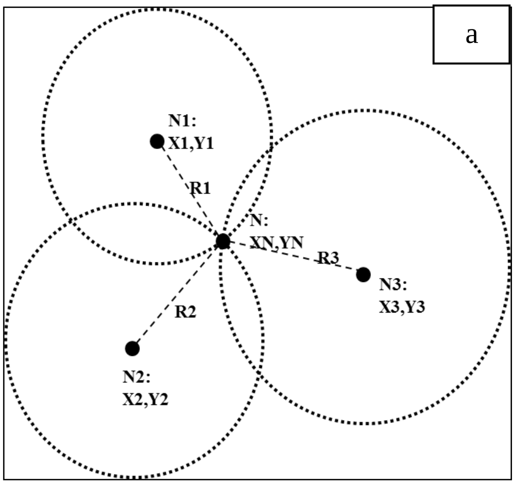
Figure 3.10: Control Packet layout for the AODV protocol.

3.5 Proposed location estimation method

The proposed location estimation method is based on two aspects merged together to determine the location of the mobile node(s). The first is trilateration. Trilateration requires the availability of beacon nodes provided that their own exact locations are known (Figure 3.11-a). The location of the unknown node is found by finding the intersection of the three circles.

The method proposed is aimed at a mobile WSN where the nodes change their location rapidly. The assumptions made for the proposal are listed below:

- The nodes are capable of collecting their movement speed either by an attached speedometer device or by methods of calculations (the number of wheel rotations, for example).
- The deployed network is surrounded by three beacon nodes which can spread a signal that covers the whole area where the nodes are deployed. The beacon nodes are stationary.
- Each node is equipped with a digital compass to update the node's location during its movement.



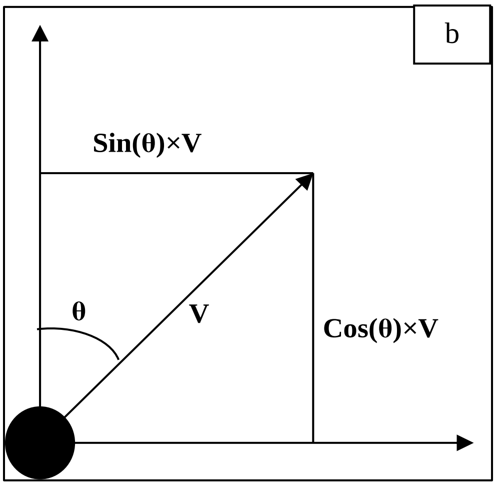


Figure 3.11: (a) Trilateration method (b) Mobility vector location update

In Figure 3.11-a, the beacon nodes are N_1, N_2 and N_3. Their actual locations are (x_1, y_1), (x_2, y_2) and (x_3, y_3) (assuming the Cartesian plane). Their distances from the unknown node N (x_N, y_N) are represented by R_1, R_2 and R_3 in equations (9) – (10).

$$(x_1 - x_N)^2 + (y_1 - y_N)^2 = R_1^2 \quad (9)$$

$$(x_2 - x_N)^2 + (y_2 - y_N)^2 = R_2^2 \quad (10)$$

$$(x_3 - x_N)^2 + (y_3 - y_N)^2 = R_3^2 \quad (11)$$

The distances from the beacons were estimated by utilising the RSSI from the wireless interface of the node. To minimize the variation effect of RSSI values, a filtering process has been introduced: the receiver node waits until it receives 10 packets from the beacon node(s) and then search for highest RSSI value. The final value is then chosen to estimate the distance of the node form the beacon node(s). Figure 3.12 illustrate a pseudocode of the filter.

```
RSSI filtering algorithm
Line1: RSSI = rssi_beacon
Line2: Receive (RSSI)
Line3: Receive rssi (RSSI) {
Line4: rssi_array[]=0
Line5: If rssi_array(length) == 10 then
Line6: Return  max (rssi_array[10])
Line7: }
```

Figure 3.12: RSSI filtering algorithm.

The first location was determined using trilateration; the location was updated using a compass (direction of movement, θ) and the speedometer (velocity, V). The location update was determined by using vectors (Figure 3.11-b). The resulting equations are given in (12) and (13).

$$x_D = x_N + Sin\,(\theta) \times V \times (t_1 - t_2) \quad (12)$$

$$y_D = y_N + Cos\,(\theta) \times V \times (t_1 - t_2) \quad (13)$$

where (x_N, y_N) was the location of the mobile node, (x_D, y_D) was the updated location, $t1$ was the time of the previous location update and $t2$ was the current time. The location estimation worked as follows:

1. The first location of the mobile node was established from a standstill or on the move using trilateration.

2. The location update was performed by utilising the compass and speedometer readings.

3. A periodic trilateration was performed for the system to minimise the error generated by the location updates.

The advantage of using such a composition is to minimise the energy consumption of the mobile node and improve the resolution of the mobile sensor node tracking. When a node calculates its current location, the digital compass draws less power than the wireless interface attached to the node. A compass, however, has an intrinsic error when providing the angle of movement for the mobile node. This is why a trilateration process for the node is performed, periodically. Distance estimation in trilateration uses the RSSI value, which is error prone and can sometimes be unreliable. The reliability is dependent on the equipment used and the deployment environment. This issue increases the challenge in estimating the location of the node(s).

3.6 Cross-layer operation detailed

The proposed methodologies for MAC, routing metric and location estimation were then integrated together in a cross-layer fashion. The cross-layer operation is detailed in Figure 3.13. At network initialisation, the mobile node started to broadcast an ND message to initiate neighbour(s) information collection and store it in a neighbour's list (NB-List). After the initialisation process, if a node in the network had data of interest to send, attached with this data was the location information of the mobile node (figure 3.14). This node then started sending RREQ packets to establish a route to the destination node.

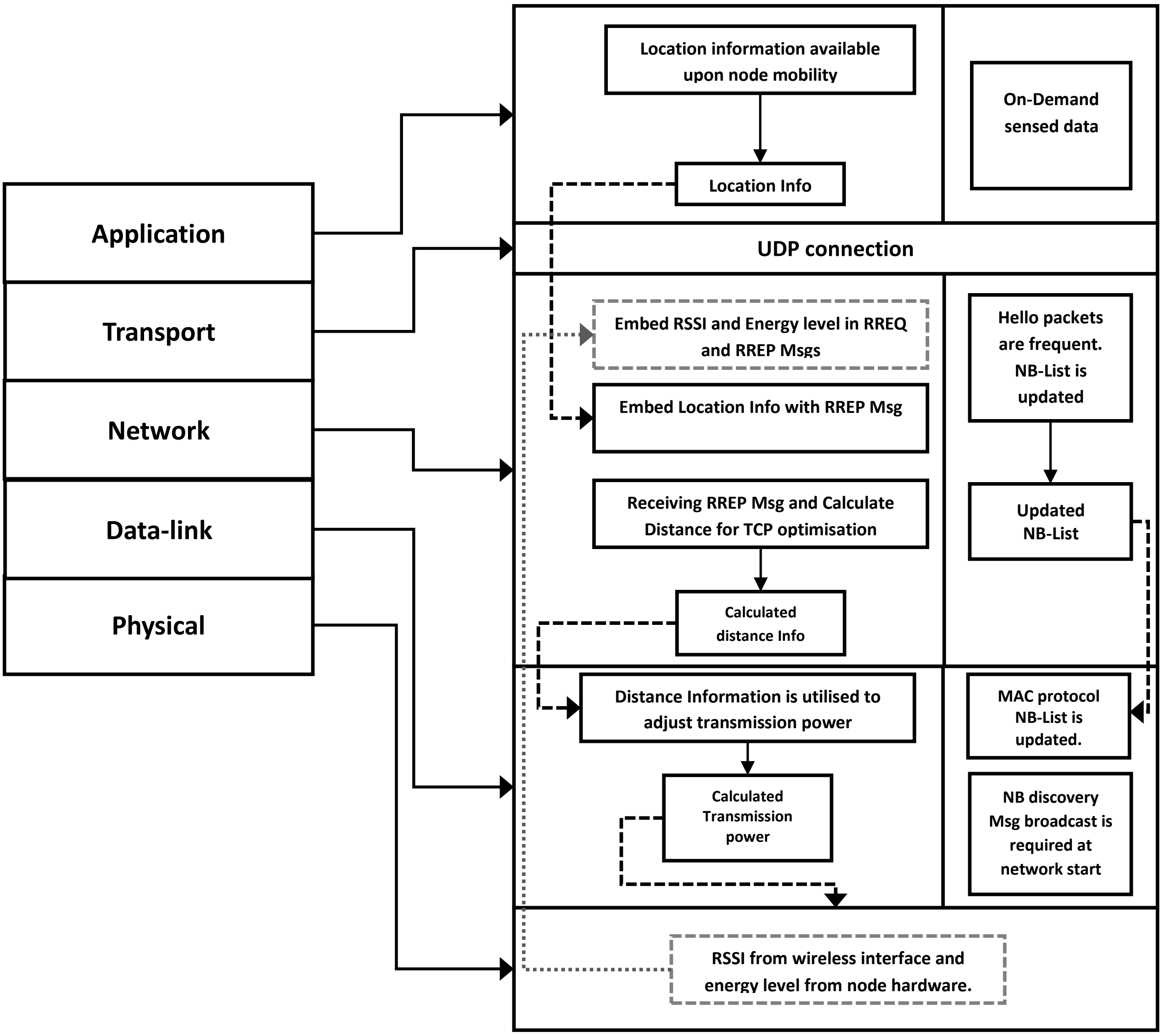


Figure 3.13: Operational model's detailed process diagramme.

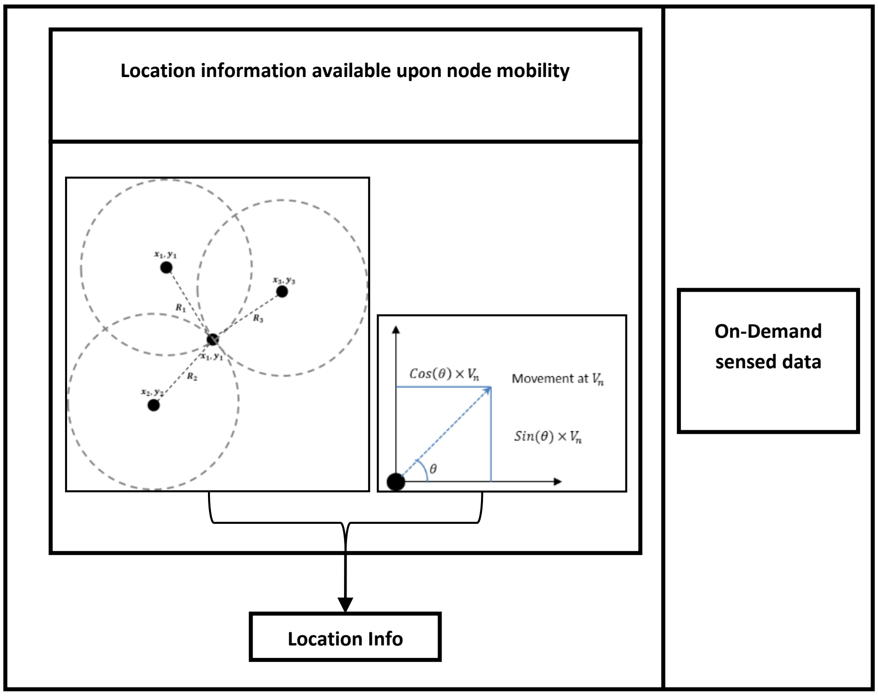


Figure 3.14: The location of the node is calculated following the proposed localisation method.

The network layer imported both the residual energy and RSSI information from the hardware and the wireless interface and attached it to the RREQ messages (figure 3.15). The routing protocol utilised in the operational model utilised a periodic neighbour maintenance message which were hello packets. Hello packets are broadcast packets; therefore, it was possible to utilise the neighbour list form the routing layer in the data-link layer. This eliminated the need for the ND message to be sent by the MAC protocol. After the destination node received the RREQ packets, it replied by sending a unicast RREP packet. The destination node embedded its own location information in the RREP message and sent it back to the next hop node in the reverse route.

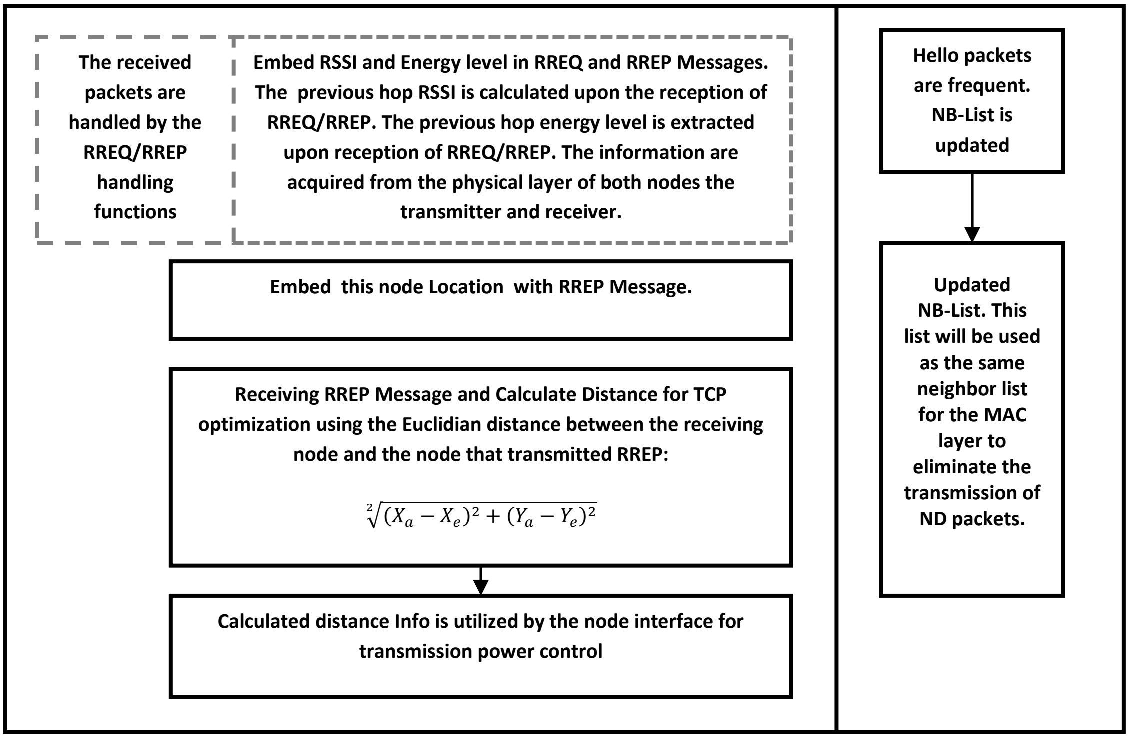


Figure 3.15 : The network layer operation upon starting route discovery receiving/transmitting RREQ and RREP packets.

Figure 3.16 illustrates the RREP packet structure after embedding the location information. The next hop node in the reverse route calculated the distance between it and the destination node and exported this information to the data-link layer. The MAC protocol utilised the transmission power control based on the distance information and calculated the required power to use when sending data packets back to the destination node (Figure 3.17). This operation was repeated through all of the nodes until the source node. After the established route passed its lifetime and there was no data of interest to send, the nodes engaged in the operation went to sleep state. Nodes that were still involved in another route were as active as the operation required.

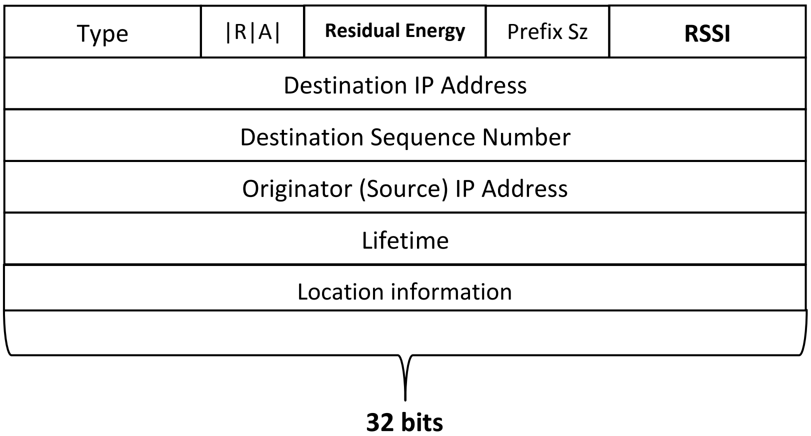


Figure 3.16: RREP Message structure after embedding the location information. A 32-bit field was required for the location information.

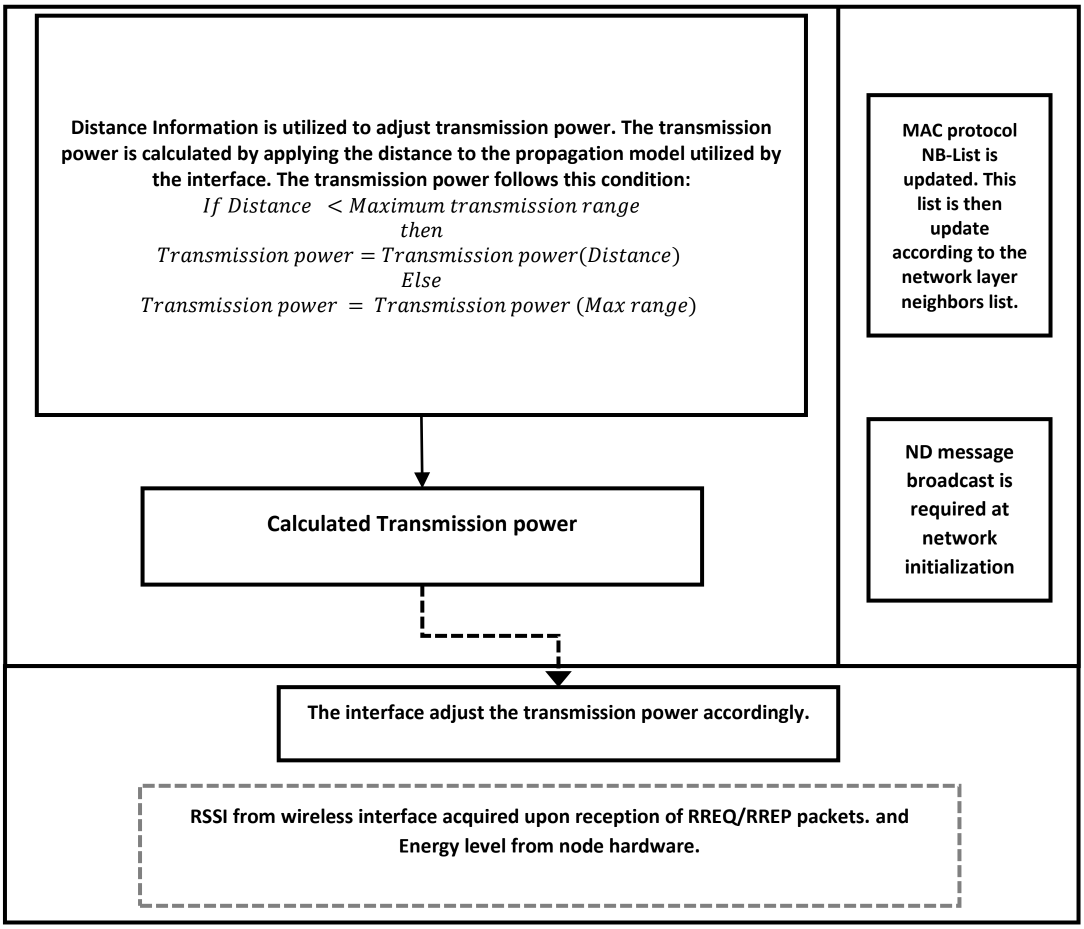


Figure 3.17 : The Data–link layer operation upon network initialization and during the transmission power control process.

3.6.1 Energy model of the cross-layer operation

Following the operation described in section 3.6, the energy consumption model can be described as follows: let Figure 3.18 represent the example network at time stamp t_s. The utilised network model is described as an undirected connectivity graph $G(V, E)$, where V is a finite set of nodes, and $(i, j) \in E$ represents a wireless link between node i and node j. The mobile node's(s') speed, position moving direction and transmission range can be represented as a function to indicate a sensor node's condition in the network in a Cartesian coordinate, that is:

$$\Phi i(t) = f\,((x(i,t), y(i,t)), v(i,t), \theta(i,t), Ri) \ldots\ldots(14)$$

where $(x(i,t), y(i,t))$ is the position, $v(i,t)$ is the speed, $\theta(i,t)$ is the moving direction of node i at time t and Ri is the communication range of node i. If node j is a neighbour of node i, the relative function can be expressed as:

$$\Phi_{j-i}(t) = g((x(j\_i,t), y(j\_i,t)), v(j\_i,t), \theta(j\_i,t), Ri, Rj) \ldots\ldots(15)$$

where $(x(j\_i,t),\ y(j\_i,t))$ is the relative position, $v(j\_i,t)$ is the relative speed, $\theta(j\_i,t)$ is the relative moving direction of node j to node i at time t and Ri, Rj is the communication range of node i and j, respectively.

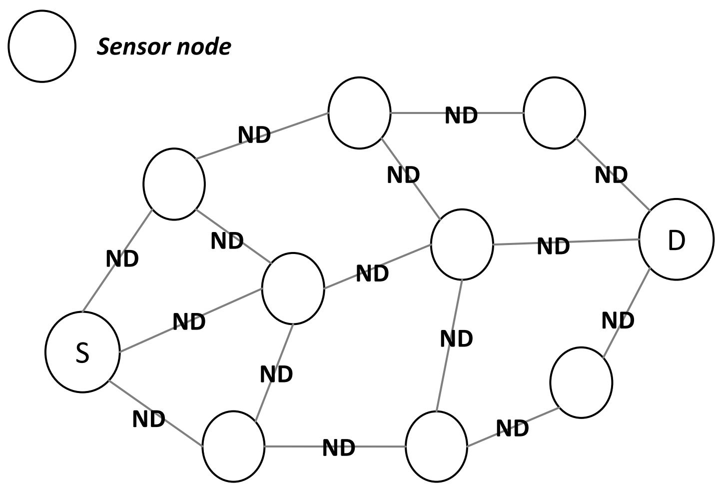


Figure 3.18: Network example at time stamp t_s.

At network initialisation (or when a node had data of interest), the nodes started to broadcast ND packets to establish their neighbour tables. Therefore, the energy consumed by the network was the energy consumed by each node after sending and receiving ND packets (Equation 16).

$$E_{initialisation} = \sum_{i=1}^{N} E_{ND}(\Phi i(t_s + t_{ND})) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

where E_{ND} represented the power consumed by one for sending one ND packet and T_{ND} represented the time required to transmit and receive ND packets by each node. The second step was to search for a route to the destination node by broadcasting hello packets to keep the RREQ messages between the nodes. The energy consumed by the nodes at this state was the energy consumed for sending hello packets plus the energy consumed by broadcasting RREQ messages as described in equation 17:

$$E_{route1} = \sum_{i=1}^{N} E_{RREQ}\big(\Phi i(t_{RREQ})\big) + \sum_{i=1}^{N} E_{Hello}(\Phi i(t_H)) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

where E_{RREQ} represented the energy consumed by the nodes for broadcasting and receiving RREQ packets and E_{Hello} was the energy required for the periodic transmission of hello packets. As described in section 3.6, the destination node then started sending back RREP messages. The RREP messages included the information of the node’s location that had sent the RREP message. This created a different set of nodes$\{P\}$ where$(P \in N)$ as the RREP message was a unicast message. The proposed operation limited the periodic broadcast of the hello packets to the nodes only involved in the active route. Therefore, the energy consumption at this state was represented by equation 18:

$$E_{route2} = \sum_{i=0}^{P} E_{RREP}(\Phi i(t_{RREP})) + \sum_{i=0}^{P} E_{Hello}(\Phi i(t_H)) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

where E_{RREP} represented the energy consumed by the node to transmit and receive RREP packets. The hello packets were only broadcasted between the nodes if $node_i \in \{P\}$. The final step was represented by sending data packets from the source node. Because the source node and the nodes in the middle of the route knew their distance from their next hop in the route, these nodes adjusted their transmission power to the required distance. This made the energy consumed during the data transmission state a function of both distance and time consumed for transmitting a full data packet(s). Equation 19 represented the energy consumed at data transmission state.

$$E_{DATA-State} = \sum_{i=0}^{P} E_{DATA}(\Phi i(t_{DATA}, R_{Distance})) + \sum_{i=0}^{P} E_{Hello}(\Phi i(t_H)) \ldots\ldots\ldots\ldots\ldots (19)$$

where E_{DATA} represented the energy consumed by the transmission of the data packets between the nodes, t_{DATA} represented the time required to send the data packet(s) and $R_{distance}$ represented the distance between node i and node j (i was the sender node and j was the receiver node). The hello packets' broadcasting energy consumption was bounded by the lifetime of the route established. Therefore:

$$\sum_{i=0}^{P} E_{Hello}(\Phi i(t_H)) \ \exists \ if \ \ (i \in \{P\}) \& (Route_{lifetime} > 0) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

If $(Route_{lifetime} = 0)$, and there was no data of interest to send to the destination node, the nodes went back to the dormant mode (sleep mode). The final network energy consumption model was represented by equation 21 below:

$$E_{Network} = E_{initialisation} + E_{route1} + E_{route2} + E_{DATA-State} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

This operation minimised the energy consumption at several levels:

1. The ND packets were needed only at the initialisation process of the network to build the neighbour tables. After initialising the network, ND packets were not needed to be broadcast anymore because the hello packets periodic broadcasting replaced the required ND broadcasting of the ND packets.

2. Knowing the location of the next hop to adjust the transmission power minimised the power consumed if the distance between the nodes in range was short.

3. Periodic hello packet broadcasting became limited to only the nodes involved in the established route. Periodic hello packets were also limited to the lifetime of the route established.

The proposed mechanism is unique as it is a cross-layer of the operation of three layers, the application, network and MAC layers, to achieve the improvements in terms of the energy consumption of the network in general.

