Cross Layer Based Protocols for Energy Aware and Critical Data Delivery Related Applications Using Wireless Sensor Networks

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Dedication

I would like to dedicate this thesis to my parents and my wife. Commitment, effort, and dedication were fundamental elements for the completion of my doctoral dissertation. Today I dedicate them this important professional achievement because without their presence, support, and comprehension I would have not achieved my goal.

Declaration

I confirm that this thesis is my own work and the use of all material from other sources has been properly and fully acknowledged.

Muhsin Atto

March 2, 2016

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Abstract

Wireless Sensor Networks (WSNs) have been an exciting topic in recent years. The services offered by a WSN can be classified into three major categories: monitoring, alerting, and information on demand. WSNs have been used for a variety of applications related to the environment (agriculture, water and forest fire detection), the military, buildings, health (elderly people and home monitoring), disaster relief, and area or industrial monitoring. In most WSNs tasks like processing the sensed data, making decisions and generating emergency messages are carried out by a remote server, hence the need for efficient means of transferring data across the network.

Because of the range of applications and types of WSN there is a need for different kinds of MAC and routing protocols in order to guarantee delivery of data from the source nodes to the server (or sink). In order to minimize energy consumption and increase performance in areas such as reliability of data delivery, extensive research has been conducted and documented in the literature on designing energy efficient protocols for each individual layer. The most common way to conserve energy in WSNs involves using the MAC layer to put the transceiver and the processor of the sensor node into a low power, sleep state when they are not being used. Hence the energy wasted due to collisions, overhearing and idle listening is reduced. As a result of this strategy for saving energy, the routing protocols need new solutions that take into account the sleep state of some nodes, and which also enable the lifetime of the entire network to be increased by distributing energy usage between nodes over time. This could mean that a combined MAC and routing protocol could significantly improve WSNs because the interaction between the MAC and network layers lets nodes be active at the same time in order to deal with data transmission.

In the research presented in this thesis, a cross-layer protocol based on MAC and routing protocols was designed in order to improve the capability of WSNs for a range of different applications. Simulation results, based on a range of realistic scenarios, show that these new protocols improve WSNs by reducing their energy consumption as well as enabling them to support mobile nodes, where necessary. A number of conference and journal papers have been published to disseminate these results for a range of applications.

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Chapter 1

Introduction

1.1 Background

This thesis describes the design of new cross layer based protocols to improve Wireless Sensor Networks (WSNs) for applications where it is crucial that various quality of service metrics (QoS) for such applications at the same time can be met. This involves supporting mobile nodes, improving reliability, extending the lifetime of the network and reducing delay in the delivery of data. To do this, some of the recently designed MAC and routing protocols have been discussed and evaluated in this research to find suitable protocols for such applications. As a result, a cross layer protocol based on the MAC and routing protocols has been designed, where cross layer information based on network conditions is taken into consideration when delivering data to a sink. This extends the lifetime of the network and improves the reliability of the data delivered. WSNs, their applications, challenges and design issues are described in this Chapter. In addition, motivations and questions regarding the research as well as objectives are given below.

A WSN is typically composed of tiny, battery powered devices called sensor nodes. Each sensor node has a capability of sensing the target environment and then sending the collected information from source nodes to a sink, perhaps over multi hop networks. WSNs support different kinds of applications in distinct areas, such as military, healthcare, agriculture and environmental monitoring. Generally, there are 3 models of applications using WSNs: continuous, on-demand and event driven. In the continuous model, sensors send data periodically to the sink. In the on-demand model, sensors sense continuously, store the data and send only when requested. In the event driven model, the sensors send data only when certain events occur [1].

The design and implementation of WSNs face several challenges, mainly due to the limited resources and limited capabilities of sensor nodes, such as power and storage. To accomplish their task, sensor nodes need to communicate with each other and act as intermediate nodes to forward data on behalf of others so that this data can reach the sink, which is responsible for taking the required decision. Different applications using WSNs have different requirements so generic results cannot be used [2].

The initial applications supported by WSNs were mostly in environmental monitoring, such as temperature monitoring for a specific area, house alarms and so on. The main objectives in such applications only involved simple data processing. Energy consumption needed to be considered for specific applications, so little attention was paid to the data delivered and reliability related issues [2], [3], [4].

WSNs have been extended and their designs have been advanced to support more complex applications, such as security, military, fire detection and health care related issues. In these applications, the data delivered and reliability must be taken as important parameters in addition to energy efficiency, because data must be collected from the sources of events and be forwarded to the sink in real time with high reliability, otherwise the applications may not fulfil their purpose [5]. This means that it is crucial that efficient routing and MAC protocols be designed to meet these requirements.

Routing is an essential feature in any multi hop sensor network. In such networks, a node should have the capability to deal with data transmission as required between source nodes and a sink in different situations. These capabilities may lead to extra energy consumption. In addition, mobility in the proposed applications using WSNs also needs to be considered. Designing mobility modules for WSN applications is a hot topic at the moment and providing mobility for such applications has been challenging over the last few years [6]. Hence efficient MAC and routing protocols need to be designed to enhance the lifetime of the network. These protocols require efficient algorithms to deal with different situations.

Recent studies [1], [5] have discussed most of the recently designed protocols with their advantages and disadvantages in terms of their suitability for the proposed applications. It has been shown that there is no protocol which is directly suitable to be used for such applications because of the challenges involved in such applications. However, TDMA based MAC protocols such as GinMAC [7] and cluster based routing protocols such as LEACH [8], TEEN [9] and APTEEN [10], have often been preferred because of the following capabilities:

- Energy can be conserved by distributing energy usage between nodes in the network when it is required in the target application.
- Delay can be decreased and energy can be conserved by aggregating and reducing redundant copies of data at the intermediate nodes in the network.
- Nodes in each cluster need only send their data to their cluster head over a single hop communication using their allocated slots, so energy is conserved.

- Only cluster head are involved for routing and forwarding data to a sink. This reduces the routing complexity in large WSNs.
- Only cluster head need to aggregate data from their members thus saving energy.

Based on these capabilities, the lifetime of the entire network and the required performance of the proposed applications can be optimized [11]. As a result, the main contribution this research aims to make to the field is designing suitable cross layer protocol based on MAC and routing protocols to improve the capability of WSNs for energy aware and critical delivered data related applications. Each of these applications has a different performance criteria which is an application specific such as energy saving, improving reliability and reducing delay for the data transmission as illustrated below. As will be shown in Chapter 2, based on the modified GinMAC and APTEEN protocols, the protocols this research proposes are implemented and measured using simulation and considers different scenarios for different applications.

1.2 Applications and Design Issues Using WSNs

WSNs have great potential in different applications because: (i) sensors are cheap and easy to deploy. (ii) WSNs can monitor large environments and (iii) sensor nodes can collect data automatically and send this to the data centre through multi hop communications [12]. However, sensors are battery powered and have limited energy (i.e., lifetime). Thus, designing energy efficient management approaches (i.e., routing protocols, data aggregation and scheduling) is crucial for WSNs. Existing WSNs are designed for specific applications due to the available sensors that are application specific [1].

1.2.1 Applications Using WSNs

In general, there are 3 types of applications using WSNs: continuous monitoring, on demand and event driven [13], [14]. Each of these schemas has advantages and disadvantages. These schemas are discussed in the following sections [15]. The following are some possible applications using WSNs under categories given above:

1.2.1.1 Continuous Monitoring Based Applications

In the continuous monitoring based applications, sensor nodes send their data to a sink continuously at periodic intervals. These applications typically are the basic traditional monitoring applications based on the collected data from the target environments. Different types of data can be transmitted in these applications such as scalar and multimedia based transmissions. The following are some examples of continuous monitoring based applications [16]:

Military Based Applications

Communication is present in almost all aspects of military applications. It is important in the distribution of commands and ensures distribution of logistical information and data collected from sensors [17]. A WSN is a tool which could possibly be used to offer the required operations for these applications, based on collecting data from sensors deployed in different parts of the target environment.

Military communications must be maintained in the area and time where needed. In general, they should be resistant to jamming, direction finding and other electronic warfare threats and provide end to end message security and reliability. Mobility between different nodes in military related applications poses new challenges. This shows that new mobility modules are crucial as the topology of the network is changed frequently [18]. As a result, different routing protocols are necessary for these applications in order to provide the required performance. Localization in WSNs where locations of nodes need to be detected over time are also required for these applications [19].

In a common battlefield scenario of military engagement there is a well-known and well-defined enemy, in the air, on land or at sea. The capabilities of military WSN applications depend not only on wireless communications fulfilling the requirements mentioned above, but also on the capabilities of sensors such as those that measure various physical phenomena [17]. In addition, electromagnetic waves, light, pressure and sound, which result from gunfire and explosions are used by sensor nodes to sense the target environment. Sensors can detect, and possibly measure, chemical, biological and explosive vapour, as well as the presence of people or objects and then inform the commanders or military centres which are responsible for taking the required decisions in real time [18].

Traffic Management and Road Safety Based Applications

WSN based traffic monitoring and the possible benefits of Intelligent Transport Systems (ITS) applications for the improvement of the quality of service metrics and mobility of nodes for different applications are summarised in the literature [20]. Compared with conventional infrastructure based monitoring systems, a WSN facilitates a denser deployment of sensors along the road, resulting in a higher spatial resolution of traffic parameter sampling. This helps drivers to find safe routes and reduces traffic accidents. The experimental data analysis given in the literature [20] shows how high spatial resolution can enhance the reliability of traffic modelling as well as the accuracy of short term traffic prediction.

Nowadays, new technologies are emerging for high resolution traffic monitoring based on either mobile or fixed wireless-interconnected sensing devices using WSNs. Mobile systems are based on probe vehicles that use localisation systems for sensing their position and speed, and on mobile wireless terminals for sharing the sensed data. These systems are interesting because of the low cost and the high flexibility associated with WSNs [21].

On the other hand, the major challenges with these applications are the end to end reliability of the data delivered, which is limited by the diffusion of equipped vehicles on the network and their penetration rate as a percentage of the overall number of vehicles. Due to these requirements and challenges, efficient routing protocols must be designed to provide the necessary services. In addition, new mobility modules are critical for such protocols to increase performance and provide the required connectivity in real time [22].

Building a Smart Home System

A smart environment is a physical world that is abundantly and invisibly interconnected through a continuous network of sensors, actuators and computational units, embedded seamlessly in the everyday objects of our lives [12]. A smart home is a residence in which computing and information technology is used to anticipate and respond to the occupant's needs and can enhance everyday life at home. Potential applications for smart homes can be found in these categories: welfare, entertainment, environment, safety, communication and appliances [23].

WSNs have become attractive technology for the research community in this field, particularly with the proliferation of micro-electro mechanical systems technology. This has facilitated the development of smart sensors for homes and other possible environments such as offices [24].

The service robot in the smart home environment using WSNs has the following key functionalities: localization, navigation, map building, human-robot interaction, object recognition and object handling. To execute these functions, a smart robotic platform can be equipped with different sensors and a smart computing system that has sufficient memory [25]. This shows that efficient protocols and intelligent computation modules are required for these applications in order to provide the necessary services for homes being monitored.

1.2.1.2 On-demand Based Applications

In the on-demand based applications, queries are generated by a sink and send to different parts of the network. To save energy, query is only sent when required and on demand. The following are some on-demand based applications using WSNs [13]:

Smart Parking Based Applications

With the rapid proliferation of vehicle availability and usage in recent years, finding a vacant car parking space is becoming more and more difficult, resulting in a number of practical conflicts.

Parking problems are becoming ubiquitous and are growing at an alarming rate in every major city [26]. Based on this, a lot of research and development is being carried out all over the world to discover and implement better and smarter parking management techniques to avoid these issues. Widespread use of wireless technologies such as WSNs paired with the recent advances in wireless applications for parking, mean that digital data dissemination may be the key to solving emerging parking related problems [27].

WSNs have great potential to contribute to providing an easy and cost effective solution for implementing smart car parking related systems for various reasons: Ease of deployment in existing car parks without excavation and expensive cable installations. The flexibility and cheap cost for sensors that can accurately detect vehicles makes WSN a natural candidate to solve the emerging car parking problems [28].

In the smart parking related applications using WSNs, the following features are important: (i) collecting sensor data from the target car park, (ii) finding available parking spaces and (iii) sending parking space information to embedded web-servers in real time so that information on available spaces can be given [29]. A typical example of a smart park system and the required architecture using WSNs is given in Figure 1.1.

Figure 1.1: An example of Park System Application [27]

Precision Agriculture Monitoring Based Applications

WSNs in agriculture is a new technology that can provide processed real-time data from sensors physically distributed in fields [30]. Based on these capabilities, a proper plan can be made to increase plant growth and avoid the affect of season changes. The agricultural greenhouse can be considered as a man-made solution, emulating an ecosystem suitable for growing crops rapidly, as shown in Figure 1.2.

Figure 1.2: Typical examples of Greenhouse and Field Agriculture Monitoring Application [30, 31]

In modern precision agriculture, greenhouses play an increasingly important role in meeting the demand-driven economy. The primary issue of greenhouses is managing the greenhouse environment optimally in order to comply with economic and environmental requirements. Although technological advancements offer innovative solutions for specific issues, achieving optimal management of greenhouses using WSNs is generally difficult [31].

Efficient control of the greenhouse environment requires an adaptive, accurate, and cost effective control system. WSNs used in these systems face a number of challenges such as monitoring the greenhouse environment, controlling greenhouse equipment and providing various and convenient services to consumers with hand held devices [32]. In addition to this, on-demand information from various parts of the target fields must be available when required by control staff. This means it is crucial that different protocols for these applications be designed in order to provide the necessary services. Further details about precision agricultural monitoring based applications, including their design requirements, can be found in the literature [31].

Water Quality Monitoring System

In water quality related applications sensors must be deployed under water in the area where the water quality needs to be monitored. Based on the data collected from sensors, a central system can detect any poor quality or unhealthy water and take any required actions in real time. Research communities have conducted a lot of research recently to find out the best frameworks and networks to provide the required performance for the water quality monitoring applications [33]. Figure 1.3 shows an architecture and required network for a water quality monitoring application where different nodes (Sensor Nodes (SN) and CHs) can be placed under water to measure the quality of water using WSNs.

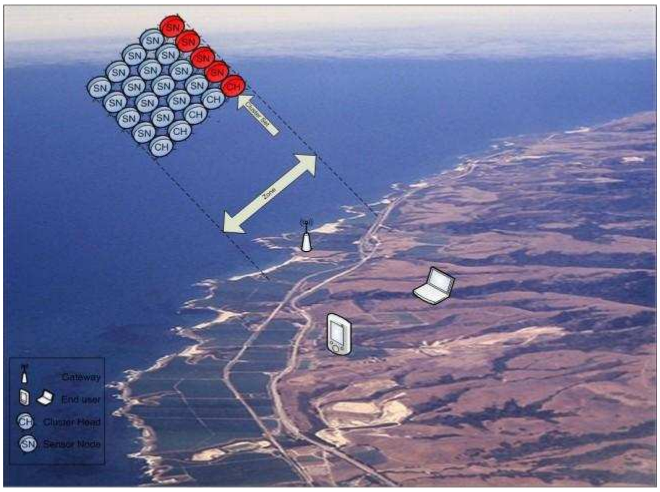

Figure 1.3: An example of Quality of Water Monitoring Application Using WSNs [34]

A traditional wired sensor network is one way to monitor the quality of water in water distribution systems. However, even though they use sensors, they are not efficient at detecting the pathogen or viruses in drinking water since they are neither wireless nor unattended [33].

WSNs have great potential in real-time monitoring of water quality in different locations because (i) sensors are cheap and easy to deploy, (ii) they can monitor the whole water distribution system, and (iii) sensor nodes can collect water data automatically and send it to the control system through multi-hop communications. In addition, data from different nodes in the water must be available when it is required by the target application at any time.

Based on these capabilities, is it crucial that efficient communication protocols such as routing and MAC protocols are designed for such applications [3]. Monitoring systems using WSNs are designed based on available sensors [12], [35]. Hence, weather and water sensors can be used for monitoring water quality due to the correlation of water quality and temperature [36].

Habitat Monitoring Based Applications

WSNs have more advantages than the traditional wired networks for adapting to habitat surveillance [37]. They can easily be embedded in the environment without creating conspicuous landmarks that change the behaviours of its inhabitants as shown in Figure 1.4. In addition, a WSN has the capability to self configure after topology is changed. As a result, the benefits of using WSNs for habitat surveillance have driven research organizations to apply themselves to resolving the difficult problems faced when using WSNs [38], [39]. These problems include how information can be collected form the sensors attached to the body of the animals and then send it back to a control centre to take the decision required. This is because the topology of the WSNs used in these applications is changed very frequently and then the data is most likely to be lost before it gets delivered.

Figure 1.4: Examples of Habitat Monitoring Environment [39]

Remote sensing and monitoring using WSNs for habitat surveillance can record the movement of the animals in the environment, which can assist in managing to find animals locations and their environmental impact [37]. In addition, this reduces the environmental impact of animals and may determine optimal management intervention strategies. However, habitat monitoring is complicated by the need to record animal movement concurrently with landscape condition, which in itself influences the animals being monitored [39]. This is due to requesting data frequently from animals when it is required in the target application is a big issue. Based on these challenges, it is crucial that new protocols are designed to provide the required performance for the target applications when different situations are considered.

1.2.1.3 Event Driven Based Applications

In the event driven based applications, sensor nodes report data only if an event of interest occurs. Nodes in the target application need to detect an event and send information back to a sink. At the sink the decision is undertaken based on the data collected from the network. The following are some event driven based applications using WSNs [14]:

Flood Detection Applications

Floods are responsible for loss of life and the destruction of large amounts of property every year, especially in poor and developing countries, where people are particularly at the mercy of nature. Flooding is an environmental disaster that negatively impacts on the livelihood, health and well-being of affected communities as shown in Figure 1.5. The hazard can be minimized by monitoring river flows and highlighting the required actions at the right time [40], [41].

A WSN has been deployed in river monitoring and promises to be an effective and low cost alternative solution for predicting floods in recent years [42]. A lot of effort has been put into developing systems which help to minimize damage through early prediction using WSNs [43]. As a network for the prediction model has to be deployed in rural areas, it could suffer from a severe lack of resources like money, power and skilled man-power [43].

Figure 1.5: Typical examples of Flooding Detection Environments [40]

One of the many technical challenges faced by the researchers has been finding the optimal approach for water measurement. After trying many different approaches, they settled on measuring water pressure to gauge the river level. Sensor boxes for taking these measurements can be installed on a bridge or in the middle of the river. This means that different types of sensors are required to detect water discharge from rainfall, humidity, temperature. The data collected from these sensors are used to detect the level of the expected flooding (low or high level) and let people evacuate the areas where flooding is detected [42], [44].

Forest Fire Detection Applications

A lot of research has been carried out into the detection of forest fires as this has long been a severe threat to forest resources and human life. WSNs have a lot of advantages over traditional wire networks because of their suitability for different applications. Forest fire detection is one of these applications [12], [45], [46].

Although many practical experiments using WSNs have been carried out into collecting and sensing data about forest fires, a suitable approach for analysing the data and triggering a fire alarm accurately is still lacking [46]. Research into fire detection and monitoring has been conducted in the past. Most of it makes use of temperature and humidity sensors, smoke detectors, infra-red cameras. In addition, aerial or satellite images are frequently used for outdoor fire detection and monitoring [47].

Besides fire detection, WSNs also provide environmental information on the forest which can be used to predict the possibility of a forest fire and the direction of the wind so that the required actions can be taken in real time to reduce damage to the target forest [48], [49].

Moreover, forest fire detection and prediction are associated with specific location information provided by the individual sensor node and this information is useful for identifying the location where fire is expected to break out [47], [50]. Figure 1.6 shows an example of an architecture for monitoring fire in the forest based on different sensors such as humidity and temperature sensors.

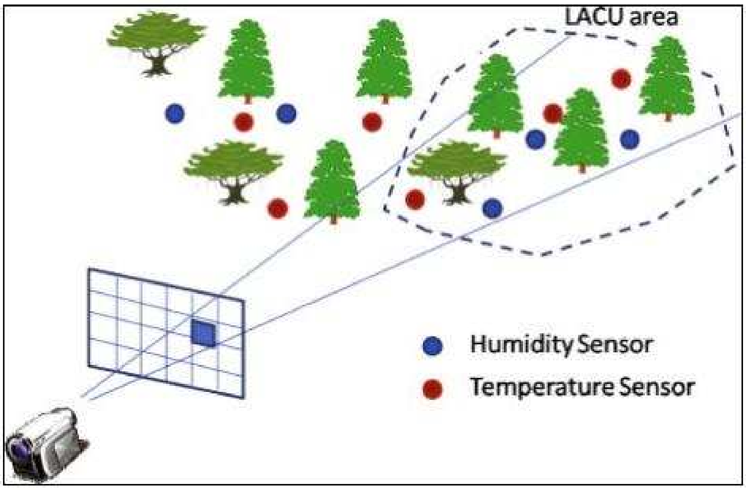

Figure 1.6: An example of Forest Fire Detection Application [47]

Security and Surveillance Based Applications

Security and surveillance systems are becoming more and more important both in civilian and military contexts. In recent years, the research community has been working on the development of sophisticated devices for intrusion detection and more generally for monitoring human activity [51]. WSNs represent a powerful backbone for target surveillance due to their distributed sensing capabilities, flexibility and easy deployment [52].

Monitoring capability is the central feature of a WSN and the services offered by a WSN for surveillance related applications can be classified into three major categories: monitoring, alerting, and information on-demand. These features have been applied to a large number of applications related to environment monitoring. In the domain of surveillance applications that are extremely application critical in nature, adding visual capabilities creates new challenges such as lifetime of the network and the required QoS [53].

Usually, the nodes in a network that are designed for these applications are equipped with embedded devices such as acoustic sensors or smart cameras that acquire information locally. This information is typically then aggregated and processed by a central unit. Based on this information the required actions can be undertaken to protect the target environments [53]. While having more sensors leads to a better detection accuracy, the limited processing and energy resources of the WSNs makes management of the sensors a very critical aspect [54].

Due to these limitations, efficient routing protocols are crucial to improve the capability of WSNs used in these applications in order to provide real time security for the environments being monitored [55].