3.6.2 Energy model validation of the cross-layer operation

The energy analysis of the cross-layer model has been verified by designing a tool using MatLab software (Appendix C). The tool computes the energy consumed by each node in the network and the final result is the energy consumption trend of the network. The comparison is made between the original operation model and the cross-layer operation model. The values used to compute the final results are generic. This is to give the expected behaviour of the energy consumption trend when the network size increases using the cross-layer model (Figure 3.19). The area of deployment is 200x200 meters. The number of nodes deployed is 15, 20, 25, 30 and 35 respectively. The maximum transmission range of each node is 40 meters and the nodes deployment is random. There is one source node and one destination (sink) node which is stationed in the middle of the area of deployment.

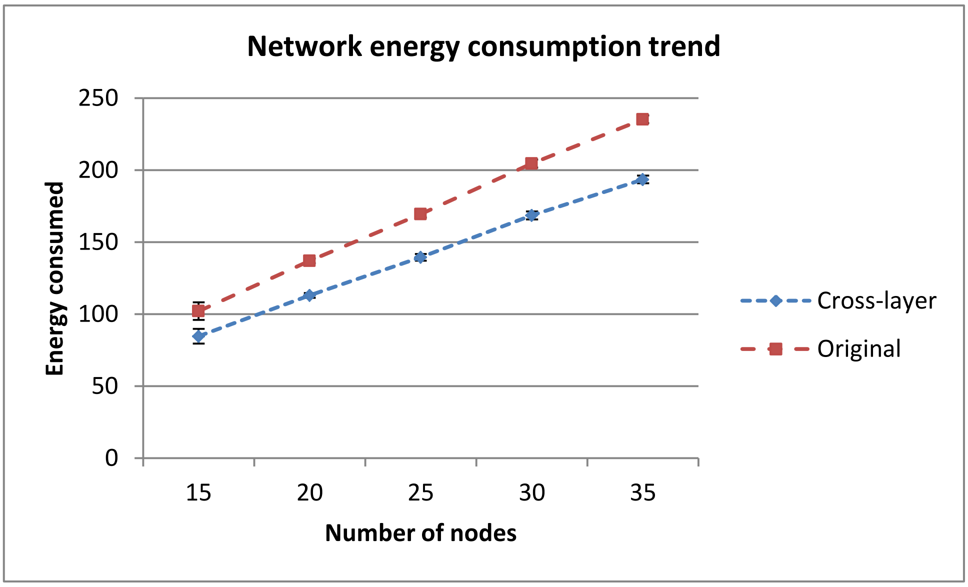


Figure 3.19 : The energy consumption trend of the network(s) using.

From Figure 3.19, it is possible to observe that the proposed cross-layer model consumes less energy than the original operation.

3.7 Network model evaluation parameters

The evaluation process of the network model is described in Figure 3.20. The inputs of the proposed model are the following:

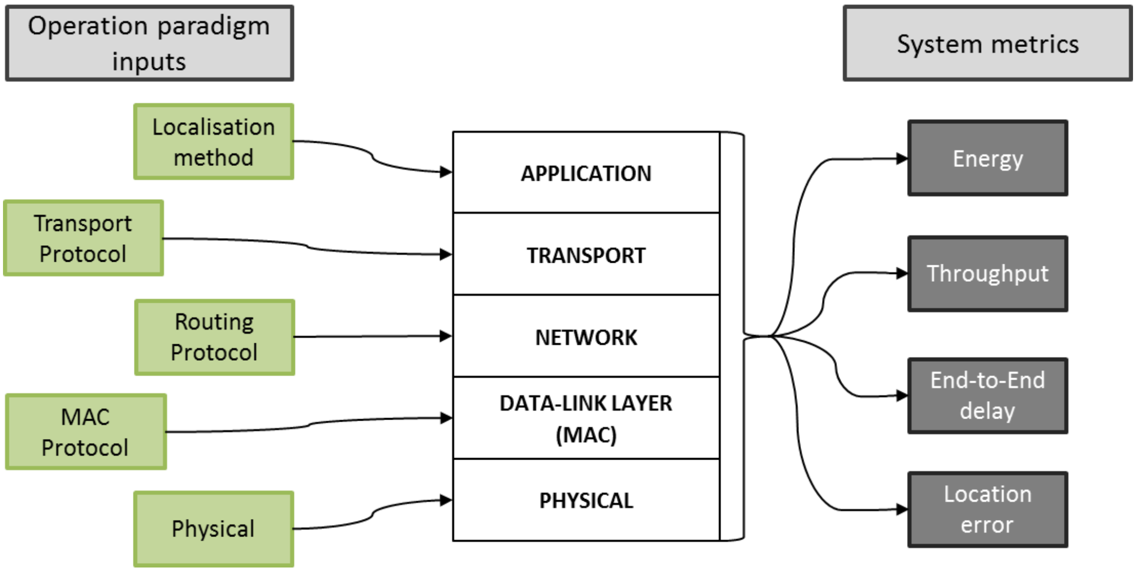


Figure 3.20: The methodology of the evaluation of the proposed operational model The input side represents the system inputs. The output side is the evaluation metrics side of the proposed operational model.

1. *Physical layer*: The physical content represents the connection's physical properties, such as: the frequency of the operation's wireless signal operation, the modulation properties and the nodes' mobility capabilities. The physical properties for the wireless interface followed the 2.4GHz frequency band and 250 Kbps data rate of the IEEE 802.15.4 hardware properties.

2. *MAC Protocol*: The MAC protocol content was an input to the proposed model. The base MAC protocol in the proposed operational model was a CSMA/CA-based MAC protocol.

3. *Routing Protocol*: The Routing protocol utilised in the proposed operational model was a reactive routing protocol based on AODV.

4. *Transport Protocol*: The transport protocol utilised for the proposed operational model was the UDP (User Datagram Protocol) which is a connection-less protocol, i.e., it transmits a packet to the medium without establishing a connection with the destination node.

5. *Localisation method*: A mobile node location estimation method has been proposed aimed at mobile WSNs that provided the node's location which was information represented in the application layer of the model.

The operational model was then evaluated by the following metrics:

Energy per packet: The energy per packet metric represented the operational model's energy efficiency during network operation. The energy per packet was calculated as the energy consumed by the whole network for a period of time to the number of successful packets transmitted from the source node(s) to the destination node(s). The energy per packet was calculated for the operational model as well as the methodologies compared to under the same hardware/physical layer specification.

$$E_{Packet} = \frac{E_{Network}}{Number\ of\ Packets\ transmitted} \quad \ldots\ldots\ldots(22)$$

System Throughput: The throughput metric represented the system data productivity during the network operation. The system throughput was represented by the amount of data that was delivered from a source to a destination during a period of time.

$$Throughput = \frac{Number\ of\ packets\ received}{Network\ operation\ time} \ldots\ldots\ldots(23)$$

Packet delivery ratio (PDR): PDR represented the percentage of the successfully transmitted packets to the number of generated packets.

$$PDR(\%) = \frac{Number\ of\ received\ packets}{Numberof\ generated\ packets} \ldots\ldots\ldots(24)$$

End-to-End Delay: The end-to-end delay metric was defined as the average time consumed to transfer one packet in the network. The end-to-end delay was calculated as the summation of the delays of every successful packet sent from the source(s) of the packet to the destination node(s) and divided by the total number of packets transmitted.

$$E - E_{Delay} = \frac{\sum_{i=0}^{n} E-E_{delay_i}}{n} \quad \text{...} (25)$$

where n was the number of packets received and i represented the packet id.

Location estimation error: The location estimation was a metric aimed to evaluate the localisation method of the networks' nodes. The estimation error was calculated as the Euclidian distance between the node's actual location and the node's estimated location.

$$Location_{error} = \sqrt[2]{(x_a - x_e)^2 + (y_a - y_e)^2} \quad \text{...} (26)$$

where (x_a, y_a) represented the node's actual location and (x_e, y_e) represented the estimated location of the node.

3.8 Model evaluation environment

The operational model's target application was mobile node tracking for social purposes inspired by the application proposed in [83]. Based on the application facts, the area of implementation was 300×300 square meters with 25 nodes deployed with a transmission range of 30 meters. By calculating the area of coverage of each node and assuming the nodes' deployment was in a grid fashion, the deployed nodes covered an area of 70700 square meters. The deployment area was 90000 square meters.

The mobile sensor nodes roamed around a fixed deployment area (Figure 3.21). The application environment assumptions are as below:

1. The system is homogenous, i.e., the nodes have the same type of equipment and capabilities (Hardware and software).

2. All sensor nodes are mobile with random periodic pauses of 50 seconds.

3. A stationary sink node is deployed in the network.

4. The deployment surface is flat.

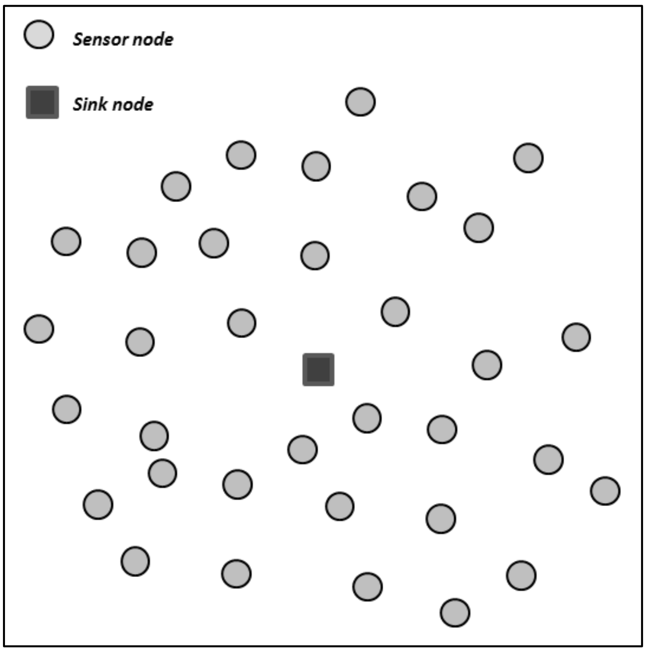


Figure 3.21 : Deployed network example

Two main implementation areas were established for the purpose of evaluating the proposed MAC protocol, routing metrics and the final cross-layer mode. The first area of implementation was of 100×100 square meters and the second was 200×200 square meters. The assumed transmission range was 40 meters for the nodes. The transmission range meets the specifications of XBee node hardware [30]. For the 100×100 square meter area, the number of nodes required to cover 10000 square meters was 2 since each node with 40 meters of transmission range could cover 5026 square meters. The number of nodes deployed started from 5, 10, 15 and 20 to reflect a more realistic and flexible scenario to evaluate the MAC protocols in.

The number of nodes deployed in grid fashion required to cover an area of 200×200 square meters was 8 nodes. The nodes deployed in the 200×200 area started from 15, 20, 25, 30 and 35, respectively. The incrementation in the number of nodes had a direct effect on the network performance. It created more occupied wireless channels and increased the number of control packets broadcast. This was to show

how scalable the routing protocol performance and the cross-layer stack were when the number of nodes increased. Since the application was monitoring the movements of human beings, the walking pace of a normal person ranged from 3.6 to 10.8 kilometres per hour (k/h). The random-way point model in NS2 uses meters per second (m/s) as the speed unit. The speeds assumed for the nodes in the simulations ranged from 1 m/s to a maximum of 3 m/s.

The propagation model utilised in the evaluation process was the Two-Ray Ground model as the nodes had a present line-of-sight and no obstacles in between. The Two-Ray Ground model had been used for evaluating mobile WSN operations in several implementations; examples are presented in [84], [70], [85], [113] and [177]. The energy model that the nodes followed contained the following states: transmission power, reception power, idle/listening power, sleep power and state transition power.

$$E_{node} = \sum_{i=0}^{n} E_{tx} + E_{rx} + E_{idle} + E_{sleep} + E_{trpower} \quad (27)$$

Where E_{tx} represented the transmission energy of the node, E_{rx} the reception energy, E_{idle} the idle/listening energy, E_{sleep} the nodes' sleep energy and $E_{trpower}$ represented the state transition power.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the evaluation process of the cross-layer operational model. As it has been illustrated in chapter 3, the operational model's optimisation level focuses on three layers: application, network and data-link layers. The next section discusses the evaluation process and the results of the SEEK-MADP MAC protocol proposed for the operational model. Section 4.3 discusses the evaluation process of the composite routing metric proposed for the routing protocol. Section 4.4 illustrates the location estimation method proposed for the operational model. Section 4.5 evaluates the cross-layer operational model.

4.2 SEEK-MADP MAC protocol evaluation

The proposed mechanism for the MAC protocol is based on the CSMA/CA medium access method. MAC protocols are a fundamental and key layer in communication networks in general. The main objective of a MAC protocol is to control the transmission/reception medium usage for a network interface card. To test the proposed MAC protocol scheme, SEEK-MADP, five simulation scenarios were developed and implemented using NS2 [178]. SEEK-MADP was compared against the SMAC protocol, SMAC-Adaptive listening and IEEE 802.15.4. Each simulation for each method ran for 31 times. The nodes were deployed randomly in an area of 100×100 meters. The sink node was a stationary node that was always stationed in the middle of the deployment area. In each scenario, there were 3 source nodes. The nodes were all mobile in a random fashion with a mobility speed of 1m/s to a maximum speed of 3m/s. Table 4.1 describes the simulation scenario parameters, such as initial node energy, propagation model and simulation time. To test how each protocol handled mobility, there was no routing protocol in the simulations.

Table 4.1: Simulation scenario parameters and values

Simulation parameters	Values
Number of nodes	5,10,15,20
Initial energy of each node in the network	1000Joules
Mobility	1m/s-3m/s
Propagation model	Two Ray Ground
Node transmission power	35 mW[30]
Node reception power	31 mW[30]
Transmission range	40 meters
Node idle power	712µW[30]
Node sleep power	144nW[30]
Simulation time	500 seconds
Mobility pauses	0 seconds, 50 seconds
Simulation runs	31 times
Packet size	100 bytes

The criteria of the evaluation for the proposed MAC protocol were: packet delivery ratio (PDR), energy per packet consumption, system throughput and finally, the end-to-end delays of the packet delivery.

4.2.1 Energy results

The goal of the proposed MAC protocol scheme is to achieve an energy efficient operation for the network in different situations whether the nodes are static or mobile. The simulation scenarios were chosen carefully to reflect both the scalability of the network and the mobility effect on the network performance. Starting with the energy analysis, Figures 4.1 and 4.2 represent the average residual energy of the deployed network for each simulation scenario. The figures show that SEEK-MADP had the least energy per packet consumption between the evaluated protocols.

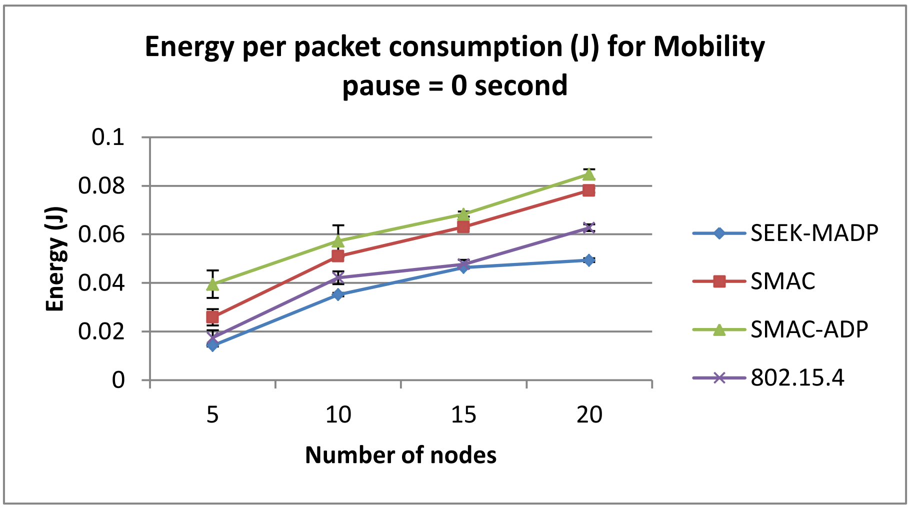


Figure 4.1: Energy per packet consumption results for mobility pause of 0 seconds. A 0 second pause means that the nodes were always moving and had no moving pause periods. This was to reflect a high mobility scenario for the nodes.

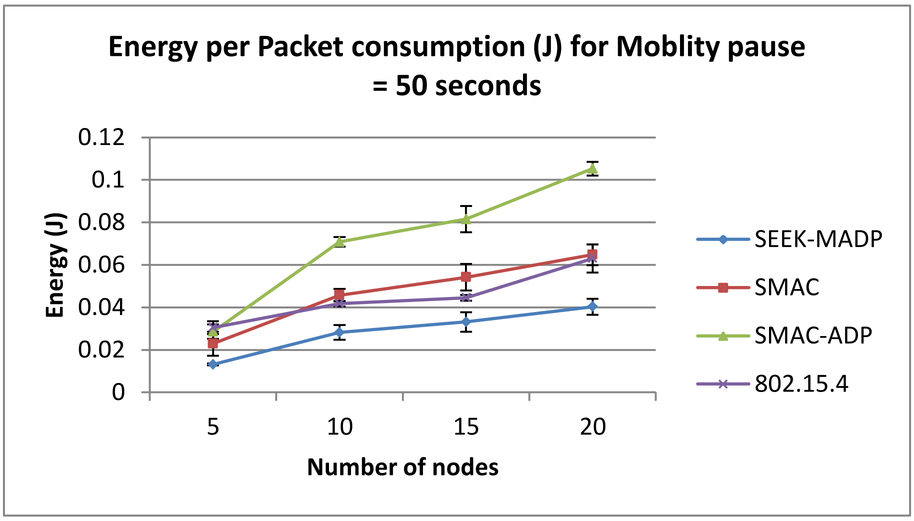


Figure 4.2: Energy per packet consumption results for mobility pause of 50 seconds A 50 second pause means that the nodes had random pauses for a period of 50 seconds for each pause during the simulation period. This was to reflect a low mobility scenario for the deployed nodes.

4.2.2 Throughput results

The throughput analyses were compared on the bases of how many packets were delivered in the given operational (simulation) period. The results are illustrated in Figures 4.3 and 4.4. Each figure shows the results of the implemented simulation scenarios, respectively. Figures 4.5 and 4.6 illustrate the average packet size received for each MAC protocol. SEEK-MADP showed impressive improvement in terms of throughput. SEEK-MADP protocol improves the throughput but increasing the packet sizes according to the mobility speed of the transmitting/receiving nodes. At 0 seconds pauses, the mobility is higher therefore the incrementation in packet size is lower than when the mobility pauses are 50 seconds. At 20 nodes in figure 4.3, there is a slight drop in the output of the network. The drop happens for the other MAC protocols implemented. At higher number of deployed nodes, the network can suffer from bottleneck which can lead to less number of packets to be received by the destination node. Such behaviour is not apparent in figure 4.4 when the mobility pauses are 50 seconds. The output of the networks is incrementing when the mobility of the network is low.

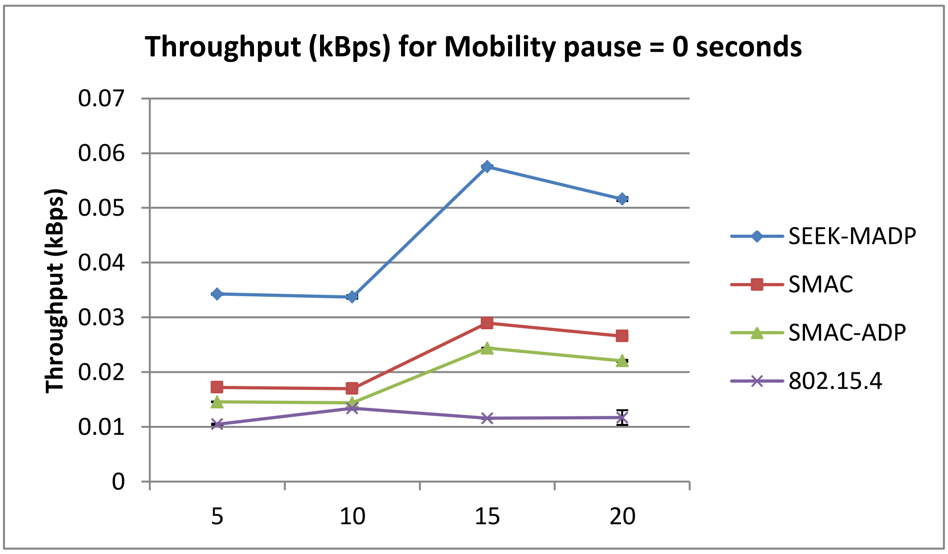


Figure 4.3: System throughput for mobility pause of 0 seconds.

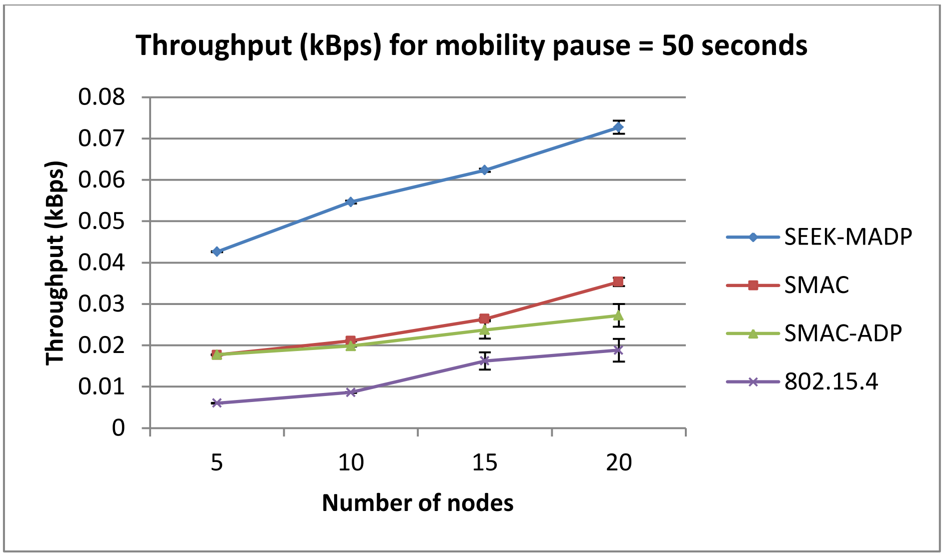


Figure 4.4: System throughput for mobility pause of 50 seconds.

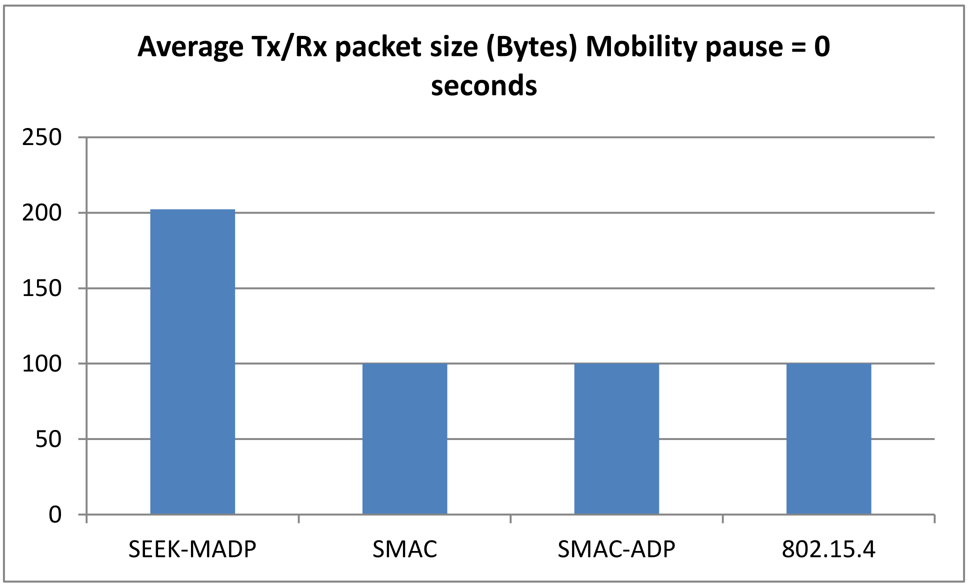


Figure 4.5: Average transmitted/received packet size for mobility pause of 0 seconds.

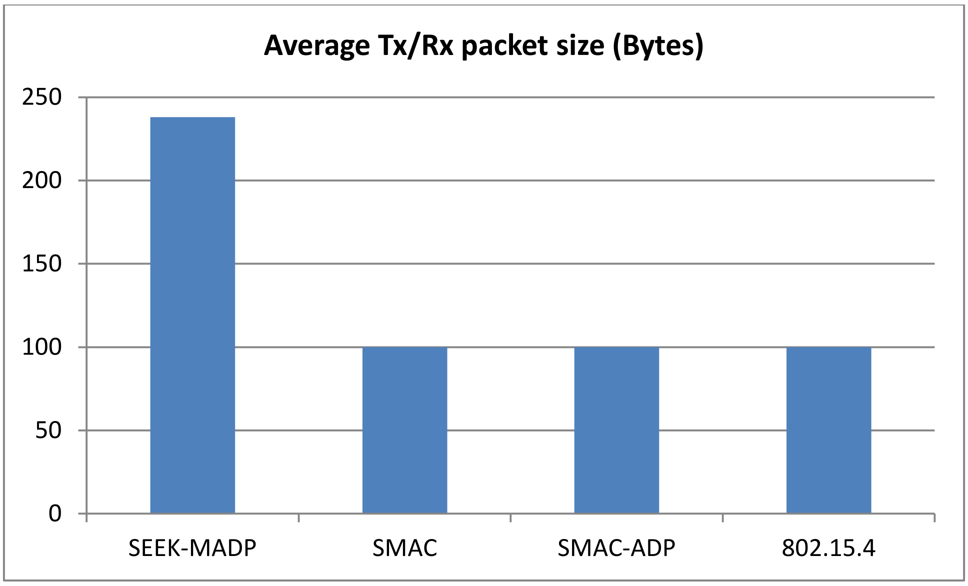


Figure 4.6: Average transmitted/received packet size for mobility pause of 50 seconds.

4.2.3 Packet delivery ratio results

The packet delivery ratio results are presented in Figures 4.7 and 4.8. SEEK-MADP shares the same behaviour as the SMAC protocol in the PDR results. SMAC-ADP showed a gradual PDR decrease when the number of deployed nodes increased albeit less vigorous than with IEEE 802.15.4.

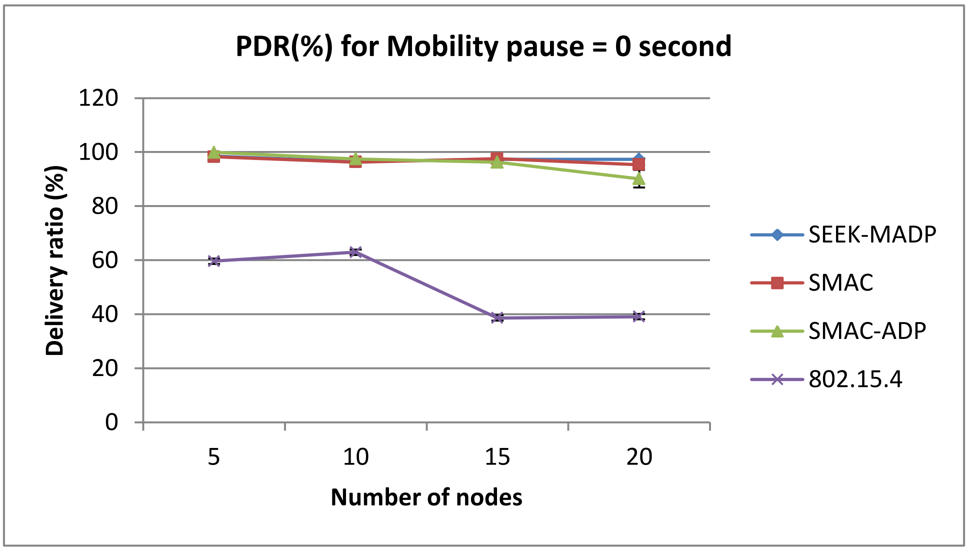


Figure 4.7: Packet delivery ratios for mobility pause of 0 seconds.

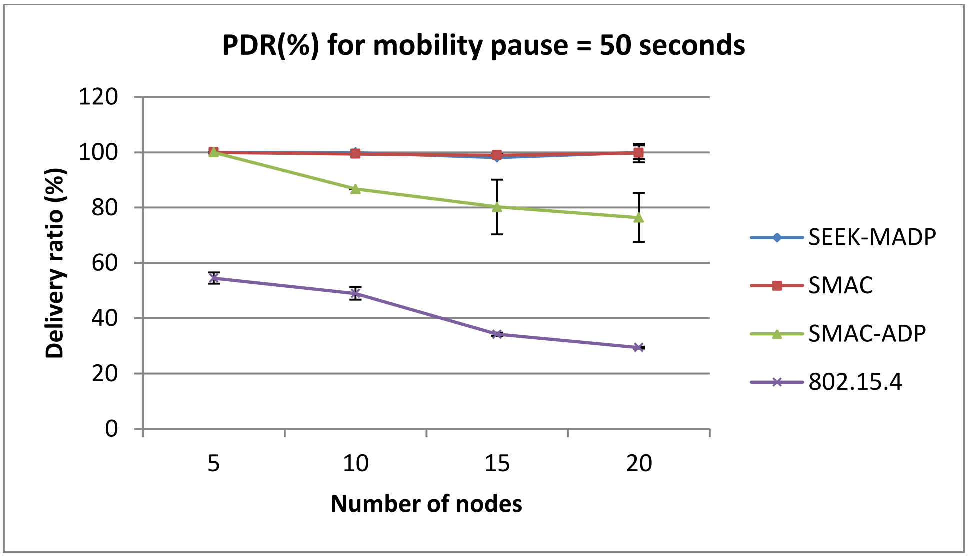


Figure 4.8: Packet delivery ratios for mobility pause of 50 seconds.

4.2.4 End-to-end delay results

The end-to-end delay results give a perspective of the message transmission delay during the network operation. The results are illustrated in Figures 4.9 and 4.10. From the figures, it is possible to conclude that the SEEK-MADP mechanism provides lower end-to-end delays than SMAC and SMAC-ADP. The lowest end-to-end delay results were achieved by IEEE 802.15.4.

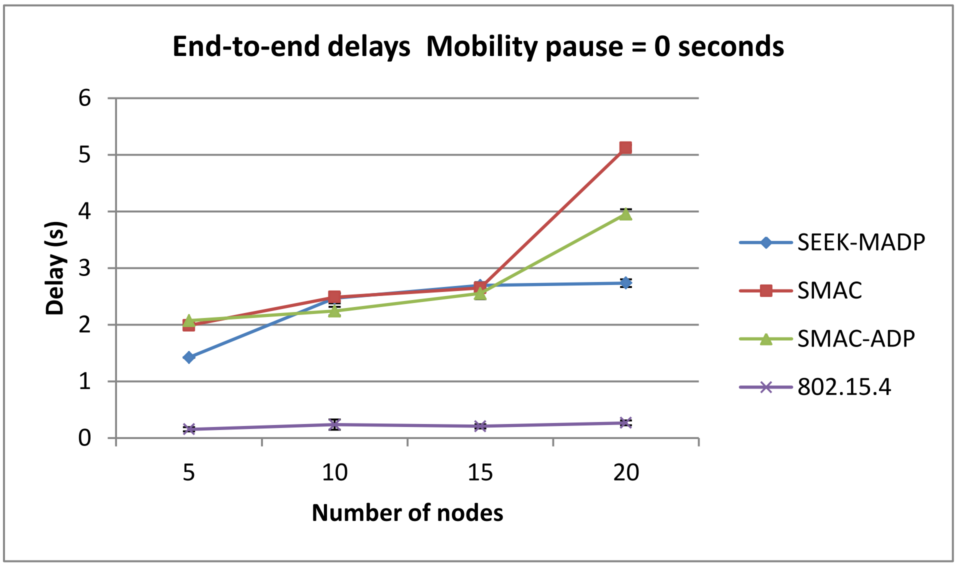


Figure 4.9: End-to-end delays for mobility pause of 0 seconds.

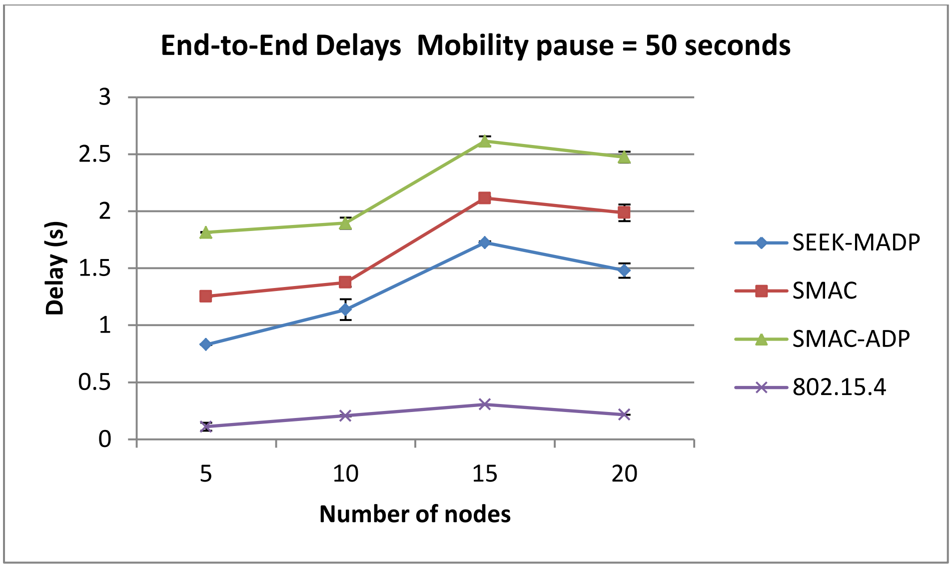


Figure 4.10: End-to-end delays for mobility pause of 50 seconds.

The above results have been converted to delays per byte since SEEK-MADP employs a variable packet size mechanism (Figures 4.11 and 4.12).

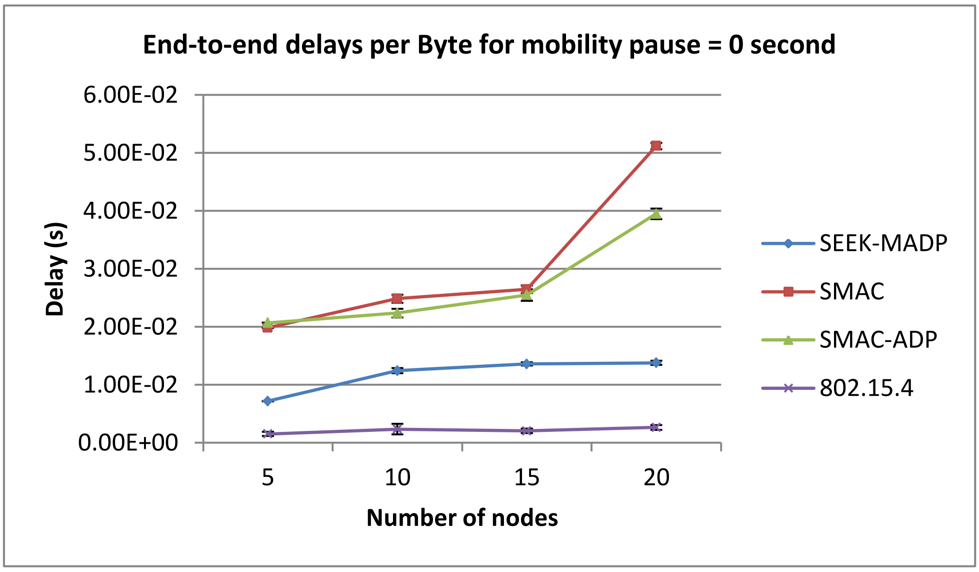


Figure 4.11: End-to-end delays per byte for mobility pause of 0 seconds. SEEK-MADP provided better message delivery delays than SMAC and SMAC-ADP. However, SEEK-MADP message delay was higher than IEEE 802.15.4.

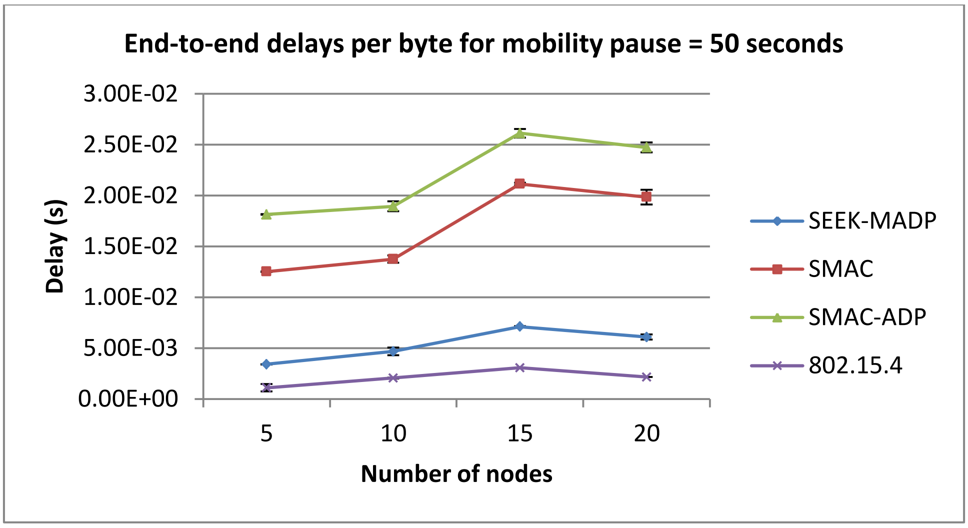


Figure 4.12: End-to-end delays per byte for mobility pause of 50 seconds.

4.2.5 Results discussion and analysis

From the figures illustrated in the energy, throughput, PDR and end-to-end delays, the SEEK-MADP MAC protocol had the least energy consumed per packet transmitted, the highest throughput, solid PDR results and the lowest end-to-end delays compared to SMAC and SMAC-ADP. SEEK-MAC had higher end-to-end delays than IEEE 802.15.4.

The IEEE 802.15.4 MAC protocol does not have an RTS/CTS mechanism as in SMAC, SMAC-ADP and SEEK-MADP (SEEK-MADP implements RTS/CTS; however, the RTS functionality is embedded on the SEEK packet when it is transmitted to the neighbour nodes) protocols which added delays to the messages sent by those protocols. However, because IEEE 802.15.4 does not have the RTS/CTS mechanism this has a high effect on the PDR results when increasing the number of deployed nodes in the network. IEEE 802.15.4 suffered from unreliability problems when increasing the number of nodes deployed. The sink node in IEEE 802.15.4 could not handle multi connections efficiently which led to a decrease in the PDR of the network.

SEEK-MADP had the highest throughput because the average packet size transmitted between the nodes was the highest. The SEEK-MADP mobility dependent adaptive data period utilised the data transmission efficiently without affecting the node(s) duty-cycle thus resulting in high throughput with low power consumption. SMAC does not have such a mechanism which means the node engaged in the connection could only transmit a static packet size; therefore, it resulted in its having a lower throughput. SMAC-ADP has an adaptive listening period. This mechanism is only effective if the data packet size passes the duty-cycle of the node. This means that the node will fragment the data packet to fragments if the data size passes the duty-cycle of the node. As illustrated in Figures 4.5 and 4.6, when the nodes tended to have high mobility, the average packet size decreased which was what the SEEK-MADP mechanism aims at. When the node’s mobility was lower (had pauses) the average packet size transmitted increased. SEEK-MADP shortened the control packets required in the MAC operation thus resulting in end-to-end delays lower than SMAC and SMAC-ADP. Because of this mechanism, the energy consumption of the nodes was also lower when using the SEEK-MADP MAC protocol.

4.3 Composite routing metric evaluation process

This section discusses the process of the development of the network layer protocol for the network operational model. The purpose of routing protocols is to provide and establish the best route possible from a source node *a* to a destination node. The process requires several steps to be performed by the routing protocol including finding the nodes that will be used for the traffic routing process. One step, however, has the potential to improve or disprove the operation of the routing protocol deployed in a network. This step is the choice of which route is the best suitable to fit the required application. To choose the best route, a routing protocol has to be programmed to follow values or criteria from which it can choose the right route. These values are called routing metrics. The proposed metric is aimed at mobile WSNs.

Extensive simulations have been performed to evaluate the proposed composite metric. The composite metric has been evaluated against the hop-count, SNR, and ETX metrics. All the evaluated metrics have been embedded in the operation of the

AODV routing protocol. Two major batches of simulations have been performed. The first batch included a deployment area of 200×200 meters. The nodes deployed were all mobile with a stationary sink node placed in the middle of the simulation area. The mobile nodes had random mobility directions. Table 4.2 illustrates the parameters for batch 1 simulations. The parameters were such as the propagation model, number of deployed nodes, mobility speed etc.

The second batch of simulations has been performed using the same parameters for the first batch; however, the MAC protocol had been changed to SEEK-MADP to check the affect of the composite metric if the developed MAC protocol was used. The compared metrics were the composite metric and hop-count metric. Table 4.3 illustrates the parameters issued for batch 2 of the simulations. The evaluation metrics were the packet delivery ratio, energy per packet consumption, system throughput and end-to-end delays.

Table 4.2: Batch 1 Simulation scenario parameters and values

Simulation parameters	**Values**
Number of nodes	15,20,25,30,35
Initial energy (Joules)	1000
Mobility	1m/s-3m/s
Propagation model	Two Ray Ground
Transmission range	40 meters
Simulation time	500 seconds
Mobility pauses	50 seconds
Routing protocol	AODV
MAC protocol	IEEE 802.15.4
Number of sources	7 nodes
Transport protocol	UDP
Application	CBR
Simulation runs	31 times

Table 4.3: Batch 2 Simulation scenario parameters and values

Simulation parameters	**Values**
Number of nodes	15,20,25,30,35
Initial energy (Joules)	1000
Mobility	1m/s-3m/s
Propagation model	Two Ray Ground
Transmission range	40 meters
Simulation time	500 seconds
Mobility pauses	50 seconds
Routing protocol	AODV
MAC protocol	SEEK-MADP
Number of sources	7 nodes
Transport protocol	UDP
Application	CBR
Simulation runs	31 times

4.3.1 Batch 1 simulation results and analysis

This section discusses the results of implementing the composite metric on the simulation scenarios when the MAC protocol used was IEEE 801.5.4.

4.3.1.1 Energy per packet results

The energy consumption results are illustrated in Figure 4.13 and Figure 4.14. From Figure 4.14, it is possible to see the advantage of the proposed routing metric as it offered the least power consumed per packet.

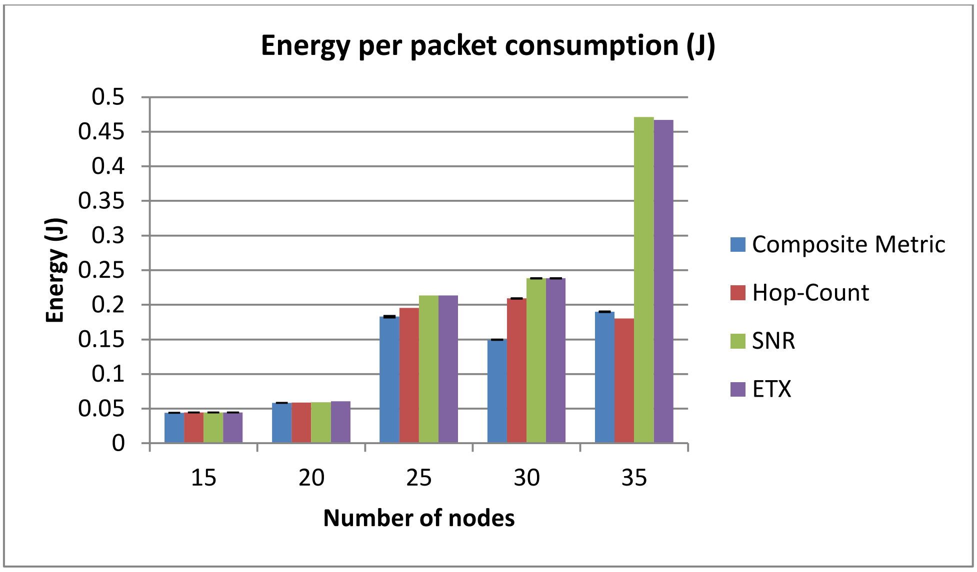


Figure 4.13: Batch 1 energy consumption per packet.

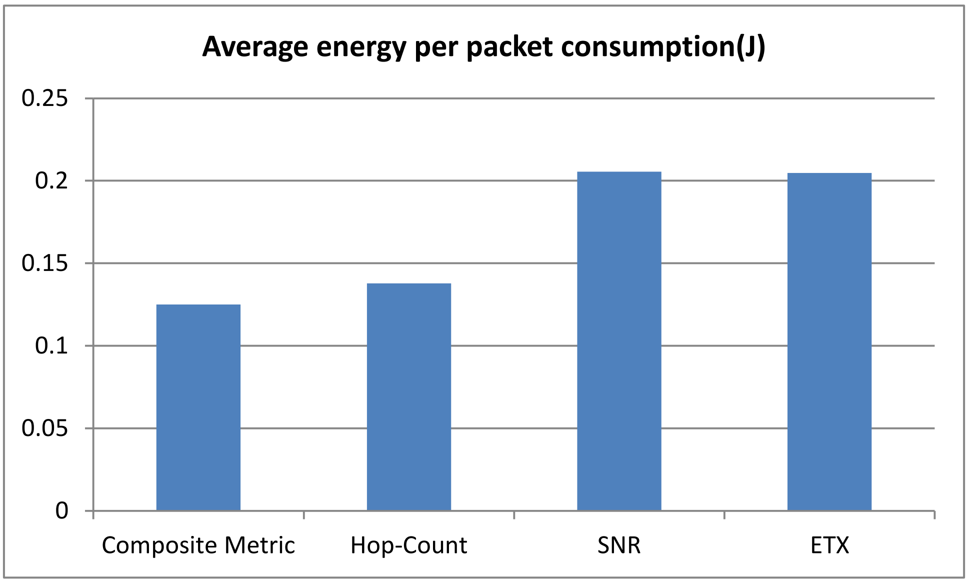


Figure 4.14: Batch 1 energy consumption per packet.

4.3.1.2 Throughput results

The throughput results in Figures 4.15 and 4.16 show that using the composite metric improved the network throughput by about 6%.

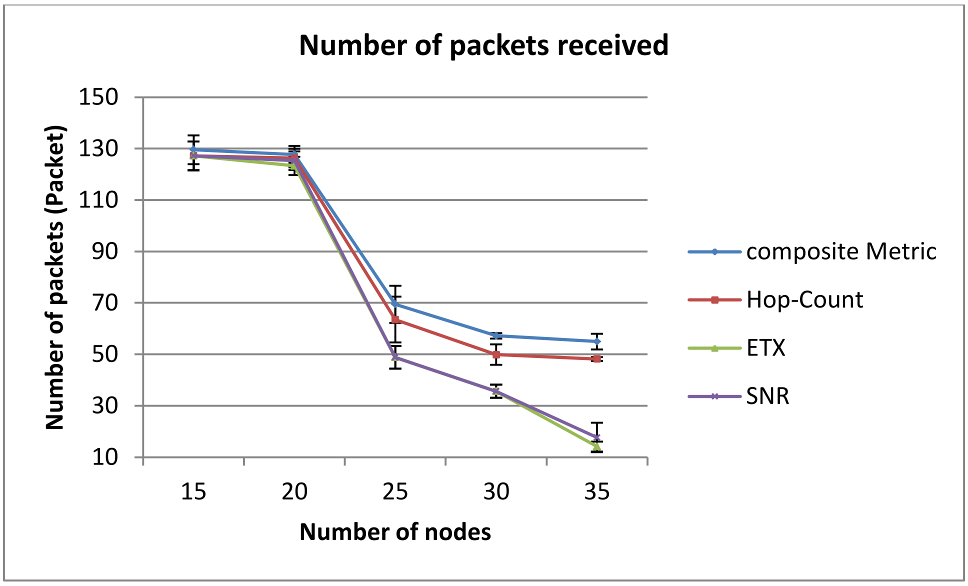


Figure 4.15: Batch 1 throughput.

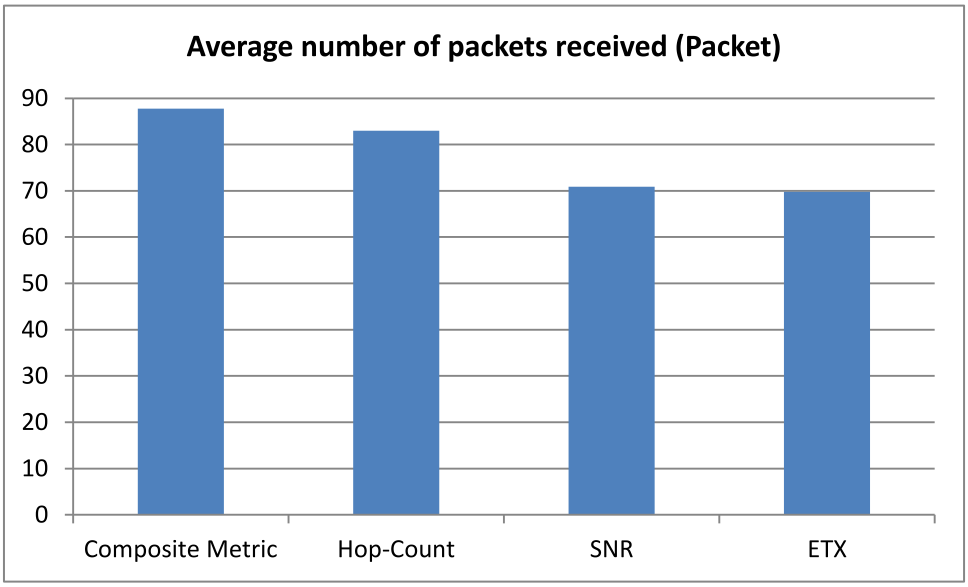


Figure 4.16: Batch 1 average number of packets received.

4.3.1.3 Packet delivery ratio results and analysis

Using the composite metric improved the PDR of the routing protocol which was about 3% more than the hop-count metric. This is shown in Figure 4.17.

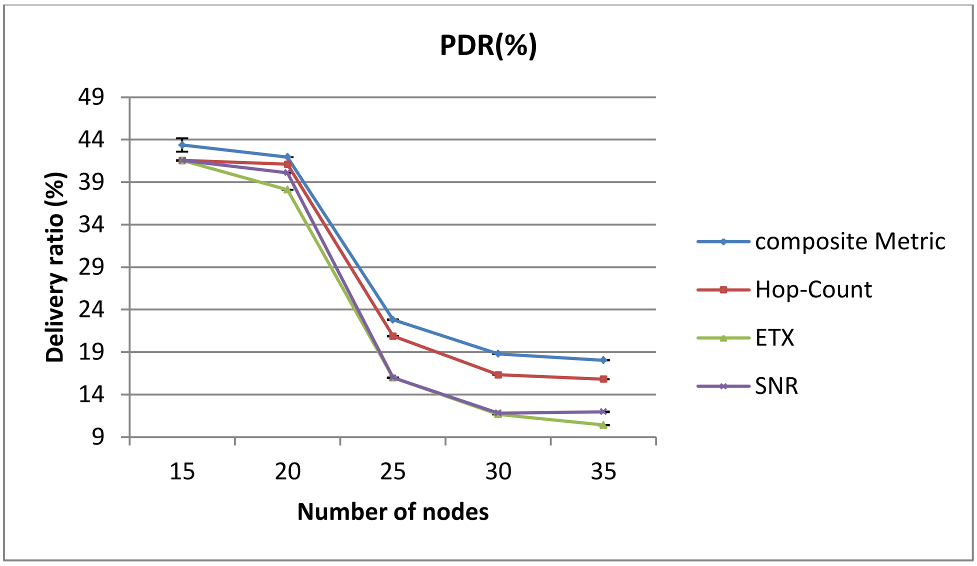


Figure 4.17: Batch 1 packet delivery ratio results.

4.3.1.4 End-to-end delay results

The end-to-end results show that the composite metric has end-to-end delays higher than the hop-count metric whilst maintaining lower delays than the SNR and ETX metrics (Figure 4.18).