Monitoring the Structural Health of Bridges

The process of continuously monitoring the status of a structure to detect possible damage can be defined as Structural Health Monitoring (SHM) [56]. The importance of health monitoring of civil structures has gained considerable attention over the last two decades [57]. A variety of methods have been proposed for SHM, which have improved over time with the evolution of technology. One of the conventional methods is visual inspection by humans for any signs of apparent damage. But this technique is limited because it relies on visible defects only [58].

A WSN is composed of a large number of small nodes that have sensing, processing and wireless communication capabilities. Based on these capabilities, a WSN for SHM applications has two key advantages: (i) system set-up and maintenance cost is remarkably reduced, (ii) no cables are required for data transfer because the communication is wireless [57].

Comprehensive systems using WSNs for these applications use a large number of sensors to monitor the target bridges. A WSN can be used for these applications to inform the bridge monitoring centres when the target bridges face abnormal load so that proper action can be taken in advance. This reduces the damage to the bridges monitored and allows the system to take the required decisions within a minimum delay. Based on these capabilities, WSNs used in these applications have a lot of challenges which need to be considered, such as limited resources and wireless communications between nodes. This means that different protocols must be designed to improve WSNs for the target applications where different factors are crucial [59].

Healthcare Applications

Nowadays, it is vital to develop advanced tools and information management systems that allow the monitoring of elderly people at home as well as patients in hospitals [60] as shown in Figure 1.7. This makes it possible to monitor movements, to control human physiological data and to track patients and physicians. WSNs are an enabling technology for the application domain of unobtrusive medical monitoring. This field includes: continuous cable free monitoring of vital signs in intensive care units, remote monitoring of chronically ill patients and providing remote assistance to people in their everyday lives. Furthermore, WSN technique can provide early detection and intervention for various types of diseases [61].

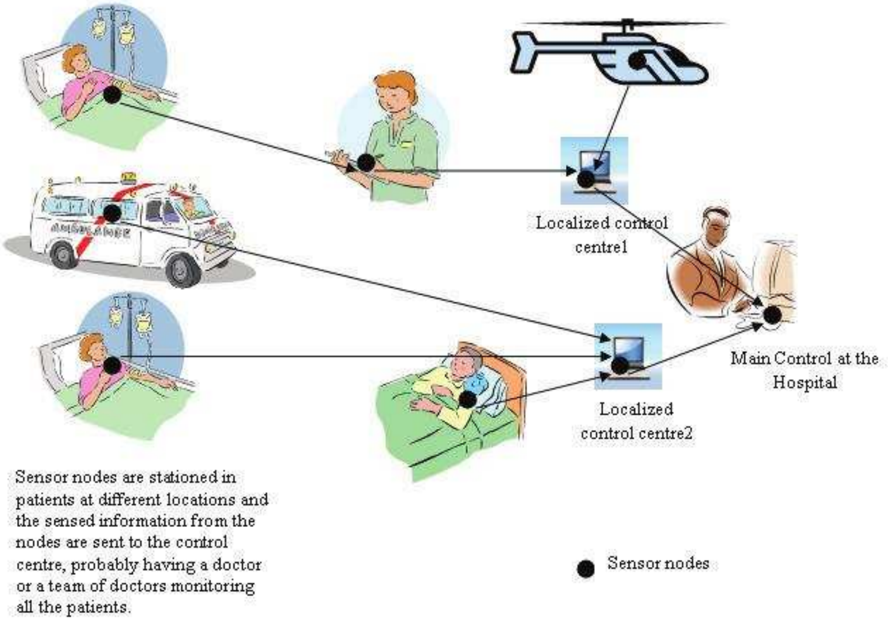

Figure 1.7: An example of Healthcare Application [60]

Sensors may be embedded on a person's body to build a Wireless Body Area Network (WBAN), making it possible to sense different kinds of vital signs: Electro CardioGram (ECG), Electro-EncephaloGraphy (EEG), pulse, temperature, etc. In order to supervise and control the surrounding physical environment (home, hospital, etc), different sensors can be deployed including infrared sensors, multimedia sensors (cameras) and smoke sensors. Thus, the structure of the transmitted data in these applications could be different such as video, audio streams and scalar data [62].

A WSN in healthcare related systems can generally be divided into two sub networks, Home Sensor Network (HSN) and Body Sensor Network (BSN) [63]. A BSN is a set of mobile sensors that are attached to the body of the patient to measure and monitor the physical parameters which need to be sensed by the target application, such as blood pressure, heart rate and so on. Each medical parameter needs to have its own sensor, for instance, blood pressure uses, heart rate uses. A HSN is a set of fixed location sensors, which need to be attached in the patient's rooms, such as kitchen or bathrooms. Each application needs to be designed based on the framework, structure and the medical parameters that need to be monitored [64].

Different routing protocols are crucial for healthcare related applications. The selection of these protocols depends on the requirements of the proposed applications. In some applications delay for the data delivered may be the main issue without considering its reliability, while others may need to produce real time data and consider its reliability at the same time [3].

1.2.2 Challenges and Design Issues in WSNs

Due to the limitations and design restrictions of WSNs, such as wireless communication and resource limitations, the design of protocols has many challenges [5]. New protocols need to consider these restrictions during their design and deployment phases. The following important factors and design issues need to be considered when designing new protocols using WSNs [12].

Data Delivery Models: A WSN is an application specific network, so data delivery models need to be designed according to the given application. Some applications need to deliver data from sensor nodes directly to the sink over a single hop away from the sink, while the others send data over multiple hops between source nodes and a sink. Data delivery models will, therefore, impact the performance of the new protocols.

Target Environment: WSNs can be used for different kinds of applications and each of these applications will have a specific requirement. For instance, a WSN used for environment monitoring needs to have specific protocols that can deal with the specific challenges. Moreover, WSNs used in real-time related applications need to have efficient protocols in order to provide the required performance for these applications.

Energy Saving: Due to the limited power capacity associated with each node in a WSN, newly designed protocols must take issues related to power consumption as their most important objective. Each node must consume as little power as possible in order to extend the lifetime of the whole network. Therefore, the trade-off between energy consumption and data delivery in the WSN have been an exciting topic in recent research studies. Energy can be saved by letting nodes go to sleep when there is no data to be sent and received [1], [4]. This must be undertaken without affecting the reliability of the designed protocols.

Connectivity: Pre-established connections between each pair of nodes in the WSN define the connectivity of the network. WSNs may be densely deployed in an area of interest, and there will probably be cases where this connection will have failed and been disconnected. This can happen when some nodes leave the network or die and this means that the topology of the WSN may change frequently. Therefore mobility may need to be considered in proposed protocols.

Hardware Constraints: Typically, nodes in a WSN are equipped with small amounts of resources, such as memory, processing capability and power. However, in some applications there is a need to store a large amount of data before forwarding it to the next hop. Because of the limited memory available at each node, that node may not be able to store all the data in its local memory. Hence some techniques need to be designed to reduce the overflow of the data at each node in the network.

Low Node Cost: As a WSN may consist of hundreds or even thousands of nodes, the cost of each individual node must be as low as possible as this will reduce the cost of the whole network.

Scalability and Adaptation: Since the number of nodes in the network may be large, and the communication links are prone to fail, then nodes must have the ability to join or leave the network. This shows that new protocols need to be scalable and to be able to adapt to any size of network.

Self-Configuration: After nodes are deployed, they need to be able to organize themselves in order to be able to communicate. In addition, when some nodes die and the topology changes, it should be possible for them to re-configure themselves without user interaction.

Security and Privacy: Due to the wireless communication between sensors in a WSN, it is possible that data may be listened to by unauthorised nodes. Hence security and privacy of data transmitted in different applications may need to be protected using security and privacy protection related algorithms.

Quality of Service (QoS) support: Some applications in WSNs may need to deliver data with specific QoS requirements, for example, delivering data at a required time with a bounded latency and reliability. This means that new protocols must be designed according the requirements of the target applications.

1.3 Research Motivation and Hypothesis

Most of the recently proposed protocols for WSNs consider either energy saving or reliability of the target applications. However, some applications may need to guarantee both energy saving and reliability at the same time in order for the application to fulfil its purpose [1]. Due to the challenges involved in designing these applications, an efficient protocol needs to be designed in order to offer the required performance. This protocol must consider all possible challenges these applications face such as wireless channels, limited battery life and self configuration. Based on this, this research discusses and evaluates some of the recently designed protocols using WSNs to find suitable protocols for these applications. This section outlines the research motivations and hypothesis.

1.3.1 Research Motivation

The motivation behind this research is to improve the capability of WSNs for different applications by supporting mobile nodes, saving energy, reducing delay and improving reliability.

1.3.2 Research Hypothesis

Based on the requirements of applications given above and the conclusion reached in Chapter 2, the questions in this research are as follows:

1. Can existing routing and MAC protocols be modified to support mobility without compromising their reliability or is a whole new approach required ?
2. Can existing routing and MAC protocols be combined into a cross layer protocol to optimize performance of different applications ?
3. What is the range of applications for which the modified protocols are suitable ?

1.4 Research Aims and Objectives

It will be shown in Chapter 2 that the main contributions made by this research are to modify the GinMAC [65] and APTEEN [66] protocols for energy aware and critical delivered data related applications, where different requirements are crucial. These modifications include (i) designing a mobility module where mobile nodes could be supported. (ii) Designing a new cross layer protocol based on the modified GinMAC and APTEEN protocol in order to improve WSNs for different applications. The target applications and their requirements in this thesis will be discussed in Chapter 2. The GinMAC, APTEEN and the cross layer based protocols are implemented and simulated using the Castalia simulator [67] where different scenarios are considered. Protocol implementations are given in Chapter 3. In summary, in order to answer the questions given in Section 1.3, this research follows these objectives:

1. Understand WSNs, concepts, challenges, applications and design efficient protocols to improve WSNs for different applications.
2. Propose efficient MAC and routing protocols using simulation for different applications where different scenarios are considered.
3. Validate the original implementation of the GinMAC and APTEEN protocols based on published results [68], [66].
4. Modify GinMAC and APTEEN protocols for the proposed applications based on real scenarios using simulation such as healthcare, environment monitoring and multimedia related applications.
5. Add new features to both GinMAC and APTEEN protocols such as new mobility and route discovery modules.

6. Simulate advanced applications for WSNs using the proposed MAC and routing protocols, based on real applications, such as healthcare and environment monitoring related applications.

7. Design a cross layer protocol based on the modified GinMAC and APTEEN protocols in order to improve WSNs used for the proposed applications.

The objectives are to provide suitable protocols to improve WSNs for different applications by supporting mobile nodes and extending the lifetime of the network as well as improving reliability as shown in Chapter 5. A list of publications which have been produced as a direct result of this research is given in Appendix A.

1.5 Thesis Structure

The remainder of this thesis is structured as follows:

In Chapter 2, the literature on the protocols proposed in this research is reviewed and the protocols are evaluated in terms of their suitability for the proposed applications given in this thesis. This involves evaluating the recently designed MAC and routing protocols for the proposed applications where different QoSs are crucial.

In Chapter 3, the implementation of and the modifications for the proposed MAC, routing and cross layer based protocols are presented. Simulation scenarios and results for validating the selected protocols, by replicating the existing works, are given in Chapter 4.