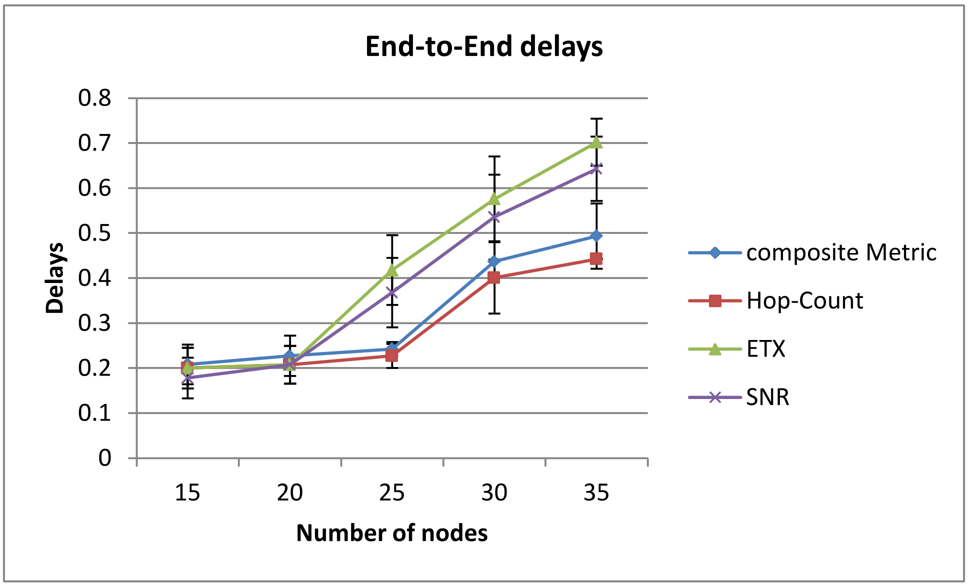


Figure 4.18: Batch 1 end-to-end delay results.

4.3.1.5 Batch 1 Results discussion and analysis

From Figures 4.13, 4.14, 4.15, 4.16, 4.17 and 4.18, it is possible to observe the improved operation of the routing protocol using the proposed composite metric. The second best metric was the hop-count metric which has been proved in the literature that it is the best metric in mobile node situations. The main issue with the hop-count metric itself was the unknown condition of the hop(s) and the links chosen in the route establishing process. This uncertainty in the chosen link's condition has an effect on the hop-count metric in terms of system throughput and PDR.

The composite metric tried to avoid this issue by checking for the link condition and providing the routing process information about the chosen hop(s). This resulted in better PDR, throughput and energy consumed per packet. The SNR metric came third in terms of the measurements considered for the evaluation process. The SNR behaviour depended on the model that described the environment where the wireless signals propagated in. That, however, was not the only issue with SNR. The SNR metric depended on the noise model of the environment where the mobile nodes were deployed. An accurate noise model can improve the operation of a routing protocol when utilising the SNR metric. ETX suffered in the mobile nodes' scenario. This affect had been observed by [129] as well. ETX employed a continuous counting of the number of successful broadcast messages. Mobility changed the network topology rapidly which affected the ETX metric calculation of the received broadcast messages.

The composite metric had higher delays than the hop-count metric because the hop-count metric forced the routing protocol to choose the route with the least number of hops. The composite metric does not implement a mechanism to calculate the number of hops included in the route. This calculation was not considered for the composite metric because of possible disconnections in the routes established. The composite metric advantage was that it chose the neighbour nodes depending on their availability and their lifetime which is an important awareness in sensor network operation. Hop-count can only tell if the neighbour is available or not. Another observation that can be made from Figures 4.16 and 4.17 is that using the composite improved the system throughput by 6% higher than the hop-count metric whilst PDR was only 3% higher than the hop-count metric. This proved the authors' assumption that using the composite metric provides the routing process with more correct information about the link chosen. The final established link using the composite metric can deliver more packets per its source node(s) than using the hop-count metric and the other metrics.

4.3.2 Batch 2 simulation results and analysis

This section presents the analysis of implementing the composite metric on the simulation scenarios when the MAC protocol used was the SEEK-MADP protocol. The metrics evaluated were only the composite metric and the hop-count metric. These results were not included in the first batch because the packet delivery ratios when using SEEK-MADP were higher in comparison to the IEEE 802.15.4 simulations.

4.3.2.1 Energy per packet results and analysis

The energy consumption results are illustrated in Figures 4.19 and 4.20. From the figures, it is observable that the composite metric improved the network performance in terms of energy consumption. At number of nodes 15, the error bars of both approaches are high, this is attributed to the number of links created by the network is low. This makes the effect of the composite metric on route choice close to that of hop-count therefore the error bars are high. From Figure 4.19, the trend of energy per packet consumption is incremental when using the hop-count metric. Using the composite metric, the trend is more fluctuating than using the hop-count metric. Increasing the number of nodes increases the network energy consumption overall. Using the hop-count metric makes the routes created based on the number of hops. The nodes are mobile which increases the number of broken links in the network therefore using only hop-count metric cannot tell how efficient the next hop is. The composite metric promotes the nodes that have high residual energy and good connection links. Therefore the network energy consumption becomes lower and more fluctuating.

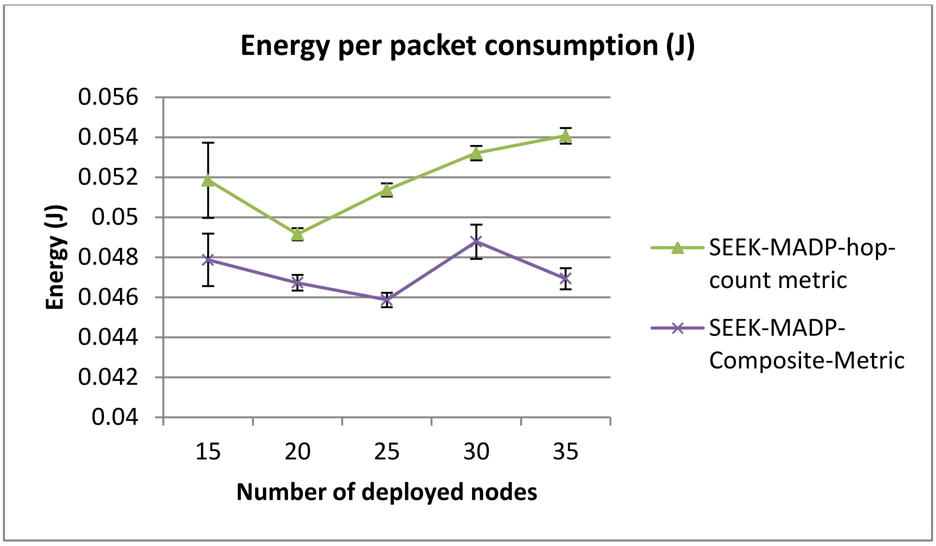


Figure 4.19: Batch 2 energy per packet results.

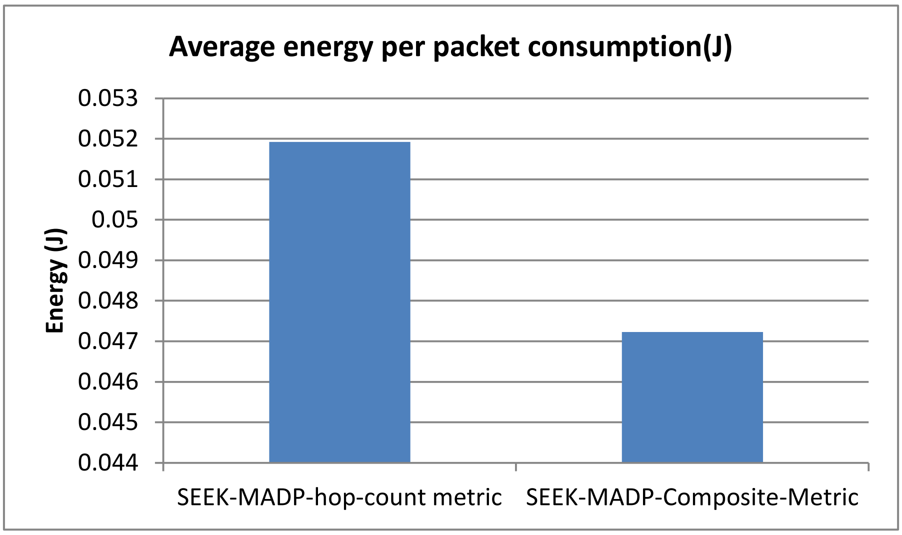


Figure 4.20: Batch 2 average energy per packet results.

4.3.2.2 Throughput and PDR results

Figures 4.21, 4.22 and 4.23 list the throughput and PDR results of the network. The main observation is that the composite metric improved the network throughput. PDR was improved as it was directly proportional to the throughput.

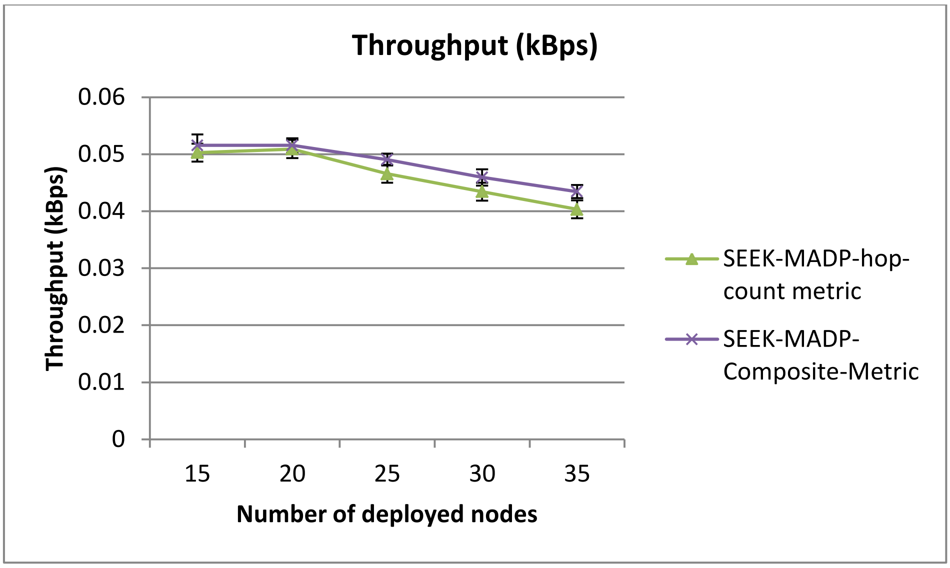


Figure 4.21: Batch 2 throughput results.

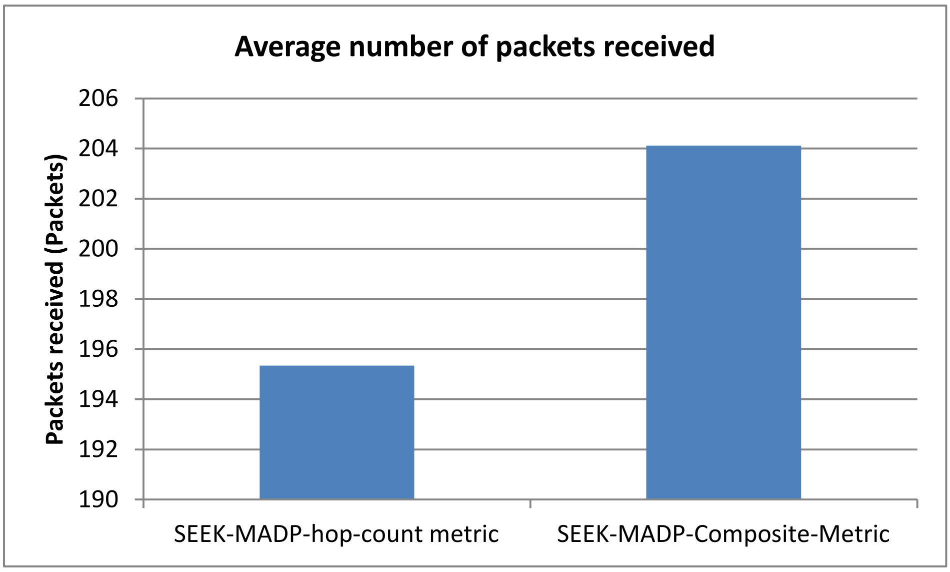


Figure 4.22: Batch 2 average number of packets received results.

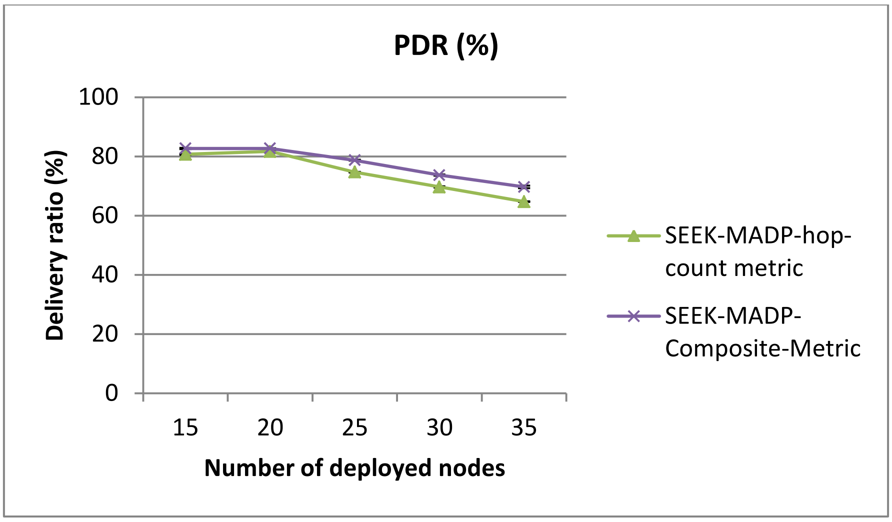


Figure 4.23: Batch 2 packet delivery ratio results.

4.3.2.3 End-to-end delay results and analysis

The end-to-end delay results in Figure 4.24 show marginal extra delays when utilising the composite metric. The results agree with the results of the batch 1 simulation scenarios. Whilst knowing the quality of the link and being energy aware of the neighbours totally improved the network performance, the hop-count advances in terms of end-to-end delays as the routing protocol will always choose the shortest hop path.

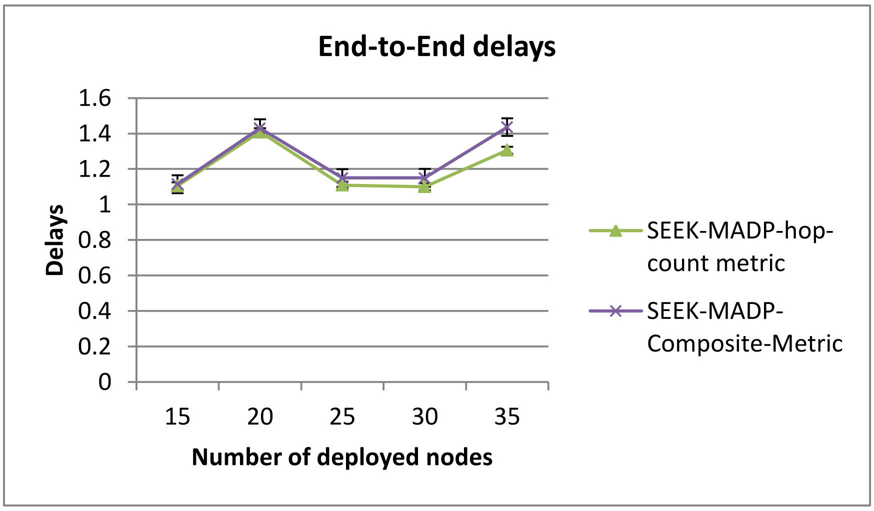


Figure 4.24: Batch 2 end-to-end delay results.

4.4 Location estimation method evaluation

This section presents the evaluation of the energy efficient localisation method for a mobile WSN. The proposed method utilises a distance-based location estimation method together with a digital compass and a speed sensor attached to the mobile nodes. Trilateration was used to estimate the very first location of the nodes by deploying three beacon nodes. The beacon nodes sent broadcast signals to the nodes and the receiver was able to estimate its distance by the RSSI levels. Each sensor node was equipped with a digital compass which gave the angle of the movement and a speedometer was used to retrieve the speed of the node. By using the first location obtained through trilateration, the angle and speed of the movement, the next location of the node in question was then estimated. The location information of the mobile node was utilised as the application layer information in the proposed network operational model. Two experiments were executed to evaluate the location estimation method. The first experiment was a simulation of the proposed method using the Network Simulator 2 (NS2) [178]. The second experiment included prototype hardware of a mobile node and implementation in an area.

4.4.1 Simulation setup and scenarios

The simulation scenario contained six mobile nodes and three beacon nodes situated at places where it was possible to cover the whole deployed network (Figure 4.25). The area of the simulation was 400 × 400 square meters.

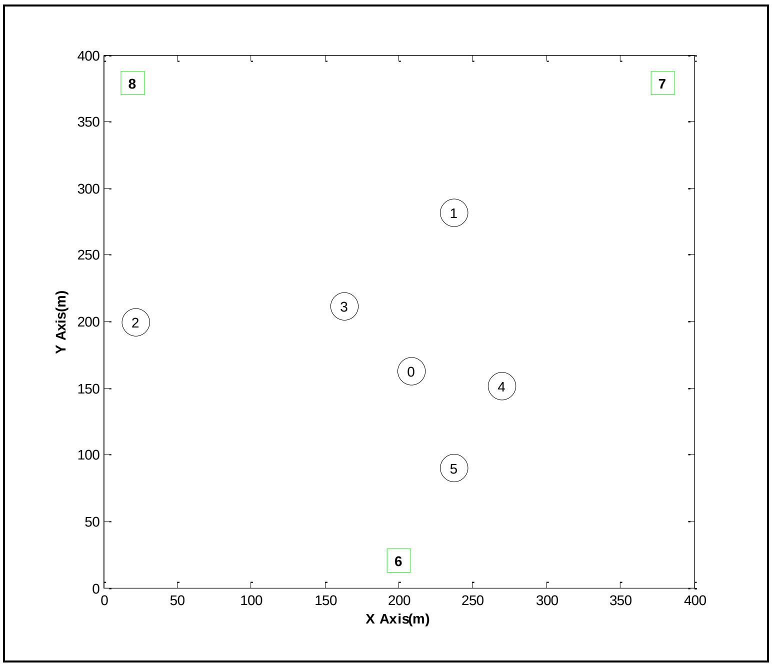


Figure 4.25: Simulation scenario.

Two simulation experiments were implemented for the same simulation scenario with different mobility settings. In the first, the mobile nodes moved in a uniform speed of 1 m/s (the speed can be translated to about 3.6 km/h, a walking speed). The second setting involved the nodes moving at a random speed which varied from a minimum speed of 1 m/s to a maximum speed of 3 m/s. The mobile nodes were randomly deployed in the area of movement. The movement directions were random for each node. The Random-Way Point mobility model [179] was used to implement the node's mobility scenario. The compass module simulated in this experiment was HMC6352 [180] manufactured by Sparkfun Co. Three configurations were implemented for each mobility scenario. The pure trilateration was the first method tested as the localisation method of the mobile nodes. The second configuration implemented the proposed method with the random compass error according to the module specifications. The third setting represented the worst case scenario where the compass was assumed to produce the orientation angle with the maximum error. Table 4.4 below shows the simulation settings which included the node transmission/reception power, propagation model, initial energy and the compass power consumption.

Table 4.4: Simulation scenario parameters

Simulation parameter	Parameter value
Simulation time	900 seconds
Node’s initial energy	2 joules
Mobile node velocity	1 m/s-3m/s
Wireless propagation model	Two Ray Ground
Compass Max. Error	1 Degree
Compass resolution	0.5 Degree
Transmission power	31 mW
Reception power	35 mW
Transmission freq.	2.4 GHz
Compass power consumption	3.2 mW

4.4.1.1 Results and discussion

The proposed method was evaluated against one of the most widely used methods of localisation in WSNs which is trilateration. The criteria of the evaluation were the energy consumption of the system and location estimation error.

4.4.1.1.1 Energy consumption results and analysis

Starting with the energy consumption evaluation, during the simulations and experiments, the average power consumption of the nodes was the same for both simulation implementations. Figure 4.26 below shows the network average power consumption results for all of the scenario cases.

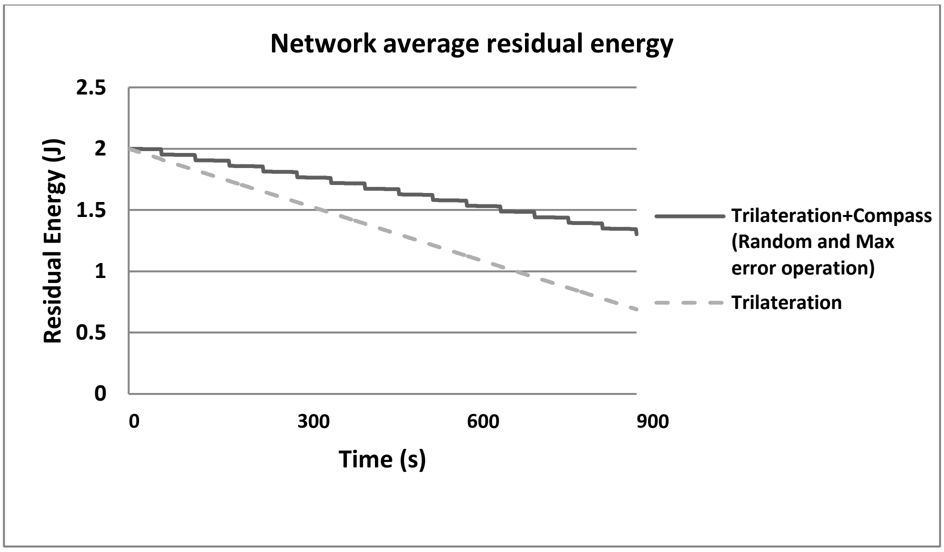


Figure 4.26: Average energy consumption of the network (the six nodes) for the pure trilateration and the proposed method.

It is observable how the pure trilateration method consumed more power than the compass mixed operation. The trilateration method required frequent usage of the wireless interface which is the most energy consuming part of the mobile node during operation; whilst, the compass module consumed far less than the wireless interface (35 mW against only 3.2 mW). The results above were extrapolated and the results came to the conclusion that using trilateration only can make nodes survive only for 1370 seconds. The proposed method prolonged the operation of the network to about 2580 seconds (88% improvement over the trilateration method) using an initial energy of 2 joules.

4.4.1.1.2 Location error results and analysis

The location estimation error was the second criteria of the evaluation for the proposed method. The error of location (L_e) was calculated by the Euclidian distance:

$$L_e = \sqrt{(x_o - x_c)^2 + (y_o - y_c)^2} \quad \ldots\ldots (27)$$

where x_o and y_o were the coordinates of the actual location of the node and x_c and y_c were the estimated coordinates of the mobile node. The result was actually the straight line distance between the actual point and the estimated point of interest. The trilateration method resulted in a random error in the location estimation over the compass operation which was more of an accumulated error in operation. However, the results were promising in terms of the location estimation accuracy of the proposed method in the normal case of operation and in the worst case scenario. The location error for the proposed method also included the error of the periodic trilateration operation. The results of the error estimation were categorised into 100 bins by following the Frequency Distribution method:

1. Find the minimum and maximum estimation error value from the original data.

2. Calculate the range by subtracting the minimum from the maximum.

3. Divide the range by the number of bins to calculate the bin width.

4. The upper limit (the first bin) is calculated by adding the minimum value to the bin width. From there, the addition of the bin width (adding bin width to the bin just one level up represents the next bin) is resumed until the number of required bins is reached (the maximum error value is reached).

5. Count the frequency of occurrences of each bin according to the original data.

The resulting histograms for the location errors are shown (Figure 4.27) for the three methods discussed.

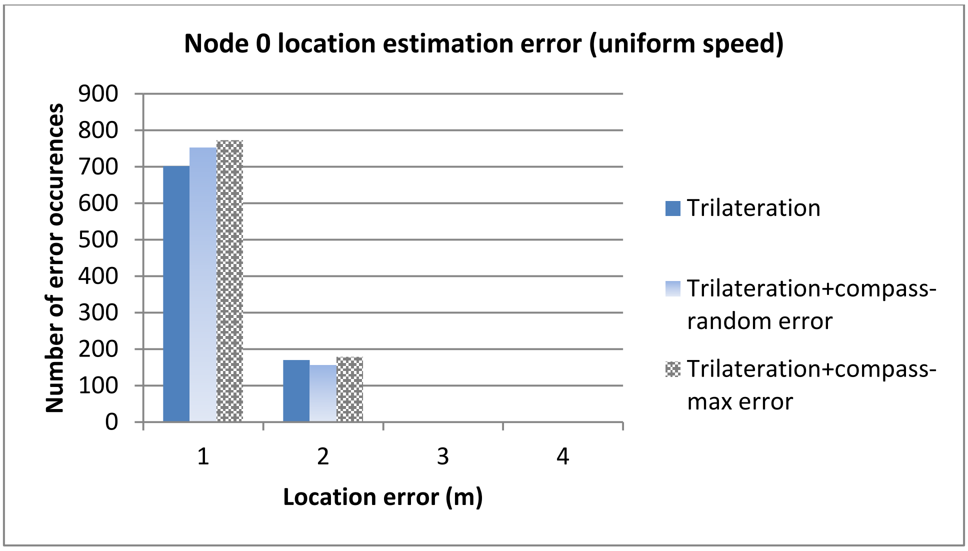


Figure 4.27: Node 0 location estimation error occurrences according to error categories (Actual results).

A trend-line of each method was described according to the relative error occurrence in the experiments to clearly illustrate the relative performance between the three methods. The produced trend-line for each method followed the multiple linear regression (MLR) model which was represented by equation (28):

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots\ldots.. + \beta_p X_{pi} + \acute{\varepsilon}_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

where $\beta_0, \beta_1, \ldots., \beta_p$, were defined as regression coefficients, i.e., coefficients to be derived from the data. Y_i was the estimated response for the i_{th} element to estimate. $X_1, X_2, \ldots., X_p$, were the predictors used to evaluate the fitting function representing the trend-line. The $\acute{\varepsilon}_i$ represented a normal random error of the approximated element. The model was implemented for all of the mobile nodes' output data for both simulation scenarios. Figure 4.28 and Figure 4.29 illustrate the location estimation errors for node 0 in both the uniform and the random mobility settings. The figures also show the results of the implemented localisation methods. From Figure 4.28, Trilateration method and proposed method (with random compass error and maximum compass error) share similar trends in location error. The proposed method generates slightly higher error compared to trilateration.