In Chapter 5, details about the proposed applications and performance evaluation as well as simulation scenarios and results for each application using the protocols proposed in the work presented in this thesis are discussed. Different scenarios for each application are considered.

Chapter 6 summarises the background and literature reviewed with research contributions. It also discusses the main findings of the research, its limitations and the areas in which this research can be expanded.

Chapter 2

Literature Review

2.1 Introduction

A WSN consists of a set of sensors with the capability of collecting data about events and sending this data back over wireless channels to a Base Station (BS). WSNs pose significant challenges for designers due to their wireless nature and the often insufficient resources available. In order to ensure the successful operation of WSNs, efficient communication protocols must be designed, such as MAC and routing protocols.

Literature on WSNs has proposed energy efficient protocols in order to deal with the limited battery life of sensor nodes, thereby increasing the lifetime of the network. In addition, further challenges are posed when mobility is considered. Based on these challenges, WSNs have been extended and their designs have been advanced to support more complex applications, such as security, military, fire detection and health care. In these applications, the data that is delivered and its reliability are important parameters along with energy efficiency. This is because data must be collected from the source of events and be forwarded to the sink within a minimum delay and with high reliability, otherwise the applications may not fulfil their purposes [69].

Applications in WSNs which need to take energy, reliability and delay in the delivery of data into consideration at the same time are called *Energy-aware and Critical data delivered Applications* [1]. This research considers these applications and different scenarios relating to them. Extending the lifetime of the network while at the same time improving the quality of the data delivered over multi hop communication for such applications is a huge challenge. Various protocols [12], [69], [70] have recently been proposed to increase the performance of different applications using WSNs when only lifetime or reliability has been considered. As a result, designing communication protocols, such as MAC and routing protocols, to optimize performance for these applications are the main contribution made by this research.

A MAC protocol in a WSN controls the accessing of channels in a network, in order to maximize the number of nodes which can share the the wireless channel without affecting the integrity of the data delivered to its destination. On the other hand, a routing protocol provides the best routes for data to be delivered over multi hop communication from source nodes to a sink [12]. Designing a cross layer protocol based on network condition to improve WSNs for different applications is, therefore, the main contribution made by this research.

A thorough background and literature review was undertaken, starting with reviewing and evaluating recently proposed works regarding MAC and routing protocols. This involved some of the recently designed protocols [12], [69], [70], [71], [72]. Protocols included in this literature have been discussed and evaluated in terms of their advantages and disadvantages in order to find suitable protocols for the applications proposed in this research.

The rest of the literature review is structured as follows: Section 2.2 illustrates MAC protocols and Section 2.3 discusses routing protocols. The advantages and disadvantages of both are evaluated in terms of energy saving, reliability and delay in the delivery of data for the proposed applications. A conclusion about the MAC and routing protocols in terms of their suitability for use with the proposed applications is given in Section 2.4 along with contributions made by this research.

2.2 MAC Protocols for WSNs

Designing a MAC protocol for WSN is not a simple task, due to the challenging environments and restrictions associated with the applications. These include energy constraints, latency, data delivery and self-configuration [1]. The main aims of designing MAC protocols are reducing energy consumption, decreasing delay and increasing the reliability of such networks. A major motivation in this section is to find a suitable MAC protocol to improve WSNs for different applications by saving energy, improving the data delivery and reducing latency in multi-hop networks. In a WSN, major energy wastage can occur [1], [73], [74].

The first and most important source of energy consumption wastage in WSNs is idle listening. This happens when a node is listening to an idle channel to share the medium as it thinks there is a possibility of receiving or sending packets. The second reason for the wastage of energy is collisions, which can occur due to a high number of sensor nodes deployed in a small area and a large number of control packets. The third reason for wasting energy is overhearing; overhearing occurs when a node listens to or overhears a packet. This is the case when it thinks it may be the intended receiver,whereas, in fact the packet is not for that particular node. Some of the most important factors that need to be considered when designing efficient MAC protocols for WSNs are: network topology, type of antenna and clustering related issues [7], [72].

In general, MAC protocols can be divided into two types which are schedule based (TDMA based) protocols and contention based protocols. Each of them has advantages and disadvantages. Schedule based protocols have no collision related problems and are energy efficient, however, scalability in a widely dispersed WSN is a big problem with such protocols. Contention based protocols have better performance in terms of scalability in distributed WSNs, however, collisions cause significant problems in such protocols.

Some of the recently proposed MAC protocols [1], [12], [73] are discussed in terms of their suitability for the proposed applications, such as fire detection, flood detection, surveillance and health care related applications. These applications deal with a hard deadline and high reliability, so energy is not only the consideration for the MAC protocol designs. Reliability of data delivered from source nodes to a sink must also be taken into account before designing and deploying the proposed applications. Details of such MAC protocols, with their advantages and disadvantages in terms of energy saving, delay and reliability of data delivered over multi-hops WSNs are discussed in the following sections.

2.2.1 Contention Based MAC Protocols

Contention based MAC protocols are also known as Random-Access MAC protocols (CSMA/CA) [75]. These protocols do not pre-allocate resources to individual sensors. Instead, they employ an on-demand channel access mechanism and in this way share a single radio channel among the contending nodes. Simultaneous attempts to access the communications medium, however, results in a collision. Effectively, these protocols try to minimize rather than completely avoid the occurrence of collisions. Traditional networks use Carrier Sense Multiple Access (CSMA) as a medium access mechanism. However, CSMA mechanism gives poor performance in WSNs due to two unique problems: the hidden node and the exposed node problems [76].

The hidden node problem is where node A is transmitting to node B and node C which is out of coverage of A will sense the channel as idle and start packet transmission to node B as well. Consequently, the two packets will collide at node B. In this case CSMA fails to foresee this collision. The exposed node problem occurs when a node is prevented from sending packets to other nodes due to a neighbouring transmitter [77].

To avoid the hidden and exposed node related problems, well-know solution algorithm using RTS/CTS messages resulting in nodes getting exclusive access to the shared channel for a some-defined time period was proposed [78].

In this research, main motivations are improving WSNs by saving energy and increasing reliability for different applications so a schedule based MAC protocol has been preferred.

The following are some contention based MAC protocols using WSNs:

2.2.1.1 Sensor-MAC

The traditional MAC protocols are not suitable to be used for WSN; they are designed for systems which are power on most of the time. This is because nodes can be powered by recharges, so there is no power limitation. However, nodes in a WSN need to be turned off as much as possible to enhance the lifetime of the entire network. Based on this, Sensor-MAC (S-MAC) protocol [73] has been designed mainly for WSNs, with energy efficiency as its primary goal.

The S-MAC protocol is based on the 802.15 IEEE standards; it uses the same techniques to share the medium. The S-MAC protocol reduces energy wasting from idle listening, collisions and overhead, using low duty cycle operations for all nodes in a multi hop WSN. It reduces the energy used by nodes in their idle listening time by putting nodes to sleep mod when there is no need to be active and there is no data to be sent or received at the current time.

The S-MAC protocol lets nodes periodically sleep, which decreases energy consumption, but increases end to end delay for the data delivery. This is due to the fact that the sender needs to wait until the receiver wakes up to receive the data. In order to reduce this delay, the S-MAC protocol uses a new technique called *adaptive listening*. This method lets nodes adaptively go to sleep in their listening time when no communications occur, thereby reducing idle times.

In addition, in a WSN there may be some cases that some nodes have more data than others to send or receive [79]. In such cases, the S-MAC protocol uses a message passing technique to divide the long messages into small packets and transmits them in a burst. This avoids retransmitting a long message again, in the case of failed delivery. Most of the proposed MAC protocols discussed in this section are based on the S-MAC protocol. Each of these protocols tries to solve problems associated with the S-MAC protocol [80].

S-MAC Techniques for Saving Energy and Reducing Delay [79]

- Duty cycle scheme in multi-hop WSNs that reduces energy consumption by nodes in their idle listening time.
- Adaptive listening technique which greatly reduces the delay occurred during periodic sleeping.
- Using message passing to reduce the energy usage and delay caused by retransmitting after long message failed delivery
- Using Network Allocation Vector (NAV) with Request-To-Send (RTS) and Clear-To-Send (CTS) messages to avoid collision and hidden terminal related problems. This is when several nodes at the same time need to communicate.

- The S-MAC protocol lets nodes interfering with each other go to sleep to avoid overhearing, thereby saving energy.
- Schedule sleep synchronization is used by each node in a WSN to organize its schedule table with its neighbours.

Choosing and Maintaining Sleep Scheduling Tables in the S-MAC Protocol [80]

Each node in the WSN needs to organize and exchange its schedule time with its immediate neighbours before starting to communicate in its allowed time period. There is a schedule table stored at each node in the WSN, including the schedule of its own and for all of its neighbours. Each node in the WSN uses the following cases using S-MAC when updating its schedule tables from the network.

- Each node waits for a fixed time before broadcasting its schedule table to its neighbours. If it does not receive any schedule from its neighbours, it will broadcast its own schedule table.
- If the node hears another schedule before announcing its own schedule, it uses the new one and simply discards its own.
- In the case where a node hears different schedule tables from different nodes, there are two possible ways to deal with this case. The first way is if the node does not have any neighbours, it simply discards its own schedule and follows the new one. The second way is if the node has already received schedule adaptation from its neighbours, it updates its own table with the newly received schedule tables and then broadcasts its updated schedule table.

Advantages:

- Using the duty cycling concept, the S-MAC protocol saves energy for nodes in WSN.
- Using the adaptive listening concept, the S-MAC protocol reduces delays associated with unnecessary waiting times for sleep periods and then reduces energy consumption.
- S-MAC has a good scalability and topology management.

Disadvantages:

- Fixed period sleeping and waking up is not suitable for the applications proposed in this research as this may cause huge delays in multi-hop networks.

- As S-MAC is a contention based MAC protocol, then the collision is not avoided in all cases and hence reliability for the data delivered is reduced.
- The S-MAC protocol lets nodes that are interfering to go to sleep, and this can cause problems when a path later on goes through one of these nodes. This shows that S-MAC does not support cross layer concepts.
- Due to the need to establish a sleep/wakeup schedule for each node in a WSN, there is an overhead which may decrease the throughput for the data delivered.
- The end to end delay in the data delivery is increased. This shows that this protocol cannot be applied for the applications proposed in this work when delay and reliability for the data delivered are crucial.

2.2.1.2 E2RMAC

In general, contention based MAC protocols have been preferred for WSN over TDMA in terms of scalability. This is because of the need for TDMA synchronization and the unsuitability of it for distributed and dynamically changed topology using WSNs. Most of the proposed contention based MAC protocols for a WSN use adaptive duty cycling protocols and wake up on demand duty cycling techniques. As a result, different channels with different powers are used to deal with data transmission [76]. E2RMAC [81] is a contention based MAC protocol which has been designed to save energy, provide reliability and offer the bounded latency for data delivered from source nodes to the sink. The E2RMAC protocol performs wakeup duty cycling to achieve its goals.

Basic Operations of the E2RMAC Protocol [81]

- Firstly, nodes are required to send wake-up tones in the network before staring to send or receive the actual data. This is to active a set of nodes that are expected to share the data transmission.
- Secondly, all neighbours of the current sender node that hear the wake-up tone, put their radios into a high power mode, to be ready for the data transmission.
- Thirdly, the sender node sends a filter packet which contains the address of the intended destination, and switches its radio to sleep mode. Then the receiver receives the filter packet and keeps its radio in the high power mode and makes other neighbours put their radios into sleep mode.
- Finally, the sender sends the data packet to the destination and goes to sleep. Then the receiver receives the data, sends back an acknowledgement (ACK) to the sender and goes to sleep.

- Intermediate nodes forward successfully received packets from sender to the next hop without waiting for back off time in which reduces overall delay.

Advantages:

- Saves energy by activating nodes before data is transmitted.
- Increases throughput when traffic is high, compared to the S-MAC protocol.
- Supports cross layer and solves the problem of data forwarding interruption using routing techniques.

Disadvantages:

- Overhearing may occur, when sender hears an ACK from some intermediate nodes and it thinks it is the intended receiver.
- The E2RMAC protocol uses wake up, filter packet and then data packet to transfer data from source node to the sink. This may increase end to end delay in large networks.
- Collision with data from other nodes in the network is not avoided as E2RMAC is a contention based MAC protocol. This decreases the end to end reliability for data delivered. This leads us to the conclusion that this protocol cannot be applied for applications proposed in this work when end to end reliability and delay for data delivered need to be guaranteed.

2.2.1.3 TMAC

The core of Time-out MAC (TMAC) is built on the notion of frames, where time is divided into equal periods. Each frame has both active and inactive parts, where each node listens to the radio channel and potentially transmits during the active part, and disables its radio to achieve energy saving during the inactive period. Nodes are expected to be synchronized, ensuring that the beginning of each frame window is aligned across the network. The length of the active period is variable (which is the main improvement of TMAC over S-MAC [73]), and is determined dynamically by using an activation time out [82].

The authors of the TMAC protocol state that the active period ends for a node if no activation event occurs before the activation time out expires. Nodes handshake each other before starting to send data using Request To Send (RTS) and Clear To Send (CTS). A sender sends RTS to request the permission to send its data and a receiver replies with CTS when data is available and channel is ready (not busy). These techniques allow nodes to access the channel and start to send data when channel is not busy to reduce collision with data from other nodes in the network. The simulation results [82] showed that energy can be saved using activation based techniques when nodes do not have data to send. However, as the TMAC protocol is contention based MAC protocols then collision in the network is not avoided in all cases.

Advantages:

- Better than the S-MAC protocol in terms of saving energy using activation based techniques based on the traffic rates.
- Good scalability.

Disadvantages

- TMAC is a contention based MAC protocol and then collision in the network is not avoided and hence data my be discarded. Based on this feature, the TMAC protocol cannot be applied for the applications simulated in this research when reliability of the data delivered is crucial.

2.2.1.4 Routing Enhanced Duty Cycle MAC Protocol

Routing Enhanced Duty Cycle MAC (RMAC) [83] is a MAC protocol that supports a cross layer approach using WSNs. This protocol has been designed to save energy and reduce delays associated with the previous WSNs discussed protocols. The RMAC protocol lets nodes in the expected path from source nodes to the sink to go to sleep and intelligently wakes them up when they need to send or receive data in multi-hop networks. In addition, the RMAC protocol achieves significant improvement for the end to end data delivered in a single cycle in multi hops. This is due to reducing the contention period much more efficiently than the S-MAC protocol. Furthermore, the RMAC protocol sends a control frame along the path to inform the nodes in the selected path of ongoing traffic before the actual data packet is transmitted [84].

Advantages:

- Saves energy by waking up nodes in the expected path before the actual data is transmitted.
- Increases throughput where traffic is high, compared to S-MAC.
- Supports a cross layer approach.
- The end to end delay is decreased.

Disadvantages:

- Reliability of data delivered is not provided. This shows that this protocol is not suitable protocol to be used for the applications simulated in this work when reliability for the data delivered is the main issue.

2.2.1.5 B-MAC

B-MAC [85] is a CSMA based protocol for WSNs. It aims to provide a flexible interface to obtain ultra low power operation, effective collision avoidance, and high channel utilization.

B-MAC was designed to reduce duty cycle and minimize idle listening using an adaptive preamble sampling scheme. This technique increases performance for different applications using WSNs such as throughput, latency and power conservation.

B-MAC achieve its goals through the periodic channel sampling which is called Low Power Listening (LPL). Each time the node wakes up, it turns on the radio and check the channel for activity to deal with data transmission. If activity is detected and the channel is free, the node powers up and stays awake for the time required to receive the incoming packets. After reception, the node returns to sleep to save energy. If no packet is received a nodes is forced to go to sleep to conserve energy. However, B-MAC introduces some overhead in the network by transmitting long preambles. This reduces its efficiency in terms of energy saving and reliability of the data delivered.

Advantages

- B-MAC is simple in both design and implementation.
- B-MAC is efficient in channel utilization at low and high data rates.
- B-MAC is scalable to large numbers of nodes.

Disadvantages

- In B-MAC, collision is not avoided in all cases as nodes use contention based techniques in channel utilization. Based on this, reliability of the data delivered is not improved in all cases and thus it is not suitable protocol for applications where reliability is the main issue.

2.2.1.6 X-MAC

X-MAC [86] is a contention based and an energy efficient MAC protocol for duty cycled WSNs. This protocol aims to adaptively select sleep times schedules for nodes to decrease both energy consumption and latency. This is achieved though the enhancement of the following problems: overhearing, excessive preamble and incompatibility with packetizing radios.

A long preamble in a CSMA period introduces some delay at each hop, which is suboptimal in terms of energy consumption. This is due to fact that non-target receivers suffer from excess energy consumption. Research leads to different methods to avoid this problem. X-MAC avoids this problem by employing a shortened preamble approach that retains the advantages of low power listening, namely low power communication, simplicity and a decoupling of transmitter and receiver sleep schedules. This approach reduces wasted energy, decreases latency and increases throughput [86].

Performance evaluation and published simulation results [86] showed that X-MAC outperforms traditional LPL based protocols in terms of saving energy by forcing non target receivers which overhear the current transmission to go to sleep immediately, rather than remain awake for the full preamble as in LPL. This reduces collisions with the data from other nodes in the network while consuming a less energy. Based on this, lifetime of network increases.

Advantages

- Simple, low-overhead, distributed implementation
- Low latency and high throughput for data transmission.
- Saves energy by reducing a long preamble delay associated with traditional LPL based methods.

Disadvantages

- The overhead of transmitting long preambles decreases the efficiency of the X-MAC protocol at very low duty cycles.
- In X-MAC, collision is not avoided in all cases as it is a contention based MAC protocol. In addition, delay for data delivered increases by sending the preamble before nodes send their actual data. Based on this, both reliability and delay of the data delivered are not improved in all cases and thus it is not suitable protocol for applications where both reliability and delay are the main issues.

2.2.1.7 SCP-MAC

SCP-MAC [87] is a MAC protocol based on a Scheduled Channel Polling (SCP) technique. This protocol was designed to minimize energy consumption and to reduce latency associated with data transmission. This is through combining the use of LPL channel probing [85] with scheduled access [88]. SCP-MAC published results and analysis [87] demonstrated that the use of scheduling in addition to LPL methods can extend the lifetime of the network. In addition, SCP-MAC can reduce latency for delivering data by avoiding long message preambles, and is more flexible to changing traffic requirements.

SCP-MAC synchronizes the polling time of all neighbouring nodes. The major advantage of synchronized polling is that a very short wake-up tone can be sent to active a node. The short wake-up tone largely reduces the overhead of transmitting long preambles in LPL. This makes SCP-MAC more robust in the face of varying traffic load. SCP-MAC includes several optimization algorithms, including optional RTS-CTS, overhearing avoidance that work with and without RTS-CTS messages, adaptive listening, an potentially fast-path schedule allocation.

Advantages

- SCP-MAC combines the strengths of scheduling and low power listening to save energy and reduce latency.
- SCP-MAC is robust in varying traffic load.

Disadvantages

- The requirement on synchronizing the wake-up times in SCP-MAC results in high overhearing, contention and delay. This shows that this protocol is not suitable to be used for applications where reliability and delay are the main issues.

2.2.2 Schedule Based MAC Protocols

To allow WSN sensors to gain access to the shared wireless medium in a cooperative manner, schedule-based MAC protocols have been proposed that regulate access to resources according to a schedule to avoid contention among nodes. Depending upon the medium access technique, the resources could be a time slot, a frequency band or a CDMA code. The main aim of schedule base MAC protocols is to achieve a high degree of energy conservation to prolong the lifetime of the network [88].

Most of the schedule-based MAC protocols for WSNs use a variant of the Time Division Multiple Access (TDMA) scheme whereby the time available is divided into slots. Using this scheme, a logical frame of N contiguous slots is formed and this logical frame repeats itself in cycle over time. Each sensor node is assigned a set of specific time slots per frame and this set constitutes the schedule according to which the sensor node gains access to the medium and has the right to transmit or receive. This schedule can be either fixed, or constructed on demand, on a per frame basis, by the base station to reflect the current requirements of sensor nodes and traffic pattern [89].

The nodes must satisfy the interference constraint which says that no nodes within two hops of each other may use the same slot [90]. This two hop constraint is needed to avoid the hidden node problem when there is chance this could happen. Energy conservation is achieved by using an on and off mechanism of the sensor radio transceiver [91]. According to the schedule of each sensor node, a sensor alternates between two modes of operation: active mode and sleep mode. A sensor is in active mode when its turn to use the assigned time slots within the logical frame to transmit and receive data frames. Outside these sensor assigned time slots, it moves into sleep mode by switching off its radio transceiver [92].

The following are some scheduled based MAC protocols using WSNs:

2.2.2.1 PEDAMACS

PEDAMACS [93] is a TDMA based MAC protocol which aims to save energy and reduce the end to end delay for a multi hop. The PEDAMACS protocol provides the extension of single hop TDMA to be used in multi-hop TDMA. It uses a high power transmission Access Point (AP) to synchronize the scheduling information of the nodes using one hop away nodes. This means that this protocol must use different transmissions to collect data and organizes scheduling information among sensor nodes. The PEDAMACS protocol requires an AP with unlimited amounts of energy to reach any node in the network and represents the route of the deployed network.

The PEDAMACS protocol depends on topology discovery information to organize nodes using different phases: topology learning, topology collection, scheduling and adjustment. PEDAMACS uses three different transmission ranges: largest transmission, lowest transmission and medium transmission. The AP uses the largest transmission range to broadcast the topology and scheduling information to the network. Sensor nodes use lowest transmission to collect data in the network and medium transmission is used to discover local topology related information [35].

PEDAMACS Phases The PEDAMACS protocol uses the following phases to broadcast the required information when collecting data from the network [93]:

Topology Learning Phase: The AP uses this phase to broadcast topology learning coordination packets to all sensor nodes in the network, to organize the scheduling related issues. The topology learning packet contains two time slots, which represent the current, and next times. The current slot time is specified for sensor nodes to set their scheduling according to this time, The next slot time is the time when nodes need to stop their transmission and wait for the AP to receive new slots. After sensor nodes receive their current and next slots, the AP needs to broadcast a tree construction packet. Nodes receive this packet according to the path from their neighbours to the AP. After the tree topology is constructed, nodes need to broadcast their most recently updated scheduling information to the whole network.