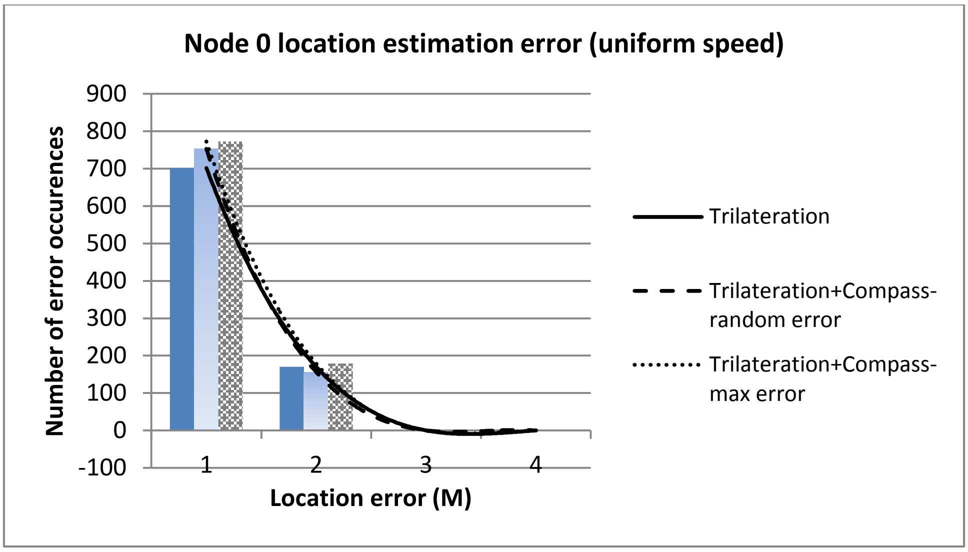


Figure 4.28: Node 0 location estimation error occurrences according to error categories.

In Figure 4.29 and Figure 4.30, the error in location estimation increased as the speed of the node increased (the random speed of the mobile node was between 1-3 m/s). The trilateration method and the proposed method had a rather similar trend of location estimation error. The compass operation with the maximum error resulted in a higher estimation error.

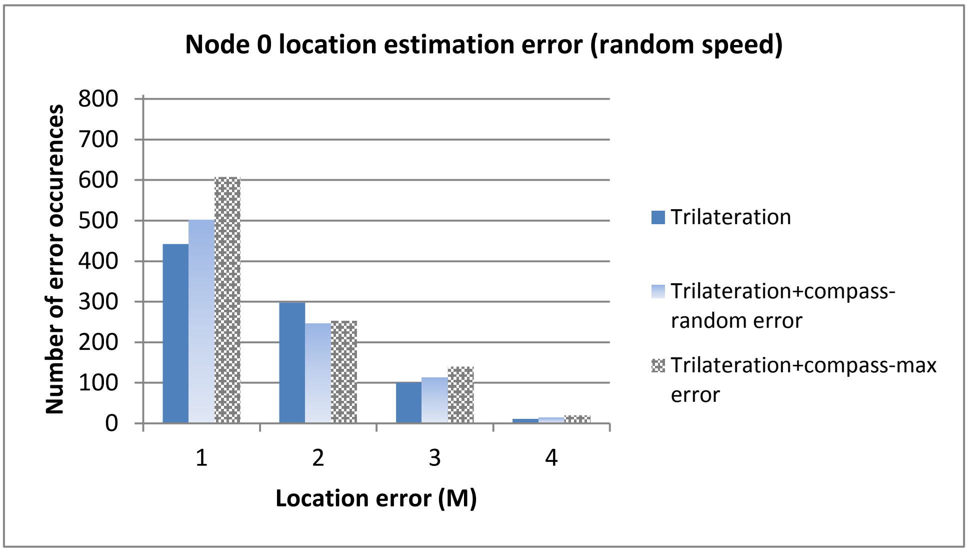


Figure 4.29: Node 0 location estimation error in random speed.

Figure 4.31 and Figure 4.32 illustrate the location estimation error for node 1. The figures follow the same trends in Figure 4.28 and Figure 4.29.

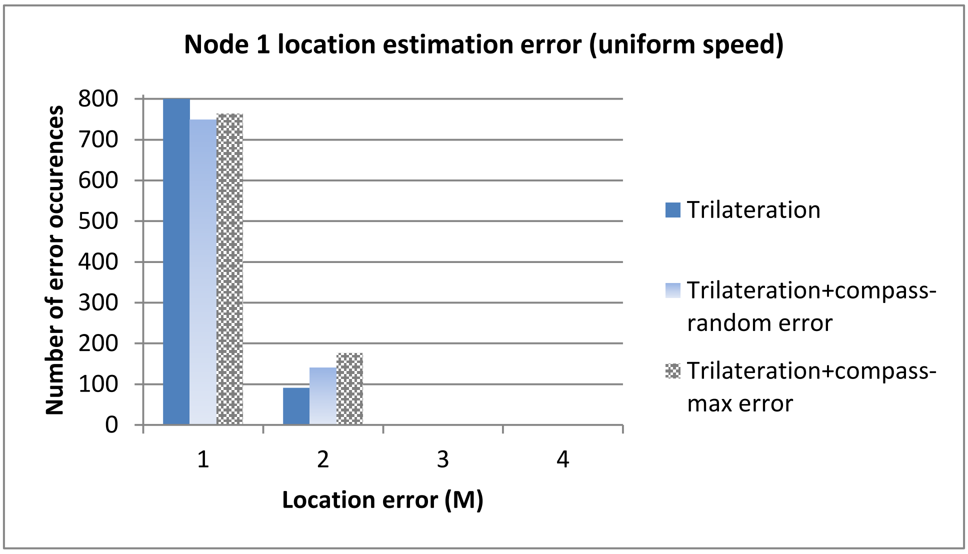


Figure 4.30: Location estimation error for node 1.

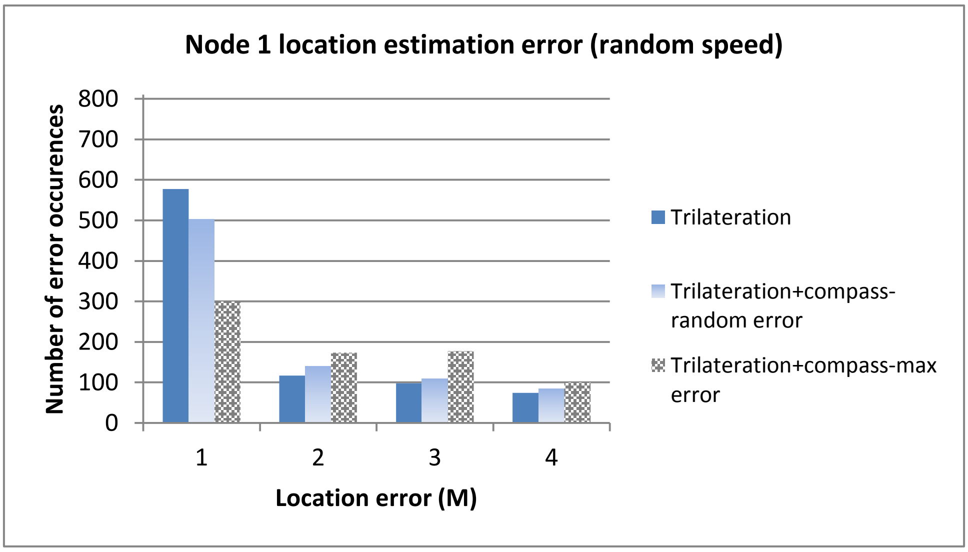


Figure 4.31: Node 1 location estimation error.

The trilateration method and the proposed method were almost on par when it came to the location calculation error in at uniform speeds. The increase in the velocity of the mobility resulted in a higher location estimation error for the proposed localisation method (Figure 4.29 and 4.31).

The estimated location error for trilateration fell into three categories: the first estimation calculation error (in implementation, node 5 had an estimation error of 0.19 m at standstill in a random speed scenario output data), the second was the displacement of the node during the location estimation operation when receiving the signals required from the beacon nodes, and the third was the sensitivity of estimating the distance based on RSSI.

In the case of trilateration, the node purely depended on the received signal to indicate the location. However, the increment in error in the proposed method was due to utilising the digital compass as the major source of the location update plus the error resulting from the trilateration as a periodic location refreshing procedure.

Figure 4.32 and Figure 4.33 show the performance of the implemented methods in terms of location estimation accuracy for all of the mobile nodes in uniform and random speeds, consecutively.

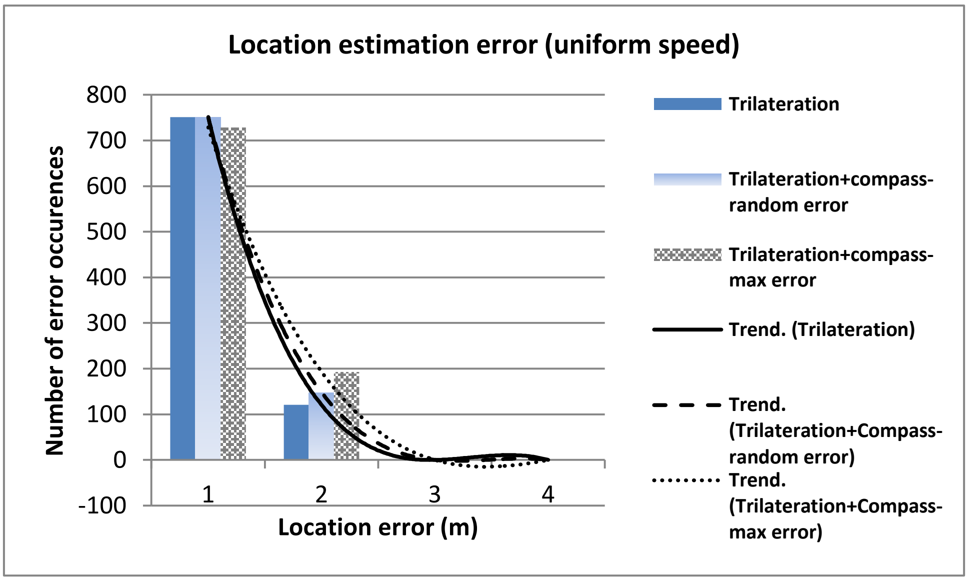


Figure 4.32: Location estimation error for all of the mobile nodes. The proposed method at a regular operation was close to the trilateration method in terms of location estimation.

The proposed method implementation results for a uniform speed scenario (Figure 4.32) are promising for overall network location estimation. The proposed method with a random compass error operation showed less location estimation error than the worst case scenario (when the compass reading included a constant 1 degree of error). The proposed method's performance was also close to the trilateration estimation method in the random speed scenario (Figure 4.33).

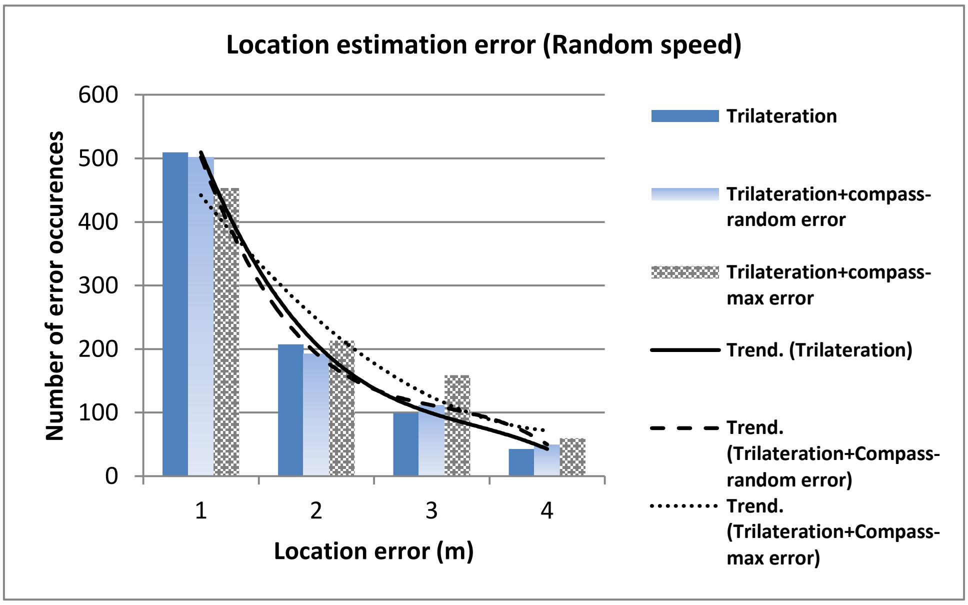


Figure 4.33: Location estimation for all of the mobile nodes at a random speed.

The overall trend of the location estimation error of the proposed method (for normal operation and the worst case operation) was comparable to the location estimation error for the pure trilateration method for the whole of the deployed mobile nodes (Figure 4.32 and Figure 4.33). This observation supports the proposed method of location estimation to be used in mobile WSNs because the method provided a similar location estimation as compared to the trilateration method for the given simulation scenarios. The proposed method outperformed the pure trilateration method in terms of energy consumption because it combined the periodic operation of trilateration (every 60 seconds) and utilised a digital compass and a speedometer to update the mobile node location. Pure trilateration implementation requires the beacon nodes to frequently transmit localising signals to the mobile nodes which can exhaust the nodes lifetime because the wireless interface power consumption is higher than the digital compass power consumption.

4.4.1.1.3 Visual location estimation simulation

To show the effect of each method on the estimation of the nodes location during its mobility, a visual trace of the nodes has been made for the proposed simulation scenarios (the uniform speed situation was considered as an example). Figure 4.34 below shows the traces of the nodes' mobility in the field of deployment.

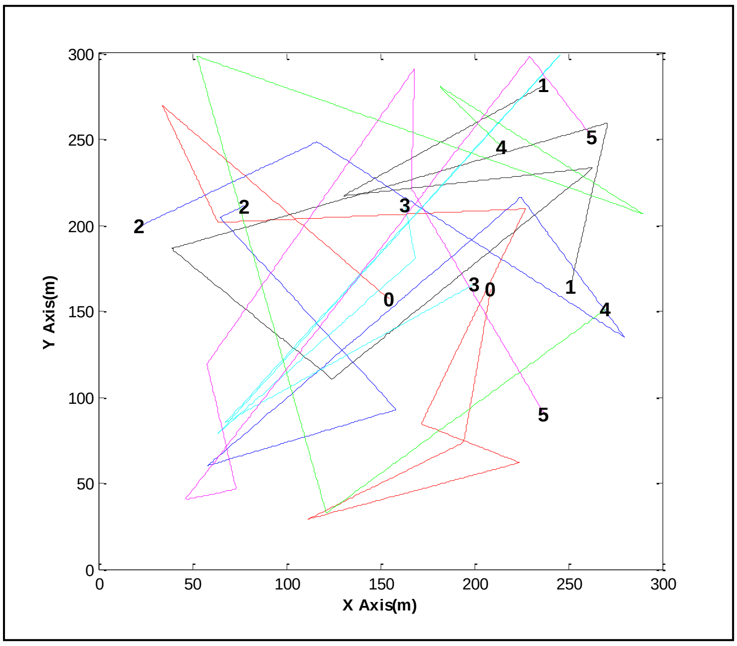


Figure 4.34: The deployed nodes' mobility traces in a uniform speed scenario.

From the trace lines shown in Figure 4.34, the node 0 mobility trace line was considered as an example to show the performance of each method of location estimation (Figure 4.35).

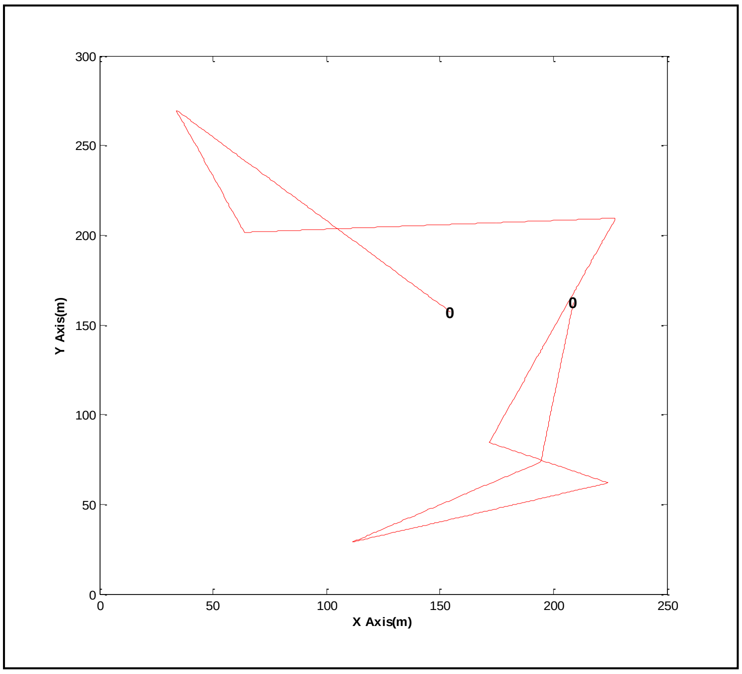


Figure 4.35: Node 0 mobility trace line. The trace line shown in this figure is the actual mobility trace for node 0 during simulation.

The deployed nodes were mobile throughout the period of the simulation. The location estimation methods were periodically initiated each for 1 second. That means there were 900 points of location estimation for each method (Trilateration), proposed method (random Compass error) and proposed method (worst case scenario). Aligning the points of each method with the actual trace line of node 0 (Figure 4.36) makes the differences impossible to appreciate (due to the fact that the area of deployment was very large as compared to the error of the estimated points from their actual points).

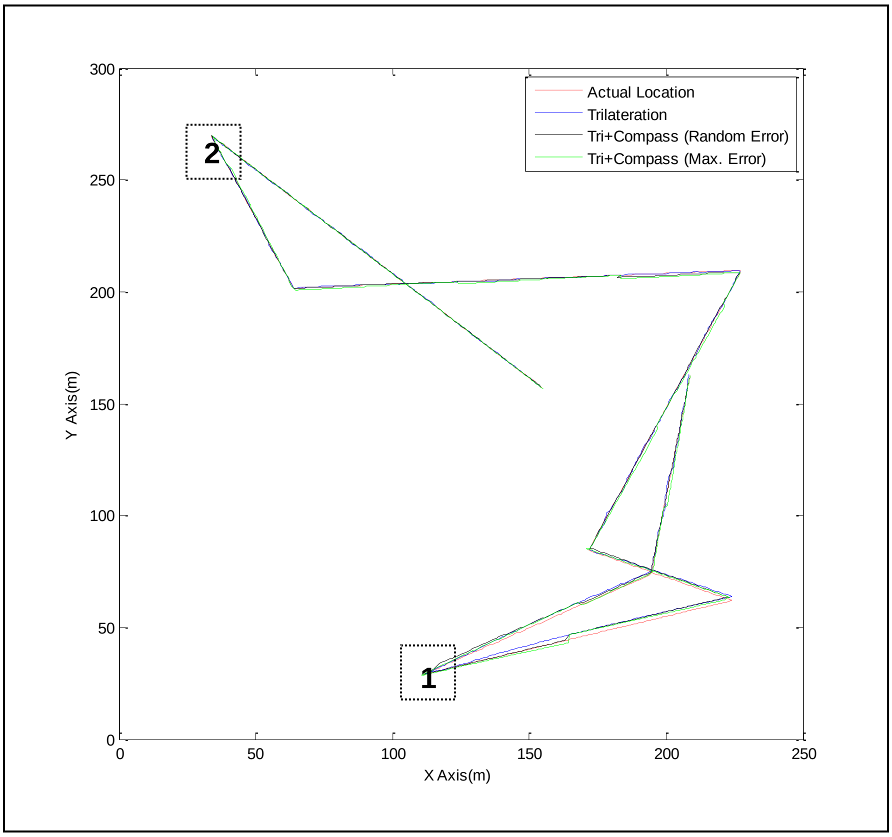


Figure 4.36: Node 0 mobility trace lines for each method of localisation. The trace lines are very condensed.

From the mobility trace line of node 0 (Figure 4.36) it is difficult to observe how each method performed in location estimation. By zooming in on the part of movement at x: 110-125m, y: 22-40m and at x: 33-41m ,y: 260-270m areas from Figure 4.37, it is possible to have a better look of how each method was estimating the node's location during movement (Figure 4.37 and Figure 4.38). It is possible to observe that the proposed method (both in the regular case and in the worst case scenario) was marginally similar to the pure trilateration method in terms of location estimation accuracy. The proposed method is aimed at mobile WSNs where the nodes change their places rapidly. The proposed method's implementation results are promising in terms of average network energy consumption and location estimation accuracy.

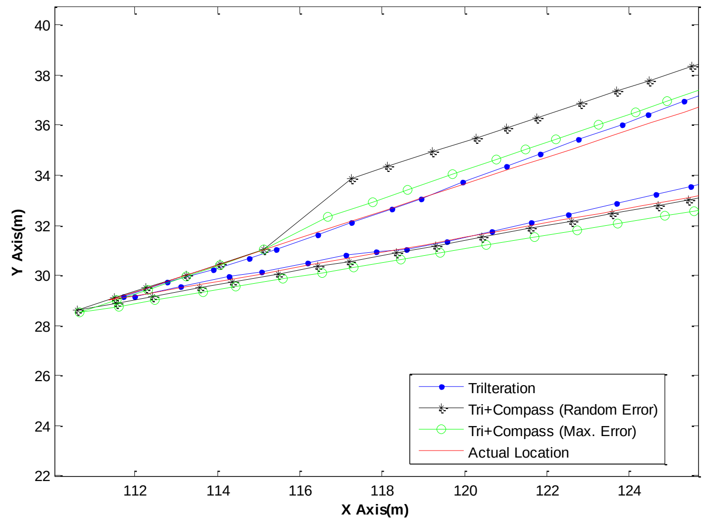


Figure 4.37: A closer look at the operation of each method for node 0 movement at uniform speed (Dotted-Box 1 in Figure 4.37).

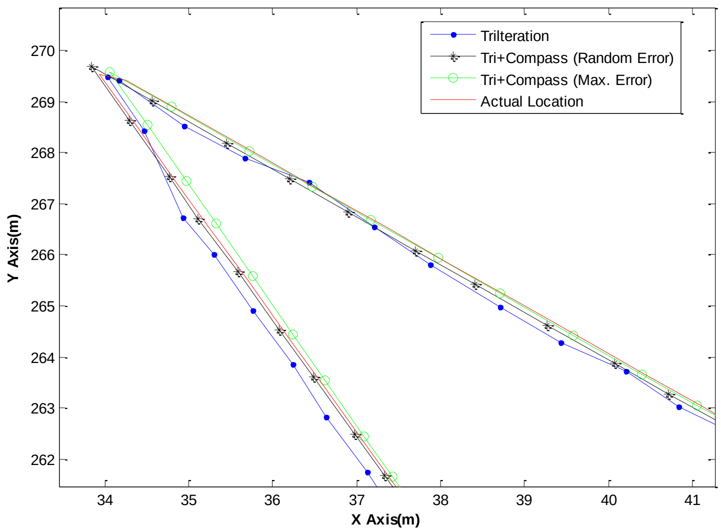


Figure 4.38: Closer look at the operation of each location estimation method for node 0 mobility at uniform speed (Dotted-Box 2 in Figure 4.37).

4.4.2 The proposed localisation method prototype implementation

A proof of concept of the proposed location estimation method has been provided as an implementation prototype of a mobile wireless node. The mobile wireless node used in the case study was a remote control toy car attached to a processing unit and a wireless interface. The processing unit was an Arduino Uno board that could run at 16 MHz and has a memory of 32 KB. The wireless interface was a series 1 MaxStream XBee module with 1 mW (0 dBm) transmission power attached to a 5dB antenna (Figure 4.39).

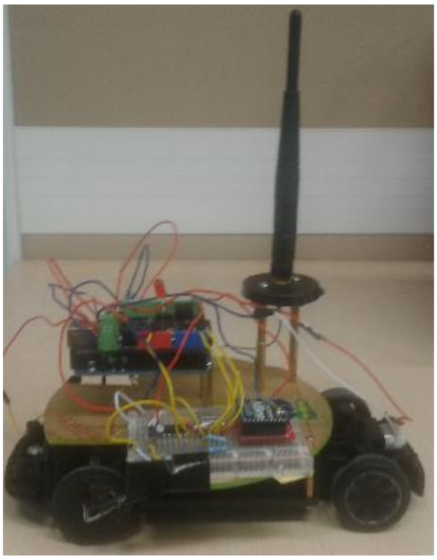
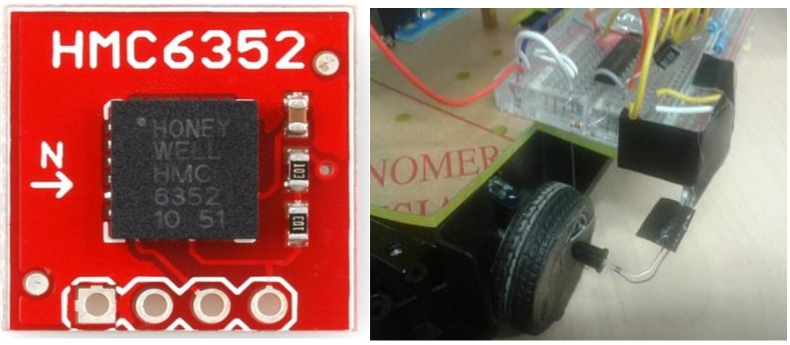


Figure 4.39: Wireless mobile node device.

The wireless node was also equipped with SparkFun HMC 6352 two-axis digital compass with non-tilt compensation. The speedometer circuit was custom made using an IR transmitter diode and a receiver diode attached to a debouncing circuit to count the number of rotations that the toy car wheel made in a certain period of time (Figure 4.40). The beacon nodes were equipped with the same XBee modules. Each beacon node was attached to a 7 dB antenna. The implementation space had an area of 6 m × 6.5m where two beacons were placed on the edges and one was placed in the middle of the x-axis of the implementation plane (Figure 4.41). Two mobility scenarios where tested–a straight line 5-meter movement and a half circle mobility for a distance of 7 meters.



(a) (b)

Figure 4.40: (a) Digital compass module, (b) IR-based speedometer circuit.