Topology Collection Phase: After the AP broadcasts its topology learning phase, topology collection packets need to be broadcast in the next time slot. Each node organizes its local topology using the information in the topology collection packet. Then they listen to their parents and transmit their local topology using the lowest transmission range. In this phase, nodes use CSMA to listen to their parents and to receive next and current time slots from receiving topology packets.

Scheduling Phase: In order to organize the scheduling tables for all nodes in the network, the AP broadcasts the scheduling packets based on its knowledge of the complete network topology. This is to set the schedule tables for each node in the network. Each scheduling packet contains the current and next time as in the previous phases. This lets nodes organize their slots and later on to divide their times into slots depending on the data transmission requirements of each node in the network.

Adjustment Phase: The PEDAMACS protocol uses this phase at the end of scheduling phase to complete the topology of the network and to add any other required modifications, such as mobility of nodes and adding new nodes. The AP broadcasts an adjustment packet to spread the rest of the information using current and next time slots as discussed above using the medium transmission range. Nodes need to access this packet to extract their scheduling slots with along to information about the time when next adjustment packet expected to be received.

Advantages:

- Saves energy for sending and receiving data in the network based on the AP capabilities.
- Increases throughput when traffic is high, compared to the S-MAC protocol.
- The end to end delay is guaranteed
- Supports cross layer concept, such as routing protocols.

Disadvantages:

- No reliability for data delivered is provided, which means that this protocol is not suitable to be used for the applications given in this work when reliability is the biggest issue.

2.2.2.2 Medium Access Control with a Dynamic Duty Cycle Protocol

Medium Access Control with a Dynamic Duty Cycle protocol (DSMAC) [94] has been proposed with the aim of reducing energy consumption and decreasing the delay associated with the S-MAC protocol, using a dynamic duty cycle. It achieves a good trade off between energy saving and delay.

The DSMAC protocol dynamically changes the state of the nodes, for instance, from active to sleep, depending on the traffic conditions, level of the consumed energy and current delay, without any predefined information. This information is recorded in the packet header (Synch Packet) by the sending sensor node and retrieved by the receiving node. This technique is called a dynamic SYNC announcement. This will save energy and decrease delays associated with the S-MAC protocol in an efficient way.

The DSMAC protocol uses synchronization table related techniques to organize the scheduling time for nodes in the network. This lets nodes know when they need to be active. Each node in the WSN maintains and updates its own schedule table, like the S-MAC protocol, from its immediate neighbours, then follows and broadcasts its schedule table. In addition, the DSMAC protocol keeps a track of the average of energy consumption and latency delay using scheduling operations related information. The DSMAC protocol estimates the current traffic load and then changes cycle dynamically if needed [95].

Advantages:

- Saves energy using multiple duties cycling related techniques.
- Decreases delay associated with the S-MAC protocol using dynamically allocated wakeup and sleep schedules. This depends on the current traffic load and level of the consumed energy.
- Increases throughput when traffic is high, compared with S-MAC.
- Good scalability.

Disadvantages:

- Does not provide reliability for data delivered.
- The DSMAC protocol lets nodes that are interfering go to sleep, and this can cause problems when the path goes through one of these nodes. This shows that DSMAC does not support cross layer concepts.
- The need for the dynamic SYNC announcement for each node in the WSN and storing the average of consumed energy and delay, causes an overhead, thereby decreasing the throughput.
- The end to end delay is increased, so DSMAC is not a suitable protocol to be used for the proposed applications where reliability and delay for the data delivered are important.

2.2.2.3 An adaptivity Energy -Efficient and Low latency MAC for Data gathering (D-MAC)

In WSNs, the traffic in most applications can be represented as a directed tree related topology and enables the applications to collect data from multiple source nodes and send to a single sink. In this case, the sink node is the root and the sensor nodes are the children. This type of topology can control the traffic in the network compared with flat topologies. Nodes in the selected path can communicate with each other to solve the interfering problems associated with the S-MAC protocol. As a result, an adaptivity Energy-Efficient and Low latency MAC for data gathering (D-MAC) [96] protocol is designed to reduce energy and latency associated with the S-MAC protocol.

As mentioned before, the S-MAC protocol lets nodes that are interfering go to sleep. This means that nodes that are two hops away from the current source node can not notify ongoing traffic. This introduces extra delay in the case where some of these nodes are selected later on in the path, thereby causing data forwarding interruption related problems. To solve this, D-MAC [96] has been proposed; the D-MAC protocol utilises a sleep schedule of each node, which is dependent of its depth in the tree. The D-MAC protocol adaptively changes the cycle for the nodes according to the current traffic load in a similar way to the DSMAC protocol.

The D-MAC protocol uses data prediction techniques for data gathering from source nodes to the sink, in case the traffic is low and the aggregated amount of data needed to be forwarded at intermediate nodes is high. This can be raised when the current duty cycle is unable to handle this transmission. Hence data prediction related approaches will let nodes be active as long as needed.

Furthermore, nodes in the D-MAC protocol send a request more data packet in the multi paths to remain active when one of them fails to send a packet to its parent. Upon receiving more data packets, parents respond their children with ACK packets to accept the request and then start to receive data. This technique is called a More to Send (MTS) [96].

Advantages:

- Saves energy using data prediction techniques for data gathering from source nodes to the sink.
- Decreases delay associated with the S-MAC protocol using data gathering and prediction techniques.
- Increases throughput when traffic is high, compared with the S-MAC protocol.
- Solves data forwarding interruption problems.
- The end to end delay of data delivered is decreased.

Disadvantages:

- Does not provide reliability for data delivered.
- Suffers from overhead due to having extra announcement in the network for each level of the traffic when predicting nodes in a WSN to be active for ongoing transmission.
- Does not support cross layer information.

- If data needs to be collected from arbitrary nodes, the D-MAC protocol may face problems.

- The end to end delay and reliability are not offered. This shows that this protocol is not suitable protocol to be used for the applications given in this research, where both the delay and reliability of data delivered are crucial.

2.2.2.4 Q-MAC

Applications in WSNs can be generally divided into three types; event-detection based applications, periodic-sensed-based applications and query-based applications. Each of these applications has its own techniques to deal with data collecting from sensor nodes and sending it back to the sink. Various MAC protocols have been proposed for each type, with the aim of energy and delay efficiency using different techniques [97].

Query-based applications are types of applications where users put their request for data into a query and send it to a specific part of the area where sensor nodes are placed. As a result, the end to end delay in such applications can be minimized whilst consuming less energy. When no queries are available in the network, node energy can simply be saved by turning off their radios. However, when a query is initiated by a user and it has been sent to the network, scheduling and synchronizing related packets will be broadcast automatically to deal with data communication. This depends on the locations of the nodes which are specified in the query. This means that the lifetime of the network is maximized because only a part of the network will deal with this data communication, and nodes in the rest of the network will be sleeping [84].

Based on the above requirements, Query based MAC (Q-MAC) protocol [98] has been designed to increase performance for different applications. The main objectives of the Q-MAC protocol are: (1) reduce the end to end delay associated with delivering data from network to a sink by informing the intermediate nodes in advance about ongoing traffic using dynamic scheduling. (2) Enhance the lifetime of the entire network by only activating the nodes that are specified in the current query. Simulation results [98] concluded that the Q-MAC protocol improves latency of 80% compared with the S-MAC protocol.

Advantages:

- Saves energy and decreases end to end delay, compared to S-MAC, using query based techniques.

- Increases throughput when traffic is high, compared to S-MAC.

- Supports multiple destinations.

Disadvantages:

- Does not provide reliability for the end to end data delivered.
- Does not support cross layer concept.
- The end to end delay of data delivered is not guaranteed. This means that it is not the right protocol to be used for the applications proposed in this research when end to end delay and reliability of data delivered are crucial.

2.2.2.5 QoSMAC protocol

QoS in WSNs is to guarantee some specific parameters which need to be considered when designing a given application. Based on this, various MAC protocols have been designed to offer different QoSs for different applications [99]. The QoSMAC [100] protocol is a TDMA and tree based MAC protocol which interacts routing with medium access to achieve its goals. This means that nodes need to organize themselves as a tree, where root is the sink and leaves are source nodes. This protocol is designed to decrease the delay and increase the reliability of data delivered over single hop communication using WSNs [101].

Advantages:

- Saves energy using cross layer and TDMA techniques.
- The end to end delay decreases, compared to the S-MAC protocol.
- Throughput increases when traffic is high, compared to the S-MAC protocol.
- Supports cross layer concepts which solves the problem of data forwarding interruption using routing techniques.
- Delay and reliability of node to node is optimized.

Disadvantages:

- If data needs to be collected from arbitrary nodes, QoSMAC may face problems.
- OoSMAC supports a small number of nodes in the network so it is not suitable protocol for large WSNs.
- The end to end delay and reliability are not guaranteed, so this protocol cannot be applied for the applications given in this work when both reliability and delay are crucial.

2.2.2.6 GinMAC

The GINSENG project [68] was designed to improve performance for applications where reliability was the main issue while consuming a less amount of energy for WSNs. This project consists of different parts such as topology management, software components, networks algorithms and planned deployment. One of the key aspect of the GINSENG project is the development of GinMAC which is responsible to assure performance for the target applications where a small number of nodes is involved in the network. GinMAC is classified as a MAC protocol in the GINSENG project using WSNs [102].

GinMAC [65] is the first MAC protocol that has been proposed to consider reliability for the end to end data delivered in time critical related operations. GinMAC is a tree based MAC protocol and uses different techniques to achieve its goals, such as reliability and timely delivered data, by considering the topology of the environment. This must be known at the deployment phase before running the application. This shows that GinMAC is a cross layer based protocol where static routing is supported between nodes and their children. An example of application using WSNs that GinMAC can support is a healthcare related application, with relatively small number of nodes.

GinMAC is a TDMA-based MAC protocol, using low duty cycling to save energy for nodes when they have nothing to send and receive. Based on the simulation results [103], GinMAC is the best MAC protocol for reliability related issues over the pre discussed MAC protocols in this section. This is the case when low data rates and small number of nodes are considered.

The GinMAC protocol uses the following three features to deal with data transmission: Off-Line Dimensioning, Exclusive TDMA and Delay Confirm Reliability Control. The Off-Line Dimensioning is used to divide the frames into three different slots, which are basic, additional, and unused slots. The Basic slot is used for forwarding one message to the sink within a frame size F. The Additional slot is used to improve reliability of the data delivered to a sink when needed. he unused slot is for improving low duty cycling to save energy. The exclusive TDMA feature selects the exclusive tree based TDMA schedule for nodes based on the structure of the networks so that each node has enough slots to deal with data communication [102].

The Delay and Reliability Control feature are used for selecting the best links between source nodes and a sink to provide the required end to end delay and reliability for the data delivered. The GinMAC protocol uses these techniques and slots to improve energy consumption, delay and reliability for the end to end data delivered over multi hop communication from source nodes to the sink [68].

Advantages:

- Saves energy for sending and receiving data in the WSN, using static TDMA based techniques,

- Increases throughput when traffic is high, compared to S-MAC.
- Supports a cross layer approach.
- Supports real time communications.
- The end to end timely delivered data and reliability are offered based on different techniques as shown above. This means that GinMAC is suitable MAC protocol with some improvement for the applications given in this thesis when a small number of nodes in the network is considered.

Disadvantages:

- Supports a small number of nodes in which decrease scalability of the GinMAC protocol for large WSNs.
- Mobile nodes are not supported and then cannot be applied o application when some nodes are mobile, such as healthcare related. This shows that the GinMAC protocol must be modified by supporting mobile nodes.
- GinMAC needs efficient routing protocol to enhance the required scalability when a high number of nodes is considered. However, this protocol with some modifications such as designing mobility module can improve WSNs for the applications given in this research when a small number of nodes is considered. Based on this, the first original contribution in this research is to modify the GinMAC protocol by supporting mobile nodes.

2.2.3 Hybrid Based MAC Protocols

CSMA based MAC protocols are popular because of their simplicity, flexibility and robustness. No infrastructure support, clock synchronization and global topology information are required. In addition, dynamic node joining and leaving are handled gracefully without extra operations. However, two conflicting nodes transmit at the same time causing signal fidelity degradation at destinations as shown in Section 2.2.1.

TDMA based MAC protocols, on the other hand, can solve the hidden terminal problem without extra message overhead. This is because these protocols can schedule transmission times of neighbouring nodes to occur at different times. However, such protocols need efficient techniques to design a time schedule required to find a collision-free schedule when nodes are transmitting data. This means that TDMA based MAC protocols have a problem with scalability when a high number of nodes are involved in the network as shown in Section 2.2.2.

As a result, hybrid MAC schemes for sensor networks that combine the strengths of TDMA and CSMA based MAC protocols while offsetting their weaknesses have been designed. The main feature of these protocols are their adaptability to the level of contention in the network so that under low contention, they behave like CSMA based protocols, and under high contention, like TDMA based protocols. They are also robust to dynamic topology changes and time synchronization failures commonly occurring in sensor networks.

Some of the recently proposed hybrid based MAC protocols are discussed and evaluated in the following sections:

2.2.3.1 Z-MAC

Z-MAC [104] is a hybrid MAC based protocol for WSNs that combines the strengths of TDMA and CSMA while offsetting their weaknesses. Like CSMA, Z-MAC achieves high channel utilization and low latency under low contention and like TDMA, achieves high channel utilization under high contention and reduces collision among two-hop neighbours at a low cost.

Z-MAC has the set-up phase in which it runs the following operations in sequence: neighbour discovery, slot assignment, local frame exchange and global time synchronization. These operations run only once during the setup phase and do not run until a significant change in the network topology occurs.

In the neighbour discovery, nodes broadcast a simple ping to get different information about one hop way neighbours. This lets nodes get their slots when they need to send and receive data. In the local frame exchange, each node maintains its own local time frame that fits its local neighbourhood size, but avoids any conflict with its contending neighbours. Thus every node forwards its frame size and slot number to its two-hop neighbourhood. This leads each node knows about the slot and frame information of its one-hop and two-hop neighbours at the beginning of the Z-MAC phase. Upon receiving slots information, each node synchronizes its schedule to slot 0 and then waits to for data transmission.

An important feature of Z-MAC is that synchronization is required only among nodes one hop away from senders and also when they are under high contention. This feature offers opportunity to optimize the overhead of clock synchronization. This is because synchronization is required only locally among neighbouring senders, and the frequency of synchronization can be adjusted according to the transmission rates of senders. This means that senders with higher data rates transmit more frequent synchronization messages [104].

On the other hand, in Z-MAC it is not define whether the owner of a slot uses its time slot or leaves it idle. Hence, other nodes with pending data have to wake up and sense the channel in the beginning of every time slot. This is in order to see if the channel is ready to be used. This causes Z-MAC to have higher delay in low traffics, and more energy consumption in high load conditions [105].

Advantages

- ZMAC adjusts the behaviour of MAC between CSMA and TDMA depending on the level of contention in the network.
- Increases throughput when traffic is high, compared to S-MAC. Z-MAC improves the ability of WSNs for different applications under medium to high levels of contention.
- Z-MAC becomes more robust to timing failures, time-varying channel conditions, slot assignment failures and topology changes than stand-alone TDMA based MAC protocols.

Disadvantages

- Z-MAC is a suitable MAC protocol for applications where expected data rates and two-hop contention are medium to high. Based on this, Z-MAC performance in terms of saving energy is reduced when a low contention is considered.
- In Z-MAC, collision is not avoided in all cases as it is a hybrid based MAC where different nodes may trying to access the channel at the same time. Based on this, reliability of the data delivered is not improved in all cases and hence it is not suitable protocol for applications where reliability is the main issue.

2.2.3.2 An Adaptive Hybrid MAC Protocol

An adaptive CSMA/TDMA hybrid based protocol [105] was designed to improve performance of 802.15.4 standard in different applications using WSNs. The aim of designing this protocol was to improve features of this standard by taking advantages of both CSMA/CA and TDMA methods. A new hybrid method was designed to dynamically assign a part of contention access period to TDMA and shares this period among nodes with high number of pending data. As a result, both energy and throughput improvement are achieved by dedicating a part of the contention access period to a TDMA.

The published results [105] show that in high traffic conditions, energy saving, end to end delay and throughput all are improved better than the 802.15.4 standard protocol as more space is given to the TDMA part. However, collision in the network is not avoided in all cases as contention is the main part of this protocol.

Advantages

- This protocol adjusts the behaviour of 802.15.4 standard by adding TDMA schedules.
- Throughput and end to end delay are improved while consuming less energy, compared to the 802.15.4 standard.

Disadvantages

- CSMA is involved in the specification of this protocol and hence collision is not avoided in all cases. Based on this, data is more likely to be lost before it gets delivered. This shows that this protocol is not suitable protocol for applications where reliability of data delivered is a big factor.

2.3 Routing in Wireless Sensor Networks

Routing is an essential feature of any multi hop sensor network [7]. In such networks, a node should have the capability to sense, route, receive, send and forward data as required between source nodes and a sink. This requires a lot of energy. To counteract this and increase the lifetime of the network, efficient routing protocols need to be designed. These, in turn, need efficient routing algorithms for different applications [106].

The objective of routing protocols is to deliver sensed information from sensor nodes in the network to the appropriate sinks using the best possible pathways. Sensed information can be represented by descriptors, which may be fused and then combined before they are routed to the sink. This section outlines a suitable routing protocol for the proposed applications, which takes energy saving, delay and reliability of delivered data over multi hop communication into consideration [107].

2.3.1 Routing Metrics for Wireless Sensor Networks

Routing in WSNs has been an active area of research for many years. Sensor nodes have a limited transmission range, processing, storage capabilities and energy resources. In WSNs data is forwarded using multi hop mechanism. Therefore, a variety of routing metrics has been proposed by various methods in WSNs for providing routing algorithms to improve the capability of WSNs for different applications [108], [109].

The routing metrics address various issues considering different optimization objectives and applying different techniques when data is delivered. These include signal strength measurements, active probing, energy consumption monitoring, and prediction of link breakage due to node mobility [110].

The existing routing metrics are classified into 4 categories based on their operations: Hop count based, Signal strength based, Mobility aware and Energy aware metrics [111].

1. Hop Count: Every link counts as one equal unit independent of the quality or other characteristics of the link. This metric choose the shortest paths between source nodes and a sink when data is delivered. This means that this metrics is not a reliable routing metric for WSNs as there are other factors such as energy, strength of signal which are crucial to

be considered in order to improve reliability of the data delivered to a sink.

2. Signal Strength: A signal strength metric has been used as link quality metrics in several routing protocols for WSNs. The signal strength can be viewed as a good indicator for measuring link quality since a packet can be transferred successfully when the signal strength is more than the threshold value. However, there may be some cases when this metric can not offer the reliable route for delivering data. This is due to the fact that sender does not take into account an energy of nodes when routes are selected. This reduces the lifetime of the network. This means that using only a signal strength metric is not good enough to be used for data delivering using WSNs.

3. Mobility aware: A mobility aware metric selects routes with higher expected lifetime to minimize the routing overhead related to route changes and their impact on throughput. This means that only mobility is the main issue in this case and hence it does not offer the reliable routes where other performance criteria such as delay and reliability for data delivered to a sink are crucial.

4. Energy aware: Energy consumption is an important constraint in WSNs. Sensors have restricted battery lifetime and are most vulnerable to the energy constraints. This means that this metric is suitable for routing protocols where only the lifetime of the network is the main design factor. This shows that this metric does not reflect the reliable route when other performance criteria such as reliability and delay for data delivered to a sink are important.

All of this led us to the conclusion that only one routing metric is not good enough to be used for delivering data in applications given in work presented in this thesis. Based on this, different metrics could be combined in order to select a reliable route before data is transmitted.

2.3.2 Routing Protocols for WSNs

Research has led to many different proposals for routing protocols [5], [12], [69], [72] , each one targeted at specific applications for a WSN. Some of these protocols use information related to node location to send data between source nodes and a sink, while others use some nodes with high energy to deal with data communication. Consequently routing protocols are classified by aspects such as the network structure, protocol, operations and the way that nodes communicate.

Most commonly, routing protocols using WSNs are classified, according to their network structure, into flat (data centric), hierarchical and location based protocols. In hierarchical based routing protocols, nodes are divided into different clusters with different roles. All nodes in flat routing based protocols are assigned the same role. In location based protocols, the geographic information about nodes is used for relaying data from source nodes to a sink [1].

Some of the recently proposed routing protocols [5], [12], [69], [72] are discussed and evaluated in this section in terms of their suitability for the proposed applications. It is crucial that energy saving, reliability and delay in the delivery of data are considered in such protocols. Based on this discussion, a suitable routing protocol for the proposed applications has been selected.

2.3.3 Classical Flooding and Gossiping Based Protocols

Flooding and Gossiping [35] are two traditional flooding-based routing protocols which can be used by WSNs, where each node needs to broadcast data to its neighbours and then each of its neighbours does the same. This is repeated until either data is received by a final destination or a maximum allowed number of hops is reached. The Gossiping based protocols broadcast data to one neighbour which is randomly selected, while flooding based protocols broadcast data to all available neighbours [5], [112].

Advantages:

- Simple and cheap for implementation.
- Suitable for applications that need high robustness.

Disadvantages:

- Overlap: If two nodes are in the same region, both of them may sense the same data at the same time. This will let neighbours receive duplicated packets which lead them to consume a lot of energy.
- Implosion: Implosion refers to the situation when duplicated data is sent to the same nodes. This will cause a collision in the network and then reduce the reliability of the data delivered.
- Resource Blindness: Flooding and gossiping-based protocols do not care about the available energy at each neighbour when broadcasting the packets but this will face the problem that some nodes may be out of energy. As a result, the lifetime of the network is too short.
- The end to end reliability and delay for the data delivered are not offered. This means that these protocols are not suitable to be used for the applications given in this research.

2.3.4 Flat Routing based protocols

2.3.4.1 SPIN

Sensor Protocol for Information via Negotiation (SPIN) protocol [113] is designed to improve the problems associated with the classical flooding and gossiping -based routing protocols. The SPIN protocol has the following two features: (1) uses energy efficiency to enhance the lifetime of the network. (2) It uses available resources adaptively to solve the resource blinding related problems. The SPIN protocol depends on negotiation for data transmission; this will avoid unnecessary duplicated data at each intermediate node in the network in which results in saving energy.