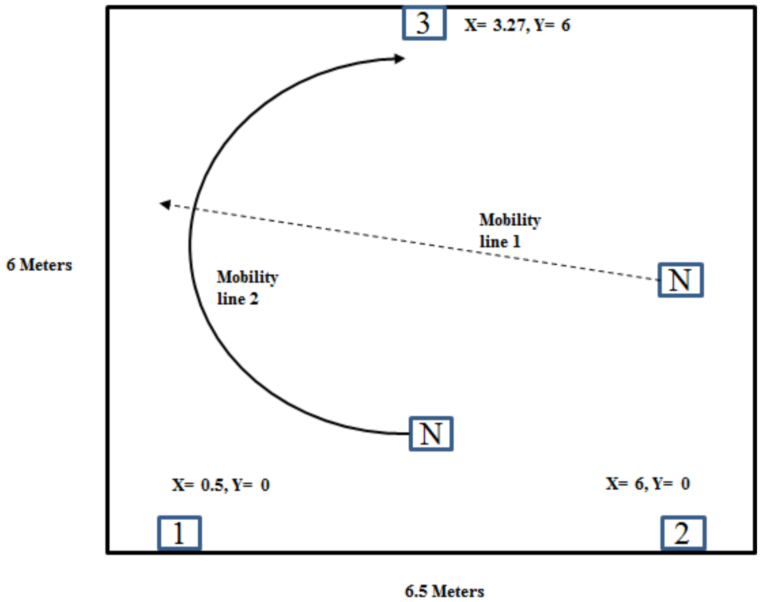


Figure 4.41: Implementation scenarios and area.

It is important to mention that the XBee modem antennae where modified and fitted with a U.FL connector to make exchanging with bigger antennae possible. The reason for this modification was because the original whip antenna had an uneven radiation pattern and was rather notorious (Figures 4.42 and 4.43).

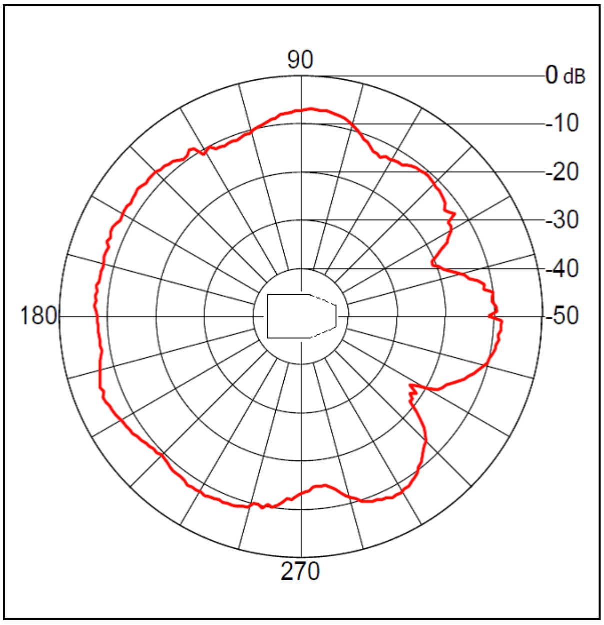


Figure 4.42: XBee modem whip antenna radiation pattern in the Horizontal plane [30].

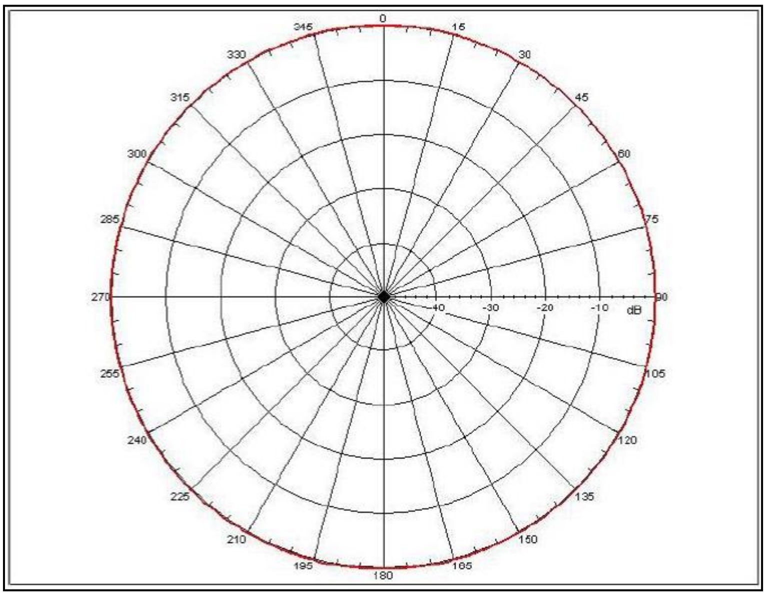


Figure 4.43: 5dB WiFi antenna radiation pattern in the Horizontal plane [181].

This uneven radiation pattern directly affected the distance estimation as shown in Figure 4.44.

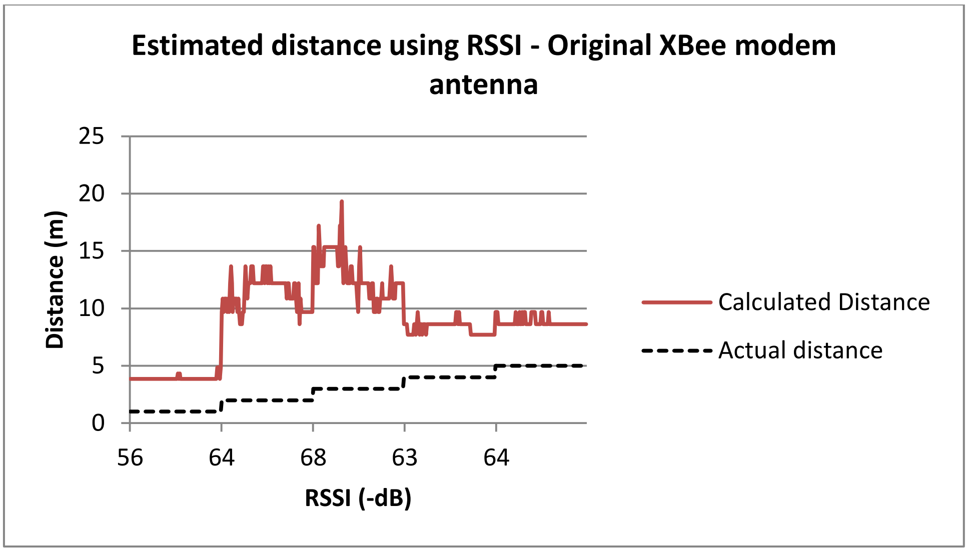


Figure 4.44: Estimated distance using the original antenna of the XBee model.

4.4.2.1 Implementation and Results

4.4.2.1.1 Location estimation validation and results

The advantage of using trilateration as the location estimation process is its cost effectiveness because it utilises the RSSI from the wireless modules implemented. However, the RSSI indicator can be erroneous depending on the situation of the mobile device. An experiment to test the RSSI reading in a stationary situation with the estimated distance for a range of 5 meters was performed and the result of the test is shown in Figure 4.45. The experiment was carried out by shooting 100 packets to the destination node and recording the received RSSI.

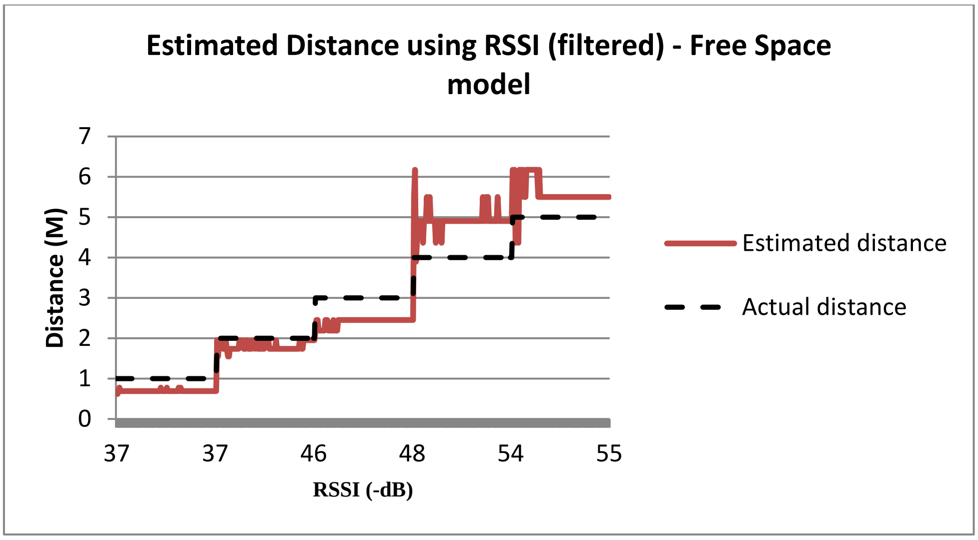


Figure 4.45: Distance estimation using the new attached antennae.

As shown in Figure 4.45, it is possible to observe a few glitches at first and then stable readings for the rest at each distance category. When the wireless node was moving, the process of estimating the distance became very erroneous because of the RSSI readings. This affected highly on the quality of the trilateration results as shown in Figure 4.46. To decrease the estimation error, a solution has been proposed. Because of the nature of wireless propagation, reflections and refractions attenuate the received power. Theoretically, the signal with the straight line transmission should have the highest level of received power. To employ this, the RSSI filtering was carried out by sending 10 packets (each separated by a period of 3 milli seconds) from each beacon node. The mobile node then performed a search process for the highest received RSSI value and then implemented it in the distance estimation formula. The advantage of this process was that the location estimation error was lower than the original trilateration process. However, because there was a search process, it added delay to the location estimation which resulted in fewer location points.

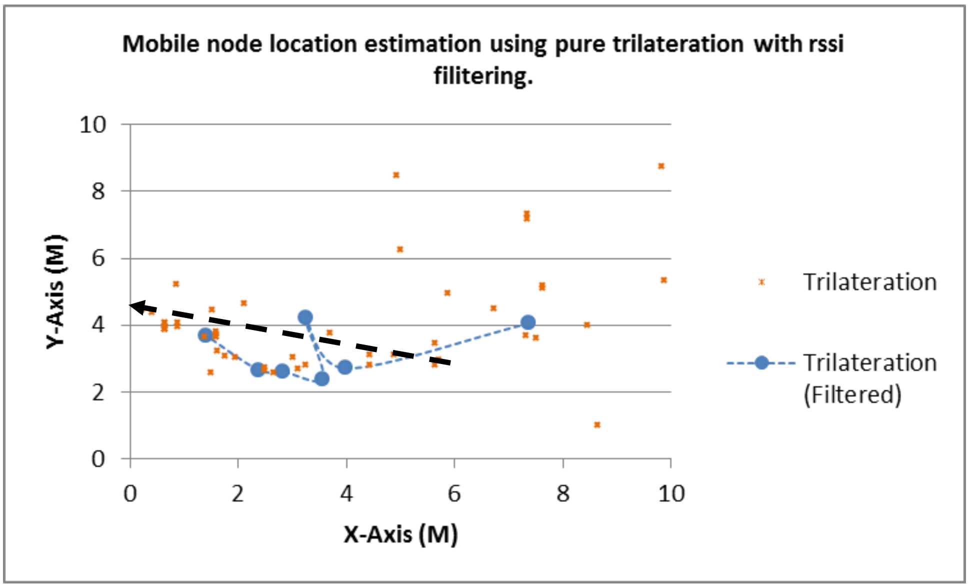


Figure 4.46: Location estimation performance for trilateration and trilateration (Filtered). The black dashed arrow is the actual movement trace-line.

Figure 4.47 shows the results of trilateration + location updates using the compass and speedometer (the solid line). It is observed that the location estimation was very sensitive to random compass errors. To minimise this irregular error, an aluminum-based thin shield was used to wrap the compass module to decrease the magnetising affect of the components surrounding it. In addition, a software-based low pass filter was applied to the compass readings to minimise the sudden over shoots in the angle estimation. The filter took the average of two readings and the latest reading was compared to the average. If the difference between the calculated average and the new reading was above 5 degrees (which was the threshold used in the implementation), then the node took the average reading as the direction value. Else, the node used the new direction reading. After implementing the shield and the filter, the estimated location became more stable and the location estimation error had the behaviour of an incremental offset (the dotted line). Figure 4.48 shows the result of the implementation of the proposed method in the half-circle mobility scenario. The average location estimation error of the proposed method was between 0.6-1.9 meters. Whilst the average error of the trilateration (filtered) was 1.52 meters. The node's velocity varied between 0.6 - 1 m/s.

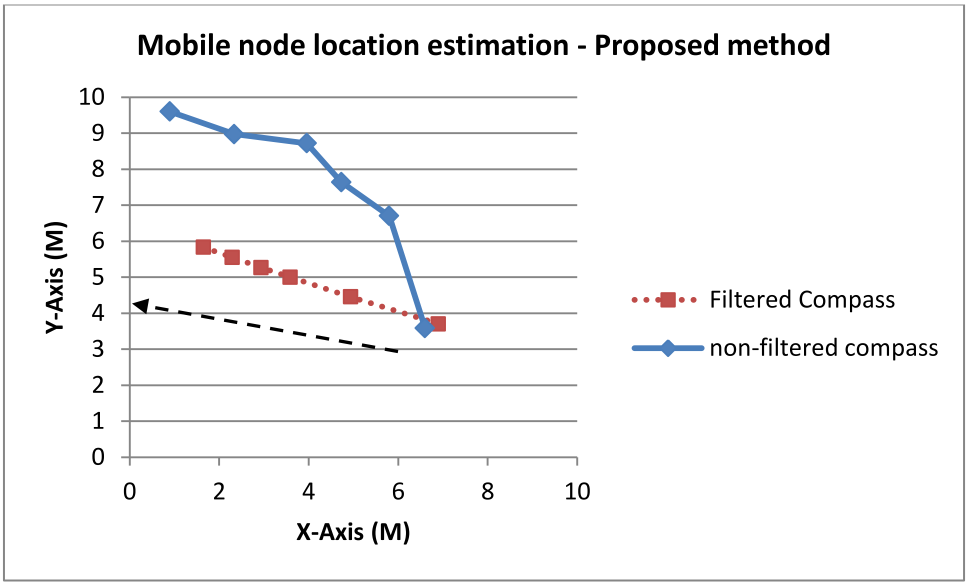


Figure 4.47: Mobile node location estimation using the proposed method (trilateration and compass/speedometer combination) with a straight movement. The filtered compass represented the implementation of the metal shielding plus the software low pass filter.

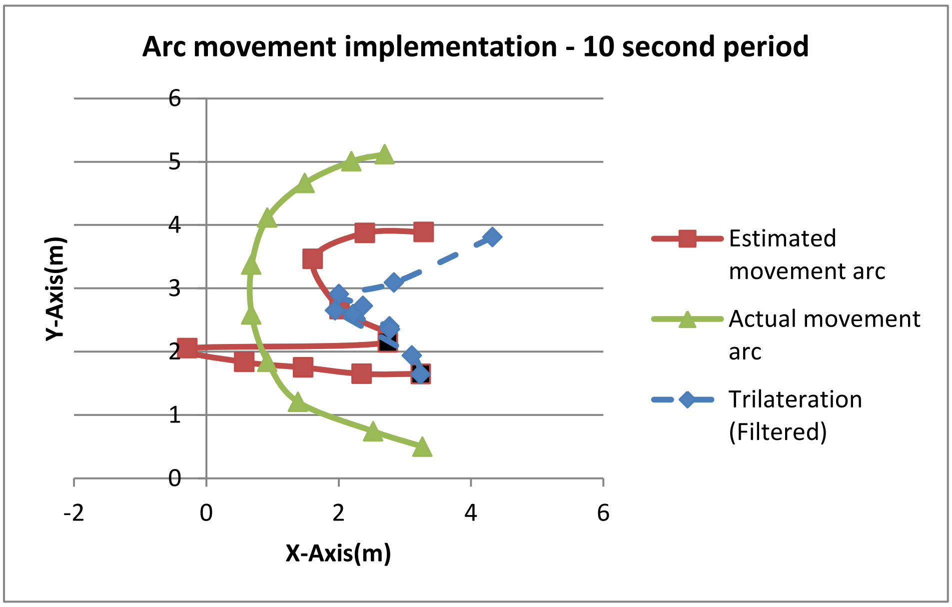


Figure 4.48: The proposed method's performance for several trilateration processes.

4.4.2.1.2 Energy consumption evaluation

To measure the energy consumption, the mobile node was deployed without movement and the supply current drawn by the system (excluding the drive systems) was measured using a multi-meter. During this period, the mobile node continuously performed trilateration, compass/speed detection and location update calculations by using the Arduino microcontroller. The results are shown in Figure 4.49.

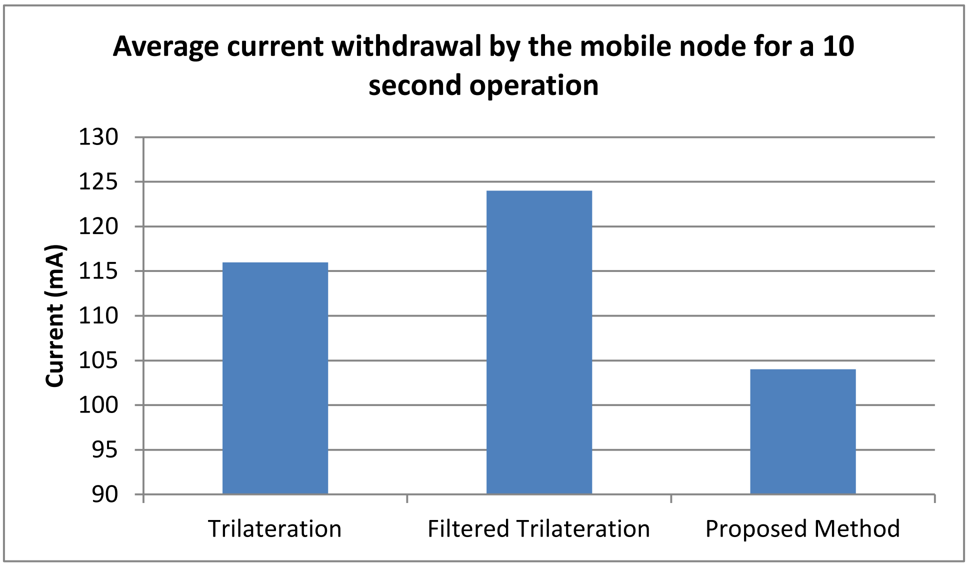


Figure 4.49: Current withdrawal by the mobile node for the methods discussed.

From Figure 4.49, it is possible to observe that the proposed method improved the system’s current consumption by 20% less than the filtered trilateration and about 16% than the regular trilateration.

4.4.2.2 Results summary

The proposed location estimation method has a location estimation error less than the trilateration method and less power consumption. Table 4.5 illustrates the location estimation results against the methods proposed in the literature with their setup methodologies.

Table 4.5: Localisation method compared against proposed methods in the literature

Localisation method parameters	**Isaac Amundson et al.** [147]	**Trilateration** [132], [165]	**Proposed localisation method**
Mobile node speed	0.1 m/s and 0.4 m/s	0.6 m/s and 1m/s	0.6 m/s and 1m/s
Location estimation average error	0.95 meters from actual location	1.52 meters from actual location	0.6-1.9 meters from actual location
Power consumption	The author did not specify	123 mA	104 mA

4.5 The cross-layer operational network model evaluation

This section discusses the operational model as a protocol stack that follows the proposed abstract model in chapter three of this thesis. The operational model has been evaluated according to a simulation scenario where a set of mobile nodes were deployed in a specific area with mobile node parameters that were the same in the simulation scenarios used during the development process of the three parts of the operational model. The three core parts that were developed to be included in the proposed operational model were:

1. SEEK-MADP MAC protocol which has been implemented as the MAC layer protocol in the proposed protocol stack.

2. The composite metric as solutions for the network layer protocol in the proposed protocol stack.

3. Localisation method as part of the application layer information with an enhanced energy consumption affect over the network operation in general.

The importance of the choice to develop and modify the above mentioned parameters was because each part has a specific action in the operational model. The

MAC layer was chosen because MAC protocols control the operation of the network interface engagement to the shared wireless medium which means that the protocol acts rather close to the physical layer of the operational model. Therefore, an energy efficient MAC protocol operation has to effect the operation of the physical layer operation and preserve energy on the node’s(s’) level.

The routing layer (Network layer) was chosen because a routing protocol controls the network traffic paths. Therefore, an efficient routing protocol operation has to reflect on the traffic balancing operation of the network in general. The focus of mobility in this research required an attention to the development process of the routing protocol as the protocol has to be able to handle rapid topology changes.

Proposing a localisation method aimed specifically at mobile WSNs was an important task in the development process of the proposed operational model. The localisation process can be power demanding if the node’s(s’) location changes rapidly. Location information is important for the end user and that is why it is considered application layer information.

The cross-layer approach has been evaluated using NS2 [178]. The simulation scenarios of the routing metric have been reused for evaluating the cross-layer model (Table 4.2). The transport protocol used was UDP. The simulation period was 500 seconds. The minimum node mobility speed was 1 m/s and the maximum was 3 m/s. to test the scalability of the proposed operational model, the number of nodes for each simulation scenario are 15, 20, 25, 30, 35, 50, 75 and 100 respectively. The proposed cross-layer model was compared against a model proposed by [182] for WSNs which was named ZigBee stack and a protocol stack with EQSR cross-layer multi-path routing protocol. The EQSR cross-layer protocol has been evaluated for two environments. The EQSR-802.15.4 has been evaluated based on the IEEE 802.15.4 MAC protocol, and the EQSR-802.11 for IEEE 802.11-based MAC protocol nodes. Two versions of the cross-layer were evaluated. The first included only the cross-layer mechanism (will be noted as Cross-layer). This configuration was to highlight the cross-layer mechanism without the improved MAC and routing and localisation mechanisms. The second version implemented the cross-layer mechanism plus the SEEK-MADP as the MAC protocol, the composite metric as the enhancement over the routing protocol and the proposed localisation method. This final configuration has been noted in the results as Cross-layer +. Table 4.6 shows the components of each evaluated model. The operational model has been also evaluated under shadowing propagation model (Appendix D).

Table 4.6: Operational models' protocol stacks

ZigBee stack	**EQSR-802.15.4**	**EQSR-802.11**	**Cross-layer**	**Cross-layer +**
Application layer Trilateration location estimation	Application layer Trilateration location estimation	Application layer Trilateration location estimation	Application layer Trilateration location estimation	Application layer Compass + trilateration location estimation
Transport layer (UDP)	Transport layer (UDP)	Transport layer (UDP)	Transport layer (UDP)	Transport (UDP)
Network layer (AODV)	Network layer (EQSR)	Network layer (EQSR)	Network layer (AODV)	Network layer (AODV+ Composite metric)
MAC layer (IEEE 802.15.4)	MAC layer (IEEE 802.15.4)	MAC layer (IEEE 802.11)	MAC layer (IEEE 802.15.4)	MAC layer (SEEK-MADP)

4.5.1 Energy efficiency of the proposed operational model

Figure 4.50 illustrates the energy consumption of the network without the inclusion of the localisation method's energy consumption for the compared protocol stacks. Figure 4.51 illustrates the energy consumption of the network when the localisation method's energy consumption was included. Figure 4.52 shows the energy per packet consumption for the evaluated protocol stacks. It is observed that the proposed cross-layer operation offered better energy consumption for the network. Cross-layer+, however, consumed higher energy than the Cross-layer stack. This is because the Cross-layer+ generated higher PDR results because of the inclusion of the SEEK-MADP MAC protocol.

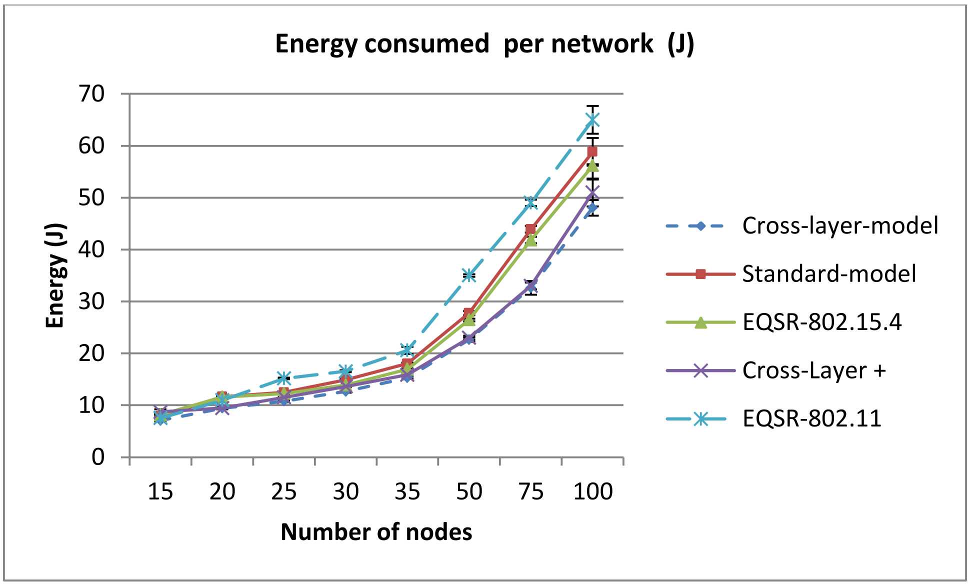


Figure 4.50: Total energy consumed by the network.

EQSR-802.11 had higher energy consumption than Cross-layer+. This attributes back to the IEEE 802.11 MAC protocol since the protocol does not have sleep periods like the SEEK-MADP or IEEE 802.15.4 MAC protocols. The energy consumption trend in the results agrees with the trend presented in the validation of the cross-layer model in chapter 3 section 3.6.2.

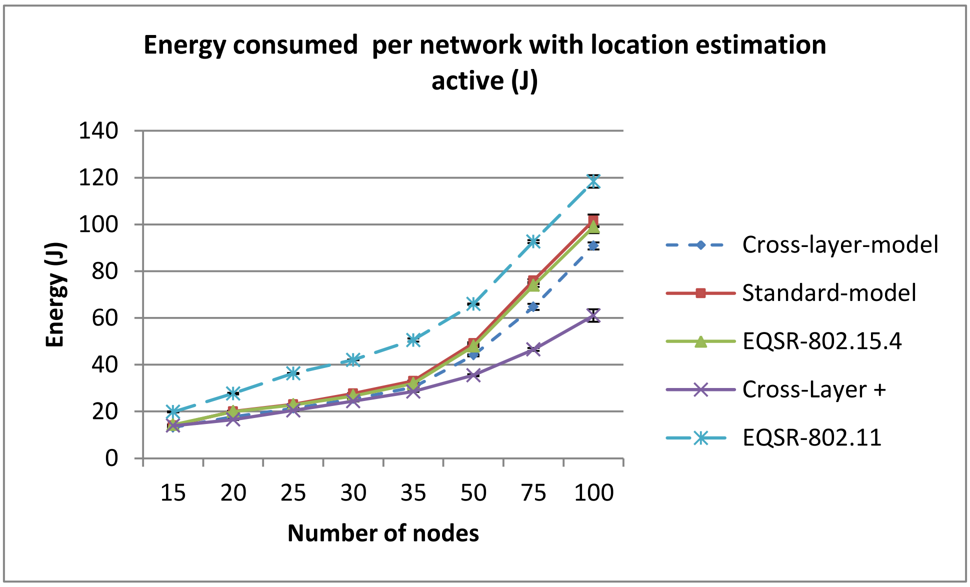


Figure 4.51: Total energy consumed by the network including the energy consumed by the localisation method.

Another factor in these results is that the cross-layer mechanism implemented in the Cross-layer and Cross-layer+ stacks limited the number of control packets transmitted between the nodes. This improved the network's overall energy consumption because of the decreased number of control packets (refer to Figure 4.57 control packet overhead results). Figure 4.51 illustrates the results of network energy consumption when including the localisation process' energy consumption. Cross-layer+ had the lowest energy consumption because the proposed localisation method improved nodes energy consumption. Cross-layer+ had the lowest energy consumed by the network per successful packet reception.

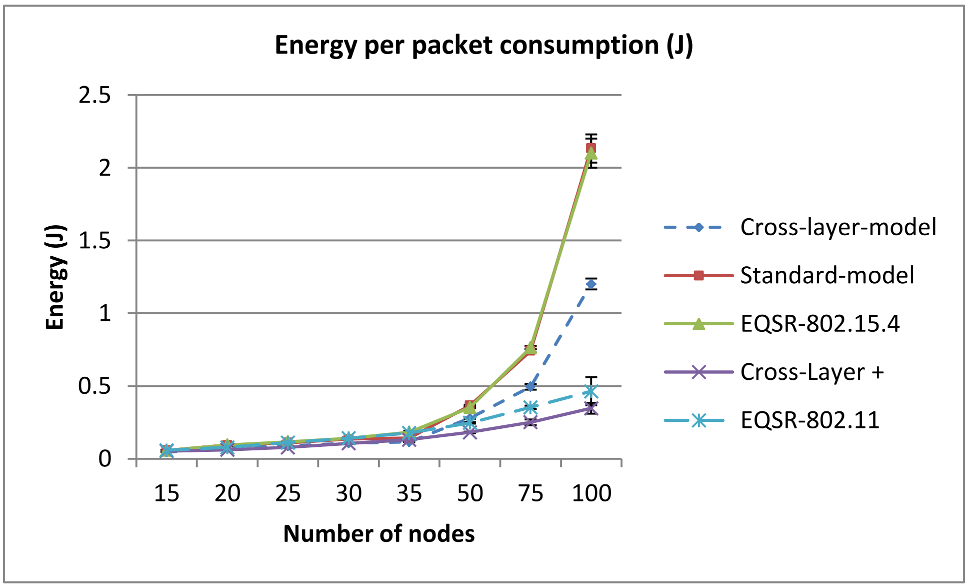


Figure 4.52: Energy consumed per packet transmitted.

4.5.2 Proposed operational model throughput results

Figure 4.53 shows the PDR results of the ZigBee, Cross-layer, Cross-layer+, EQSR-802.15.4 and EQSR-802.11 protocol stacks. Figure 4.54 shows the throughput results of the evaluated models. From the figures listed, it is possible to conclude that the Cross-layer model bests the ZigBee stack. The Cross-layer model produced higher PDR and throughput than the EQSR-802.15.4 model. This improvement in PDR and throughput was related to the minimisation of the control packets. Minimising the number of broadcasts of control packets decreased the usage and occupation of the wireless channel resulting in better throughput. Cross-layer+ had the highest PDR and system throughput. EQSR-802.11 had the second highest system throughput and PDR because of the usage of the IEEE 802.11 protocol. As mentioned above IEEE 802.11 has only active period and listening period. This improved the network operation drastically with the EQSR protocol; however, it still lacks behind the Cross-layer+ model.

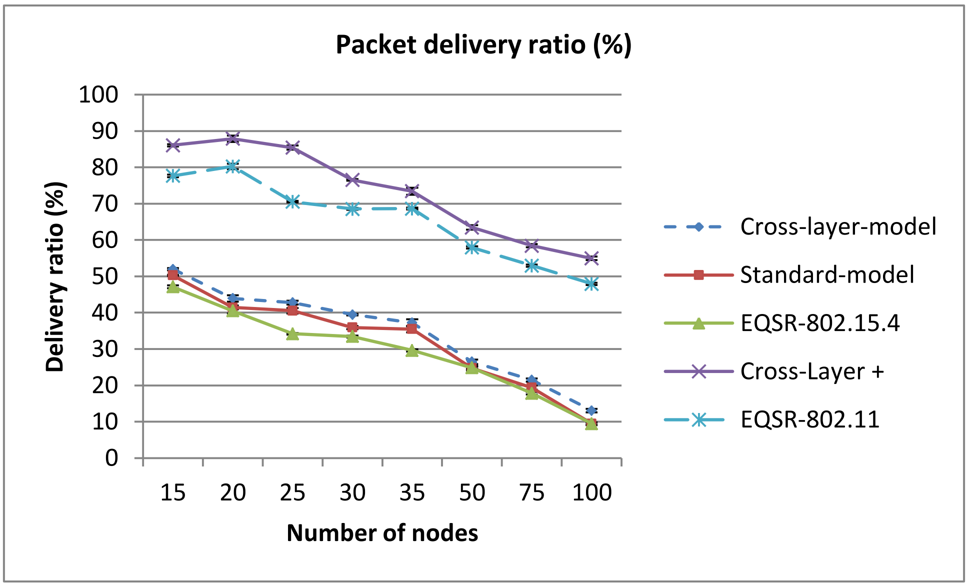


Figure 4.53: Packet delivery ratio.

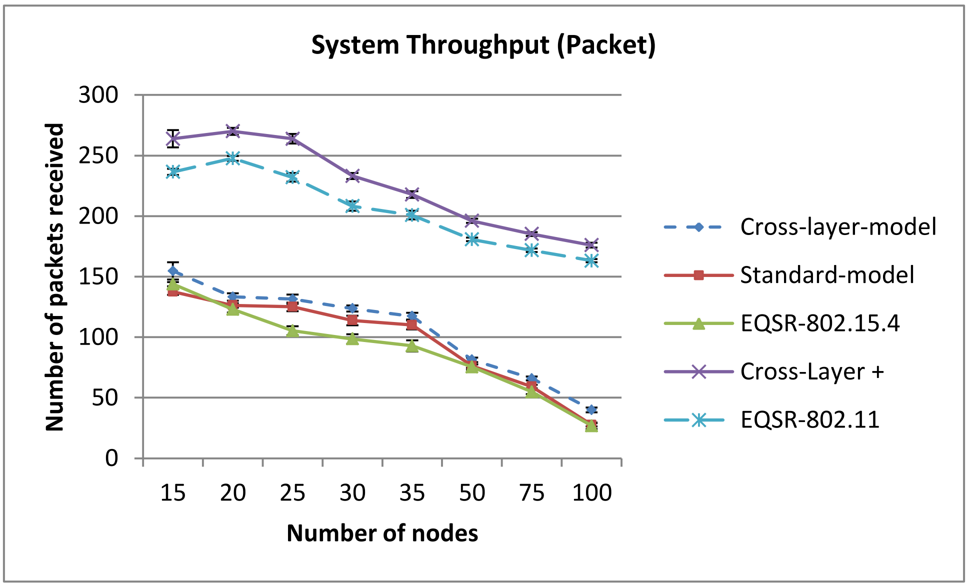


Figure 4.54: Throughput of the network.

4.5.3 End-to-End delay results

Figure 4.55 shows the end-to-end delays as a function of the deployed nodes in each scenario. ZigBee stack offered marginally higher message delays than the Cross-layer model. The EQSR-802.11stack recorded the lowest message delays overall. The Cross-layer+ stack showed high end-to-end delays. This was directly related to the MAC mechanism used in the stack. SEEK-MADP has been shown to have high end-to-end delays because of the handshaking mechanism required for establishing the connection. Another reason was that the duty-cycle of SEEK-MADP was not adaptive to the data period which is the only adaptive part of the duty-cycle. This affected highly the end-to-end delays of the protocol.

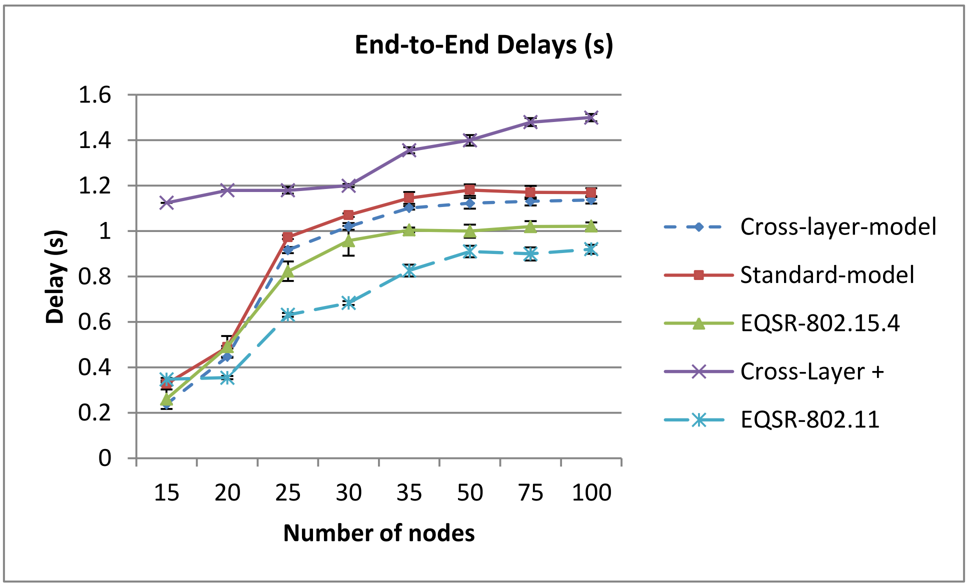


Figure 4.55: End-to-end delays.

4.5.4 Control packet overhead

The proposed Cross-layer model included a control packet mechanism that minimised the number of control packets used during active routes. Figure 4.56 and Figure 4.57 show the effect of this mechanism over the Cross-layer operation. EQSR-802.15.4 has also recorded fewer control packets than the ZigBee stack. EQSR-802.15.4, however, had a marginally similar normalised routing load as the ZigBee stack. EQSR-802.11 had the highest control packets produced since the stack does not have a mechanism to control the dissemination of control packets as in the Cross-layer and Cross-layer+. EQSR-802.11 had a lower normalised routing load than the ZigBee stack and EQSR-802.15.4 stack because it generated higher throughput than both of the protocols. EQSR-802.11's normalised routing loads were higher than those of the Cross-layer and Cross-layer+ stacks.

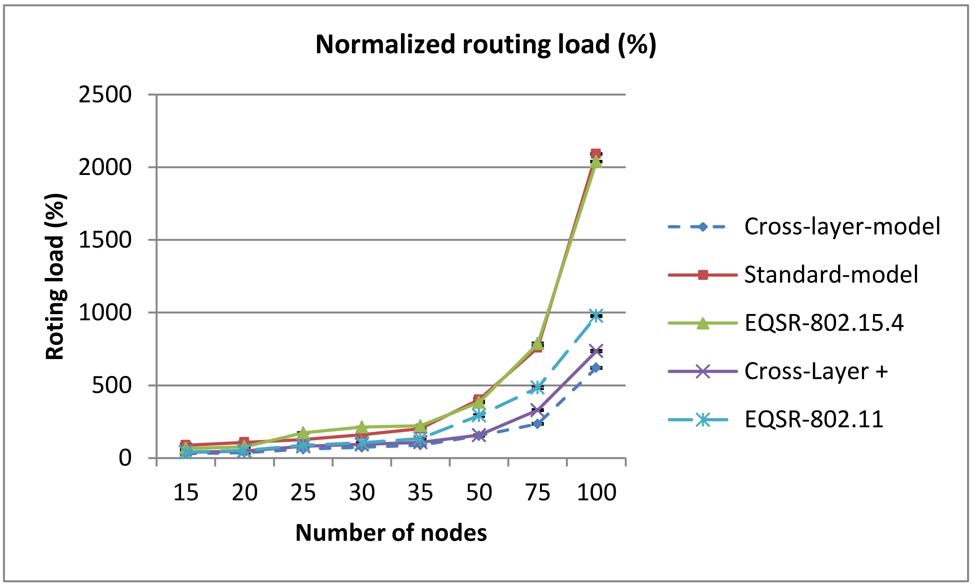


Figure 4.56: Normalised routing load.

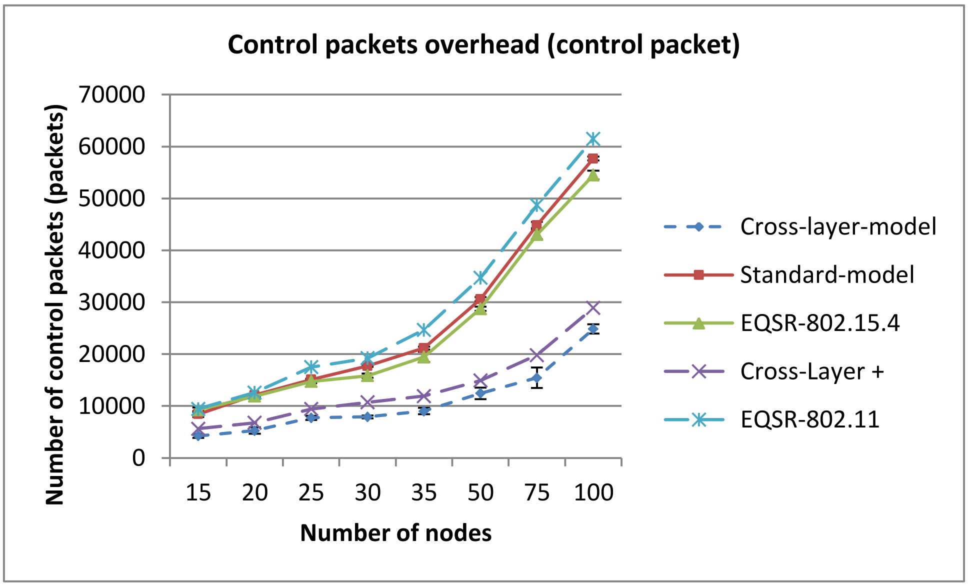


Figure 4.57: The control packets produced by each evaluated protocol stack.

4.5.5 Shadowing model implementation

Figure 4.58 represent the results of the network energy consumption after using the shadowing model. Figure 4.59 is the energy consumption per packet results. Figures 4.60 and 4.61 illustrate the packet delivery ratios results and the end-to-end delays respectively while figures 4.63, 4.64 and 4.65 represents the system throughput, the normalized routing load and the control packets overhead results. Table 4.7 illustrates the simulation parameters used for the shadowing model implementation. From figure 4.58 and 4.59, the trend is similar for the evaluated models. The Cross-layer + has the lowest energy consumption for the network. The energy consumed per packet is the lowest for the Cross-layer + model and in second is EQSR-802.11 since it produced the second highest number of packets.

Table 4.7: Simulation scenarios parameters and values

Simulation parameters	**Values**
Number of nodes	15,20,25,30,35
Initial energy (Joules)	1000
Mobility	1m/s-3m/s
Propagation model	Two Ray Ground
Transmission range	40 meters
Simulation time	500 seconds
Mobility pauses	50 seconds
Routing protocol	AODV
MAC protocol	SEEK-MADP
Number of sources	7 nodes
Transport protocol	UDP
Application	CBR
Simulation runs	31 times
Pathloss exponent (β)	2.7
Shadowing deviation (σ)	5 dB
Reference distance	1 m

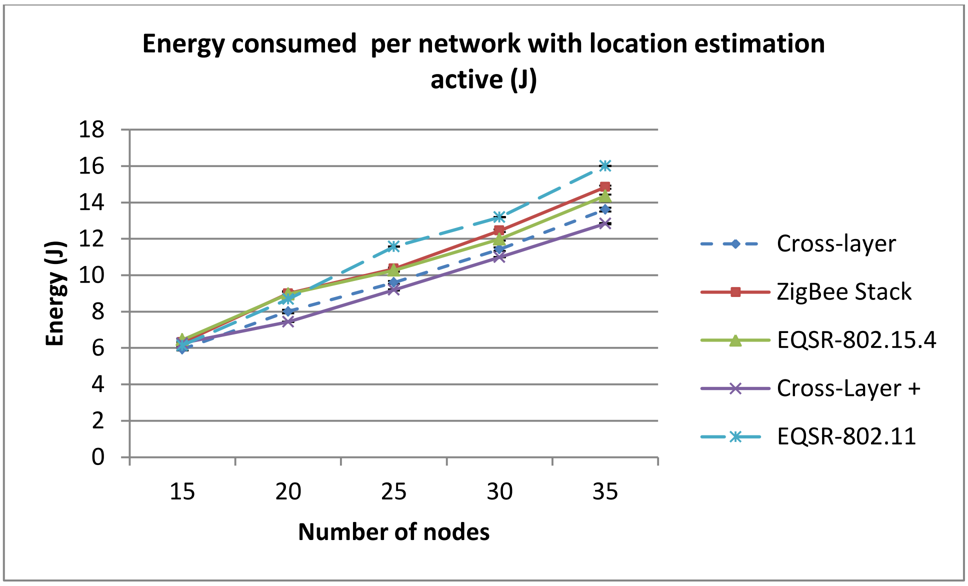


Figure 4.58: energy consumed per network after applying the shadowing propagation model.

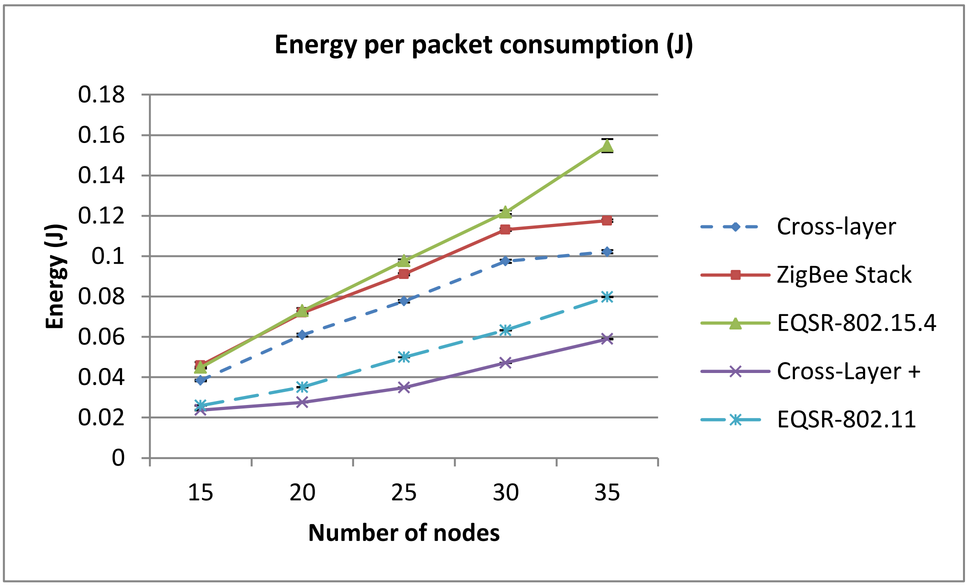


Figure 4.59: energy consumption per packet using Shadowing propagation model.

From figures 4.60, the trend of the packet delivery ratios are the same however, the output has become lower because of the effect of environment shadowing which increases the possibility of failed links. The end-to-end delay results in figure 4.61 show that the delays have increased in general for all the evaluated methods. This is all due to the effect of shadowing on the wireless signals.

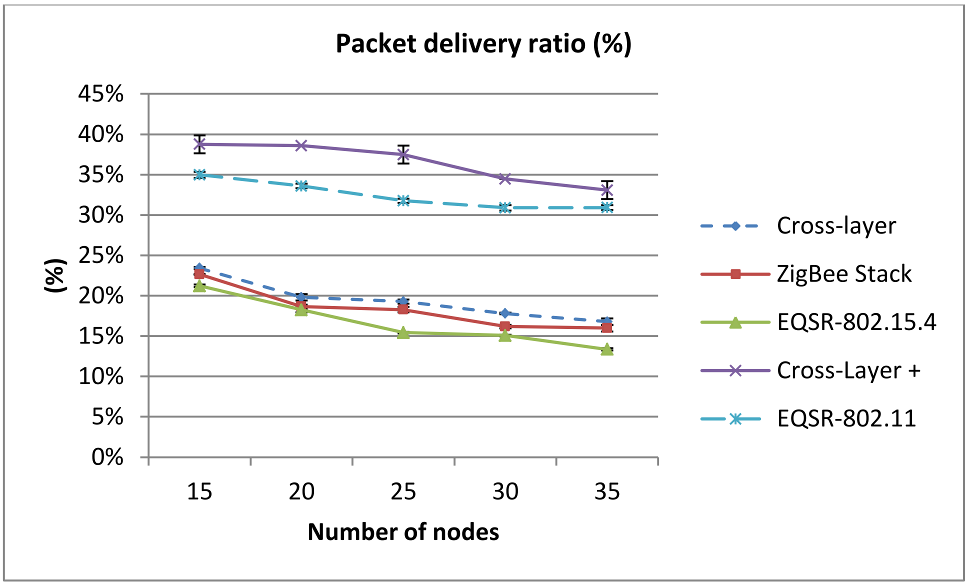


Figure 4.60: PDR results after applying the shadowing model. it is possible the drop in the packet delivery ratios when using shadowing model.

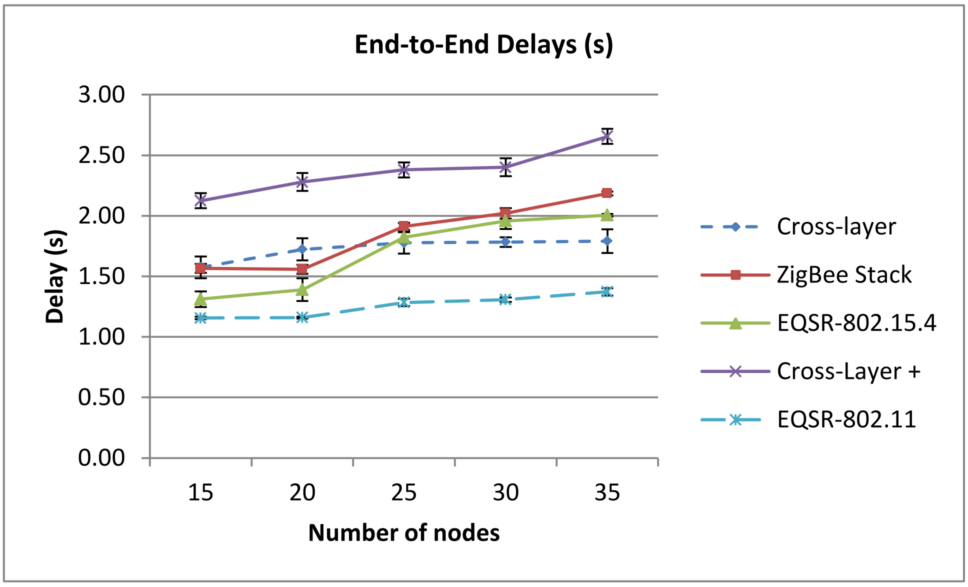


Figure 4.61: End-to-end delays results.

The throughput results in figure 4.62 are synonymous to the results of packet delivery ratios in figure 4.63.

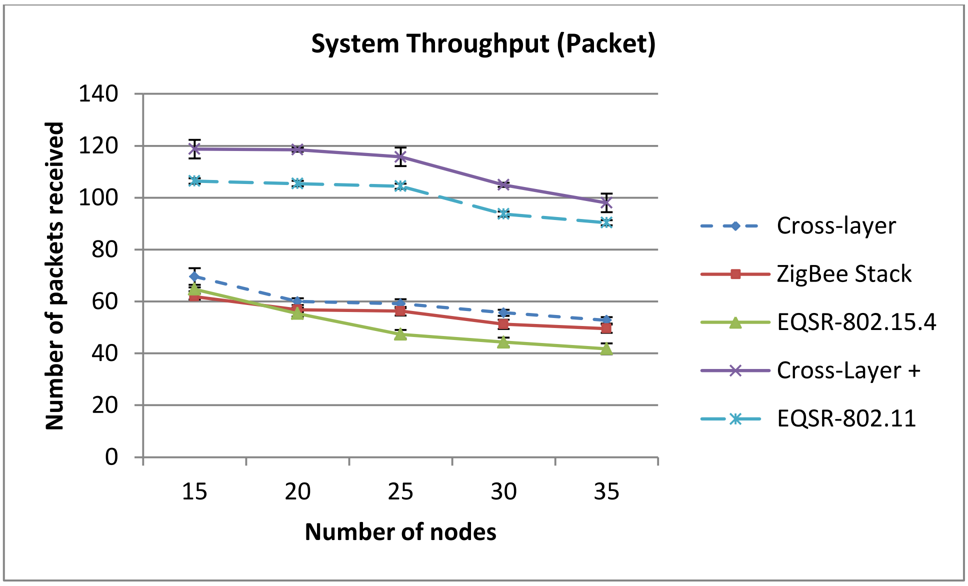


Figure 4.62: System through put results.

The normalized routing load and control packet over results in figures 4.64 and 4.65 show that the Cross-layer and Cross-layer + has the least routing loads and control packet overhead because of the utilization of the control packets minimization procedure in the cross-layer model.

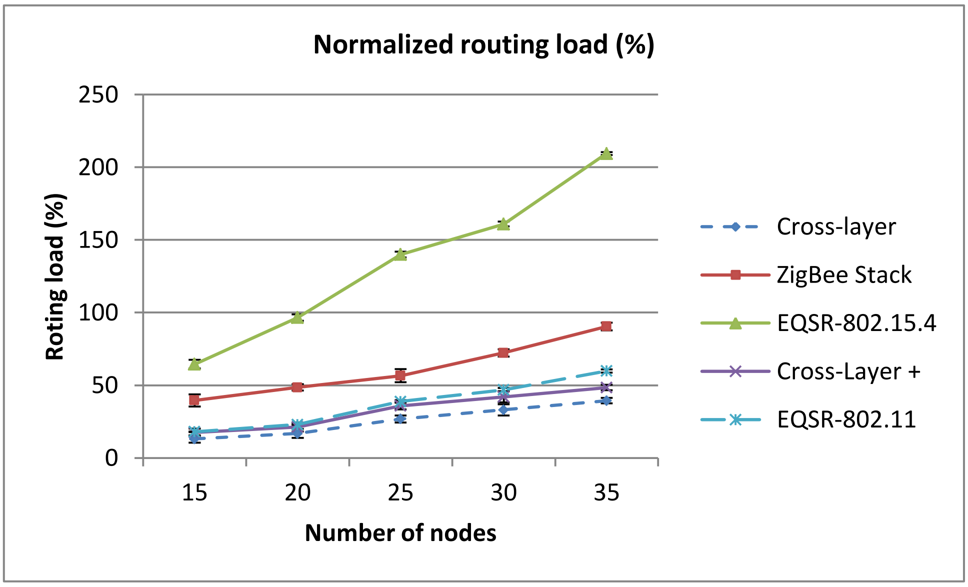


Figure 4.63: the normalized routing load after applying the shadowing model.

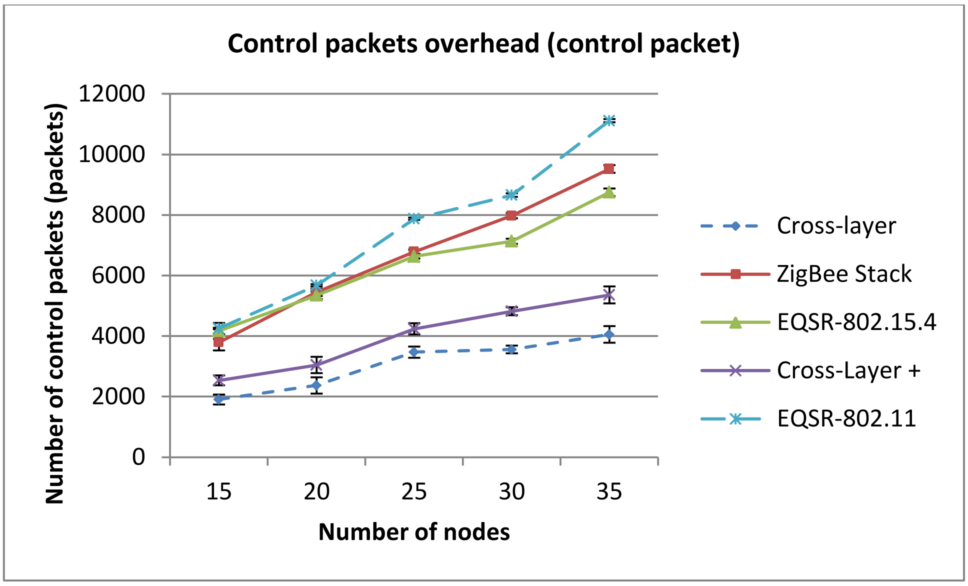


Figure 4.64: number of control packets after applying the shadowing model.

4.5.6 Results discussion and analysis

From the figures listed in the energy, throughput and end-to-end delay sections. It is possible to conclude that the Cross-layer model offered better energy consumption and better throughput by a margin than the ZigBee model. The cross-layer mechanism improved energy consumption by reducing the number of broadcasts of the control packets. The model also included a transmission power control mechanism that operated during data transmission. As for the Cross-layer +, there are several elements that attributed in its efficient performance: the localisation method utilised in the Cross-layer+ model consumed less power than the traditional trilateration method. This, therefore, improved network energy consumption when the number of nodes increased. The SEEK-MADP MAC protocol improved the network throughput.

In Figure 4.51 at the 15 node mark, the ZigBee stack consumed less power than the Cross-layer approach. This only happened because the number of nodes deployed was low and because the ZigBee stack’s PDR was at 40% which improved throughput (Figure 4.53 and Figure 4.54). However, the Cross-layer model at the same point consumed a higher amount energy; the main reason was because the PDR at that exact point was about 4% more than the ZigBee model (Cross-layer + had about a 40% higher PDR). Another reason was because the distances between the nodes connected at the 15 node point were higher; therefore, the adaptive transmission power control gave an effect but not high. When the number of nodes deployed increased one could see that the effect of the adaptive transmission power control became higher as the distances between the nodes deployed was lower which resulted in less power being consumed for transmission between adjacent nodes. The delay results, however, are in favour of the EQSR-802.11, and the EQSR-802.15.4 comes in second. IEEE 802.11 offered stable end-to-end delays more than the IEEE 802.15.4 and SEEK-MADP MAC protocols. IEEE 802.11 operates on the bases of active and listen/idle periods which means that the node(s) are always available for connection.

EQSR protocol is a cross-layer multipath routing protocol. However, the cross-layer mechanism is used to have an effect on the choice of the routing metric. The protocol showed lower end-to-end delays than the ZigBee, Cross-layer and Cross-layer+ protocols. One of the metrics used in the EQSR route choice is the node buffer size. If the next chosen hop has a buffer size that is less occupied than the other node(s), it makes the chosen node capable of accepting the packet(s) faster which attributes to the lower end-to-end delays. The EQSR protocol showed marginally less control packet broadcasts than the ZigBee stack.

The proposed cross-layer model offered efficient energy consumption and higher throughput that were better than the ZigBee based model. The contributed elements of the SEEK-MADP, the composite metric and the localisation method accompanied by the proposed cross-layer operational mechanism to utilise adaptive transmission power control have illustrated the effectiveness of utilising such an approach to improve the operation of mobile WSNs.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter discusses the conclusions of the research that has been carried out and illustrates the contributions and achievements regarding the proposed operational model.

5.2 Main Goal

The main outcome of the research underhand is a cross-layer, energy efficient operational model with an efficient system throughput and end-to-end delays aimed at mobile WSNs. The process of composing and developing the proposed operational model was deduced from application-based facts about the research field in general. The proposed model focused on the following issues regarding WSNs:

The first issue was the WSN operation in mobile situations where the nodes deployed in the network were fully mobile and the possible challenges for such an operation's scenario.

The second point of focus was the communication medium sharing process between the deployed nodes. MAC layer protocols are responsible of maintaining this operation; therefore, MAC protocols for a WSN were the second point of focus in this research.

The third point of research was focused on how to balance the traffic flows in the network when the nodes deployed were mobile. Routing protocols are responsible for finding the best possible route between different nodes. Routing protocols aimed at WSNs was the third point of focus in this research.

Finding the location of the phenomena under monitoring by a WSN is an important process and requires concentrated consideration if the nodes are mobile. Providing a mobile node location estimation method is an important concept that needed to be addressed in the proposed operational model. Localisation for a WSN was the fourth point of focus in this research.

The final findings of this research were achieved by meeting the objectives which are discussed as follows:

1. SEEK-MADP is an energy efficient MAC protocol scheme for mobile WSNs. The SEEK-MADP protocol is energy efficient in mobile scenarios and offers better energy consumption and delay guarantee over the IEEE 802.15.4 MAC protocol. However, the SEEK-MADP MAC protocol has higher message delivery delays than the IEEE 802.15.4 protocol.

2. A cross-layer energy aware and link aware composite routing metric for mobile WSNs. The composite metric improves the network performance by a significant margin over the hop-count metric. The composite metric has also been evaluated against SNR and ETX metrics and was found to offer better network performance than the later ones.

3. An energy efficient localisation method for mobile WSNs. The localisation method is aimed at mobile sensor nodes. According to the implementation results of the method, the proposed localisation method proves to be energy efficient as it improves the network lifetime by 15% more than the pure trilateration method. The accuracy of the location estimation is according to the results on par with location estimation accuracy of the trilateration method.

4. An energy efficient and delay efficient cross-layer operational model for mobile WSNs. The cross-layer operational model improves network performance by reducing the network interface transmission power during data packet transmission. The model improves control packet overhead by limiting the broadcasting of control packets to the active nodes in the active

routes. This mechanism improved the network lifetime immensely and the packet delivery ratio marginally.

5.3 Significance of the proposed operational model

The research process enlarges the vision of the WSNs' operations in different fields of applications. The proposed operational model can serve as a building block for other enhancements and improvements in terms of other possible technologies applied on WSNs. There is always room for improvement and optimisation for the operational model in general. However, technologies that insure enhanced data reliability and security can be integrated into the proposed operational model. Mobility is the main challenge of this research. The introduction of an operational model that encompasses mobility and provides feasible results is an important significance of this research.

5.4 Limitations of the proposed operational model

The proposed operational model has the following limitations:

1. The end-to-end delays as observed from the results are the highest. This can be attributed to SEEK-MADP MAC protocol since the protocol operates using a static duty-cycle rather than an adaptive one. The end-to-end delays can also be attributed to the routing metric in the routing protocol. The choice of the route does not involve the number of hops for the route.

2. The application target is social based applications. This limits the mobility speed of the nodes to the range between 1M/s and 3M/s.

3. The proposed location estimation method requires the availability of three beacon nodes to estimate the mobile node(s) location using trilateration. The requirement of three beacon nodes can increase the expenses of the network and limits the area of mobility of the nodes.

5.5 Recommendation and future developments

As mentioned in the operational model significance and limitations sections, optimisation and enhancements are always possible. However, through the process of development and implementation, it is possible to draw several points where it is suitable to optimise and enhance the final product. The points that the authors of this work would like to address and recommend as possible points of interest are:

1. SEEK-MADP MAC protocol offers in general efficient energy consumption and better energy consumed per packet than IEEE 802.15.4; however, the fixed duty-cycle for the listen/sleep operation affects, highly, the packet end-to-end delay. An adaptive duty-cycle mechanism is a possible enhancement that can be integrated in the operation of the SEEK-MADP MAC protocol to achieve better packet end-to-end delays. This adaptive mechanism needs to be efficient to not have an effect on the energy consumption of the system.

2. The routing metric whilst it enhances the system throughput of AODV, it can be improved to encompass the hop-count metric during the choice of the next hop, i.e., during the process of building the routes, counts the number of hops that has been passed. The routing protocol counts the next hop based on the proposed routing metric. This should result in choosing the shortest hop-count route with each hop having the best characteristic according to the composite metric. This process can enhance the energy consumption without affecting the system throughput. However, it is possible to deduce that there might be some increased message delivery delay because of the two phase route choice.

3. The proposed localisation method depends on the fact that there has to be three beacon nodes available during the sensor node operation and mobility. The beacon nodes are required to be static/non mobile. This can limit the type of applications where such a method can be utilised. A possible way to enhance the mobility of the beacon nodes is to let them roam around the sensor nodes in a controlled fashion so that the nodes can still be refreshed with the trilateration location method and utilise the compass direction for the

rest of their operational period. The synchronisation mechanism needs to be introduced to control the timings of the location refreshing process.

4. To improve the number of control packets broadcasting and reduce the routing overhead, a directional broadcast method can be used, i.e., the source can start broadcasting a control. The node that receives this control packet can check if its location is closer to the sink node than the source node. This node can then forward this broadcast to other packets. If the next hop is further than the source node to the sink node it drops this control packet and never forwards it to the neighbour nodes.

The above mentioned development points are some of the possible points of interest that can be undertaken for further research and development for the proposed operational model.

5.6 Application types

The criteria of applications for WSNs are enormous and range from civilian home-based applications (such as smart-house) to high-end applications (radiated environmental monitoring, military tracking applications etc.). For the proposed operational model, the categories of applications that are suitable include the following:

1. Health and elder care centre.

2. Kindergarten and social monitoring applications.

The proposed operation model can be further studied and tested to be utilized in higher level applications with mobility as a challenge. Applications such as:

1. Anti-theft and vehicular networks.

2. Rescue and firefighting applications.

3. Smart-city applications.

5.7 Final remarks

The proposed operational model is an invaluable approach to achieve a general framework of operation for mobile WSNs. The proposed model has proved to be both energy and delay efficient. The model can be utilised for several types of applications with different delay requirements. The model can be optimised on several levels which makes it a building block and a trajectory to enlarge the spectrum of possible issues, solutions and applications that can be implemented and evaluated through utilising the proposed operational model.

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APPENDIX A

PUBLICATIONS

1. Journal papers:

   Marwan Al-Jemeli, Fawnizu Azmadi Hussin, "*Energy Efficient and High Throughput Composite Routing Metric for Mobile Wireless Sensor Networks*", International Review on Computers and Software (IRECOS), September 2013 (Vol. 8 N. 9). (SCOPUS impact factor: 0.259)

   Marwan Al-Jemeli, Fawnizu Azmadi Hussin,*"On Location Estimation Methods For Mobile Wireless Sensor Nodes"*, Research Journal of Applied Sciences, Engineering and Technology (ISI indexed Journal), Accepted and in publication (April 2014).

   Marwan Al-Jemeli, Fawnizu Azmadi Hussin, *"An energy efficient cross-layer network operation model for IEEE 802.15.4-based mobile Wireless sensor networks"*, IEEE Sensors Journal (ISI IF: 1.85), Accepted and in publication.

   Marwan Al-Jemeli, Fawnizu Azmadi Hussin, *"SEEK-MADP: A mobility adaptive destination seeker MAC protocol for mobile wireless sensor networks"*, Computers & Electrical Engineering Journal (ISI IF: 0.9), Submitted and under review

2. A book chapter on the results of the first stage of the research:

   Marwan Al-Jemeli, Fawnizu Hussin and Vooi Yap (2010). MAC & Mobility In Wireless Sensor Networks, Wireless Sensor Networks: Application-Centric Design, Geoff V Merrett and Yen Kheng Tan (Ed.), ISBN: 978-953-307-321-7, InTech

3. Three conference papers publication and presentation:

   Paper 1: Marwan Al-Jemeli, Fawnizu Azmadi Bin Hussin and Brahim Belhaouri Samir, "SEEK: An Energy Efficient Control Packet Approach For

WSN Mac Layer Design", 2011 International Conference on Communication and Broadband Networking (ICCBN 2011), June 17 - 19, 2011, Kuala Lumpur, Malaysia

Paper2: Marwan Al-Jemeli, Fawnizu Azmadi Bin Hussin and Brahim Belhaouri Samir, "A Link-Quality and Energy Aware Routing Metric for Mobile Wireless Sensor Networks", ICIAS 2012, KLCC, Kuala Lumpur, Malaysia, June 2012.

Paper3: Marwan Al-Jemeli, Fawnizu Azmadi Bin Hussin and Brahim Belhaouri Samir, "An Energy Efficient Localization Estimation Approach for Mobile Wireless Sensor Networks", ICIAS 2012, KLCC, Kuala Lumpur, Malaysia, June 2012.

4. Applied for two IPR (Intellectual Property Rights) for the following:

IPR1: SEEK: A MAC protocol approach for Wireless Sensor Networks (31st Dec. 2011).

IPR2: A link and energy aware routing metric for mobile Wireless Sensor Networks (31st Dec. 2011).

APPENDIX B

TOOLS OF IMPLEMENTATION AND EVALUATION

The proposed network operational model's development process was performed by utilising the following tools:

The Network Simulator 2 (NS2) version 2.34 [178] is a discrete event simulator that is used to simulate computer networks in general applications. NS2 is probably the most widely used simulator in the research field of conventional computer networks (that includes wired and wireless networks). The simulator was proposed in 1989 as a replacement for another simulator called "REAL network simulator". NS2 is written by C++ language. The simulator supports different packages that are implemented for networking systems. NS2 is a widely used tool to evaluate and simulate WSN systems and protocols. One of the reasons for the popularity of the simulator is because the software is open source and free of charge (licensed under GNU). The simulator supports different packages for several types of network organisations; however, this present research interest has been on wireless mobile networks. The packages supported by the simulator for mobile wireless communication systems include the following:

MAC protocols

Included in NS2 packages are the following MAC protocols: CSMA, TDMA, IEEE 802.11, IEEE 802.15.4, S-MAC and several contributed MAC protocols.

Routing protocols

The routing protocols that are included in the (all-in-one) package of NS2 are: AODV, DSR, DSDV, TORA, PUMA and M-DART.

Radio propagation models

NS2 supports the following radio propagation models: Free Space mode, Two-Ray ground model and shadowing model.

Transport protocols

The simulator supports both transport protocols, TCP and UDP.

NS2 is an object oriented simulator written in C++; however, it uses another text-based language to configure and create the simulation instance. The second language is Object oriented Text command line (OTcl). The OTcl written codes are linked with their C++ packages to run a simulation instant (Figure B.1). NS2 can run under several operating systems that are Linux-based (e.g., Ubuntu, FreeBSD, RedHat) and can run also under apple OSX. NS2 can be installed under Microsoft Windows if the latter is supported with the required Linux environment core (e.g., Cygwin Linux to windows environment instructions and tools).

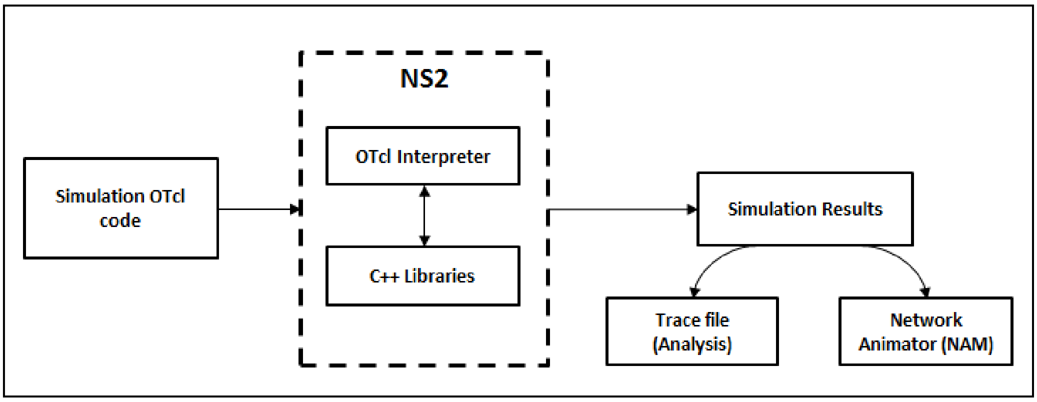

Figure B.1: The linkage between OTcl script and NS2 C++ libraries.

The API of the mobile node in NS2 has the following settings illustrated in Figure B.1. The options in the node configuration API in Figure 16 are the following:

- adhocRouting: this option sets the routing protocol that the mobile nodes will be configured with.
- llType: this option sets the Link-Layer interface of the MAC protocol used for the simulation.
- macType: this option sets the MAC protocol that the network interface attached to the nodes will operate as.
- ifqType: this option sets the network Interface Queue type in order to receive the incoming packets according to a specific buffer operation type of a network interface in real life applications.

- ifqLen: this option sets the network interface queue length for incoming and outgoing packets according to a specific buffer limit of a network interface card in real life applications.

- antType: this option sets the antenna type attached to the nodes.

- propType: this option sets the propagation model for the wireless signal propagation in the simulation scenario.

- phyType: this option sets the network interface type that nodes have in the simulation scenario.

```
$ns_ node-config  -adhocRouting DumbAgent \
        -llType $opt(ll) \
        -macType $opt(MAC) \
        -ifqType $opt(ifq) \
        -ifqLen $opt(ifqlen) \
        -antType $opt(ant) \
        -propType $opt(prop) \
        -phyType $opt(netif) \
        -channelType $opt(chan) \
        -topoInstance $topo_ \
        -agentTrace ON \
        -routerTrace ON \
        -macTrace ON \
        -energyModel $opt(energymodel) \
        -idlePower 1.0 \
        -rxPower 1.0 \
        -txPower 2.0 \
       -sleepPower 0.001 \
       -transitionPower 0.2 \
       -transitionTime 0.005 \
        -initialEnergy $opt(initialenergy)
```

Figure B.2: Mobile node API settings in NS2.

- channelType: this option sets the interface connection channel type.

- topoInstance: this option sets the topology file of the simulation scenario.

- agentTrace: if this option is set, NS2 will trace the transmitted and received application agent’s packets in the network.

- routerTrace: if this option is set, NS2 will trace the transmitted and received routing agent packets in the network.

- macTrace: Setting this option lets NS2 trace the MAC protocol control packet operation in the network.

NS2 also defines an energy model that represents the energy consumption of the mobile node for several states of operations. The options are available in Figure 16 and are the following:

- energyModel: setting this option will set the nodes with an energy model that monitors their energy variations during simulation.

- idlePower: this option sets the power consumed by the node when it is in an idle state.

- rxPower: this option sets the reception power of the node.

- txPower: this option sets the transmission power of the node.

- sleepPower: this option sets the power consumed by the node when in sleeping mode.

- transitionPower: this option sets the power consumed by the node when transiting from sleep state to active state.

- transitionTime: this option sets the time of the nodes transition from sleep state to active state.

- initialEnergy: this option sets the nodes initial energy of their power sources.

Such versatility in options and settings is the major reason for making NS2 a widely used simulator for network research.

The Random-way point mobility model is used to represent the mobile nodes' movements across an area [179]. The model is included as a package in NS2 and serves the general purpose of providing and generating a mobility scenario during a simulation period. The package includes options regarding the mobility of the nodes. Those option are: the area coordinates of the simulated mobility, the number of nodes that are mobile, the maximum speed of the node mobility, the minimum speed of the node mobility, the period of the node mobility and the period of pauses (if required) of nodes during the simulation process. The model was used as the tool to produce and generate the mobility situations of the deployed nodes during the experimentation of the proposed operational model. The following parameters were used to establish mobility using the random-way point model (Figure B.3):

- Area: two-dimensional (2D) deployment region,
- $f_{init}(x)$: the initial nodes distribution,
- t_p: the pause time of each node,
- s_{min}: the minimum speed of each node,
- s_{max}: the maximum speed of each node, and
- Direction of each node between $[0, 2\pi)$.

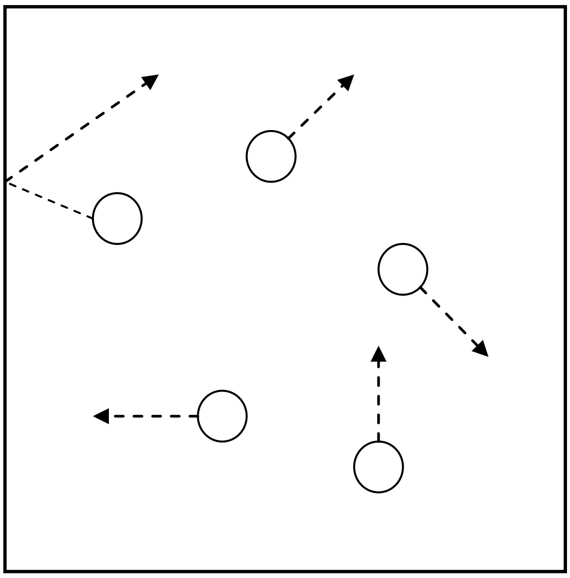

Figure B.3: Mobile node's movement using the Random-way point model.

APPENDIX C

ENERGY MODEL VALIDATION TOOL

Below is the energy model validation tool as a Matlab (m file) text. The energy values can be generic values or based upon specific calculated values for various length of bits for each packet. This tool is used only to validate the trend of energy consumption of the cross-layer model against the original stack:

```
nodedistance = zeros();
maxx = 200; maxy=200; maxn = 35;
q = zeros(maxn);
e = 1000;
l(maxn)=zeros;
%nodeloc = rand(maxn, 2)* maxx;
node(maxn) =
struct('NodeNum',zeros(maxn),'nEnergy',zeros(maxn),'Loc',[zeros(maxn,1),
zeros(maxn,2)]);
rss(maxn,maxn) =
struct('NodeNumber',zeros(maxn),'NodeDistance',zeros(maxn));
eND=1; eLoc=1; eRREQ=2; eHello=1; eRREP=2; eData=3; eConsumed(maxn) =zeros;
eConsumedE(maxn) =zeros;
nConsumptionO(35)= zeros;
nConsumptionE(35)= zeros;


for a = 1:35,

 nodeloc = rand(maxn-1, 2)* maxx;
for  i = 1: maxn-1,
    node(i)=struct('NodeNum',i,'nEnergy',e,'Loc',[nodeloc(i, 1), nodeloc(i,
2)]);
end
nodeloc(maxn,1)=100;
nodeloc(maxn,2)=100;

node(maxn)=struct('NodeNum',maxn,'nEnergy',e,'Loc',[nodeloc(maxn,1),
nodeloc(maxn,2)]);

for i = 1:maxn,
    for j = 1:maxn,
        rss(i,j) =
struct('NodeNumber',i,'NodeDistance',sqrt((node(i).Loc(1)-
node(j).Loc(1))^2+(node(i).Loc(2)-node(j).Loc(2))^2));
    end
end
for i = 1:maxn,
    for j = 1:maxn,
        nodedistance(i,j)=rss(i,j).NodeDistance;
    end
end
for i = 1:maxn,
for j = 1:maxn,
if  0 < nodedistance(i,j) && nodedistance(i,j) <= 40
q(i,j) = 1;

    else
        q(i,j) = 0;
end
end
end

%end
%end
```

```
for i = 1:maxn,
    for j = 1:maxn,
        if q(i,j) == 1
            q(j,i) = 1;
        end
    end
end

[dist, p] = dijkstra(q,1,maxn); %to return the path from source to
destination.

%colordef white,
%   figure(1);
%   axis equal
%   for i = 1:maxn,
%   hold on
%   box on;
%   plot(nodeloc(i, 1), nodeloc(i, 2), 'k.', 'MarkerSize', 5);
%   lscatter(nodeloc(i, 1),nodeloc(i, 2),i);
 %  grid on;
 %  end
%gplot(q,nodeloc,'r-');

%this is to calculate the energy consumed by the network
if dist ~= inf

for i=1:maxn,
eConsumed(i) = eND + eLoc + eRREQ + eHello;
for j=1:dist+1,
    if i==p(j)
eConsumed(i) = eConsumed(i)+ eRREP + eData + eHello;
    end
end
end




for i=1:maxn,
eConsumedE(i) = eND +  eLoc + eRREQ + eHello;
for j=1:dist+1,
    if i==p(j)
eConsumedE(i) = eConsumedE(i)+ eRREP + eData +eHello;
    end
end
end
end
nConsumptionO(a) = sum(eConsumed);
nConsumptionE(a) = sum(eConsumedE);

nConsumptionO = nConsumptionO';
nConsumptionE = nConsumptionE';

end;

fConsumedO = mean(nConsumptionO);
fConsumedE = mean(nConsumptionE);

%clear;
```