The negotiation technique used by the SPIN protocol is based on the energy and the possibility of available overhead at each intermediate node. Nodes handshake each other using metadata and then adaptively decide if they need to communicate, depending on their available resources. This negotiation technique reduces overlap and implosion problems associated with the flooding and gossiping based protocols. The SPIN protocol is a data-centric based protocol and each node needs to send an advertisement (ADV) message to other nodes in the network then waits until it receives a request (REQ) message from one of its neighbours. The metadata is not part of the application but it is used to describe how data needs to be sensed, collected and send it back to the sink [114].

Advantages:

- Solves the implosion and overlap problems.
- Saves energy by specifying which nodes are interested in data transmission instead of broadcasting to all nodes in the network.
- Reduces duplicated packets at intermediate nodes in the network.

Disadvantages:

- Advertisement related techniques cannot guarantee delivering data to the interested nodes that are far away from the source nodes.
- The SPIN protocol is not a scalable protocol.
- No end to end reliability for data delivered is offered. This shows that the SPIN protocol cannot be used for applications proposed in this work.

2.3.4.2 Directed Diffusion Protocol

Directed Diffusion (DD) [115] is a data centric routing-based protocol for WSNs which aims to save energy and provide good scalability. The DD protocol is based on naming data that needs to be sensed and collected by source nodes in the network before transmitting it to a sink. To do this, the DD protocol uses attribute-value pairs, which describes the data that needs to be broadcast in the network.

The key idea behind this protocol is to combine the data collected from different sensors using data diffusion related issues in order to eliminate redundant data. This will save energy, thereby extending the lifetime of the entire network. The DD protocol collects data from multiple sources then aggregates it and send the data back to a sink. Each intermediate node in the DD protocol stores a copy of the received data into its a local cache before broadcasting it to its neighbours [116].

DD Techniques The DD protocol uses the following techniques to deal with data communication [116]:

- Data Naming: At the start of the DD protocol, a sink describes the data by high level naming and attribute-value pairs, with precise details depending on the proposed application.
- Interest, Gradients and Data Propagation: After the data is named, a sink needs to put it in to a query and propagates it to the network. This is followed by setting up gradients to carry data from the source nodes and send back to a sink.
- Reinforcement: After data is propagated and gradients are set up, a sink can reinforce one particular sensor to deal with events which need a high data rate transmission.

Advantages:

- Solves the implosion and overlap problems.
- Uses different data diffusion related techniques to reduce redundant data very efficiently by performing data aggregation and caching at each intermediate node in the network. This saves energy and prolongs the lifetime of the network.
- Improves the effective bandwidth of the data transmission.
- DD is a scalable protocol.

Disadvantages:

- Cannot be applied to continuous based applications, for instance monitoring based applications.
- Matching data to the queries may result in extra overhead in the network.
- No end to end reliability for data delivered is offered.

- Recording data and implementation of data aggregation may cause extra overhead. Therefore, DD is not suitable protocol for the applications given in this research.

2.3.4.3 Rumor Routing

The Rumor Routing (RR) [117] protocol has been designed to solve problems associated with the flooding and gossiping -based protocols using a very long life node which is called an *Agent*. Each node in the network has a small table to store events identified from the network during their active period time. This table is called the *Events Table*.

Nodes generate agents to propagate their data to the network using their event tables via queries. Interested nodes will respond to the query by simply inspecting their events table and put the event to the query and then broadcast it to the network. As a result, this technique will save energy by reducing the number of transmissions, thereby increasing the lifetime of the network. However, there will be only one possible path for the data to be transmitted using agents in the RR protocol, which is not a suitable case for most of the applications using WSNs [118], [119].

Advantages:

- Solves the implosion and overlap problems.
- Saves energy by reducing collision in the network.
- Reduces duplicated packets at each intermediate node in the network.

Disadvantages:

- Maintaining and storing list of events and agents may cause extra overhead in the network.
- RR is not a scalable protocol.
- Only one path is possible between source nodes and a sink.
- No end to end reliability for data delivered is offered.
- Based on these features, the RR protocol is not suitable protocol for the applications simulated in this research.

2.3.5 Topology Management Protocols in WSNs

2.3.5.1 Geographic Adaptive Fidelity

Geographic Adaptive Fidelity (GAF) [120] is a energy aware and topology management based routing protocol that is mainly designed for mobile ad hoc networks, but could also be applied for WSNs. The aim of this protocol is to increase the lifetime of the network by maximizing the number of nodes into sleep mode when there is no data to be sensed. This must not affect the accuracy of the data and the level of fidelity. Nodes in the GAF protocol form a virtual grid for the covered area and use their GPS to identify themselves and construct the virtual grid that they need to be included. Some nodes in the network are selected to be leaders and they are responsible for data communication on behalf of the other nodes. These leader nodes are also responsible for monitoring the connection of the network when topology is changed. Nodes that are located at the same points in the recently constructed grid are considered to be equivalent in terms of the routing cost.

Nodes in the GAF protocol use three different states to decide when they need to become active, to go to sleep and how to discover their neighbours. The first state is called Sleep State; in this state nodes go to sleep and turn off their radios in order to save energy. The second state is called an Active State; nodes use this state to indicate when they need to become active for data transmission. The third state is a Discovery State which is used by nodes to discover their neighbours in the grid that need to be used for data communication [121].

Advantages:

- Saves energy by using location based techniques such as GPS.
- Improves the bandwidth and delay for the data transmission.
- Reduces the overhead in the network by flooding the query only to the appropriate region of the network.
- Supports mobility.

Disadvantages:

- Extra overhead from constructing the virtual grids.
- No end to end reliability for the data delivered is offered.
- The GAF protocol assumes that all nodes have the ability to find its locations, and this will introduce extra cost in the large networks. Hence, this protocol cannot be applied for the applications given in this research where both reliability and energy saving are important.

2.3.5.2 SPAN

SPAN [122] is a topology management routing protocol designed to save energy using WSNs. SPAN is a distributed and randomized algorithm where nodes make local decisions on whether to sleep, or to join a forwarding backbone as a coordinator. Each node bases its decision on an estimate of how many of its neighbours will benefit from it being awake as well as its remaining energy.

SPAN adaptively elects coordinators in the network based on nodes' remaining energy in order to extend the lifetime of the network, compared to LEACH where only RSSI is considered. Coordinator nodes in SPAN stay awake continuously and perform multi-hop packet routing within the ad hoc network. Non coordinator nodes remain in power-saving mode and periodically check if they should wake up and become a coordinator. SPAN rotates and minimizes coordinate nodes to make sure that nodes are equally selected as coordinators similar to LEACH where nodes are selected as CHs in different rounds. This distributes energy usage between nodes and then increases the lifetime of the network.

SPAN accesses and combines information from different layers such as MAC and routing layers to find a best path to deliver data from source nodes to a target destination. This means that this protocol supports cross layer concepts.

After the coordinators selection, each coordinator advertises its self to its neighbours. Then nodes join different coordinators based on different attachments metrics. These metrics are selected based on the requirements of the target applications.

SPAN differs from GAF in two cases: (i) nodes in GAF need to know their locations in order to construct virtual grids while in SPAN nodes use broadcast messages to discover a list of available neighbours and react to the changes in the topology of the network. (ii) SPAN supports cross layer concept so that non coordinate nodes can still receive data when they are in a low power mode while GAF does not support cross layer concept [120].

Advantages:

- Saves energy by distributing energy between nodes.
- Improves the bandwidth and delay for the data transmission.
- Reduces the overhead in the network by selecting different coordinators in the network. This is because nodes send data to their coordinators over single hop communication as in LEACH.
- Supports mobility and cross layer concepts.
- Reduces duplicated packets at each intermediate node in the network.

Disadvantages:

- Suffers from overhead due to coordinators' announcement in the network.

- As SPAN uses contention when nodes become coordinators, then some overhead is introduced in the network. This causes a collisions and extra energy consumption. As a result, both the reliability for data delivered and lifetime of the network are decreased. This leads to the conclusion that the SPAN protocol is not suitable protocol for the applications simulated in this research.

2.3.5.3 EEMR

An Energy Efficient Integrated MAC and Routing protocol (EEMR) [123] is a cross layer protocol based on MAC and routing layers using WSNs. It aims to optimize forwarding energy efficiency on the premise that end to end delay is restricted under the predefined upper bound. EEMR employs the minimum angle of source and destination nodes to prolong the network lifetime.

In EEMR, relay nodes election is launched in the channel access phase simultaneously through intriguing a competition for relay among active nodes that are closer to the destination. Energy efficiency, link state and duty-cycling are considered synthetically to elect optimal relay in each hop dynamically.

EEMR accesses and combines information from different layers such as MAC and routing layers, like SPAN, to deliver data. In addition, nodes are selected as coordinators and non coordinators nodes join to different coordinators as in SPAN based on different metrics. However, EEMR calculates the average power cost, link state. These cost metrics are exploited together with hop count to select a better relay node, compared to SPAN when topology of the network is considered when coordinators are selected.

Advantages:

- Saves energy by distributing energy between nodes.
- Improves the bandwidth and delay for the data transmission.
- Reduces the overhead in the network when different relay nodes are selected.
- Supports mobility and cross layer concepts.
- Reduces duplicated packets at each intermediate node in the network.

Disadvantages:

- Suffers from overhead due to calculating link related metrics to select better coordinators in the network.

- As EEMR uses contention when relay nodes are selected, then collision is not avoided in all cases as in SPAN. This reduces a number of packets delivered to a sink. This leads to the conclusion that the EEMR protocol is not suitable protocol for the applications simulated in this work.

2.3.6 Location-based Routing Protocols in WSNs

All location based routing protocols in a WSN are required to have information about the locations of the nodes in a network using GPS or localization algorithms [124]. In addition, each node needs to be able to determine its position and all of its neighbours. These protocols are addressed using their locations as sensor nodes cannot be addressed using traditional IP address. This means that a sink will only broadcast a query to a specific area of the network instead of broadcasting to the whole network. This will increase the lifetime for each node, thereby extending the lifetime of the entire network.

The key idea behind the location based routing protocols is to contact the specific region of the network that is specified in the query using the sensors near to the expected events. This leads to save energy for the rest of nodes by simply forcing them to go to sleep [72], [125].

2.3.6.1 Sequential Assignment Routing Protocol

Sequential Assignment Routing (SAR) [100] is another location based routing protocol designed to provide good QoS for end to end data delivered in a WSN. The minimum QoS needs to be specified depends on the given application. For instance, some applications may need to guarantee the reliability of the data, while others just need to consider delay. This protocol adds the notation of QoS metric into a routing table when selecting different routes for delivering data to a sink.

The SAR protocol uses the following three factors for data transmission: (1) energy saving, (2) QoS on the path and (3) priority of the packets. The SAR protocol supports multiple paths to increase the reliability for the end to end data delivered. So the objective of the SAR protocol is to use QoS-based metrics to select reliable routes when data is transmitted, whilst consuming less amount of energy. This increases the lifetime of the network and performs the standard services for the target application.

Advantages:

- Saves energy by having multiple paths from sensor nodes to a sink.
- Improves the bandwidth of the data transmission.
- Provides different QoS for end to end data delivered.

- Good scalability and robustness.
- Supports mobility.

Disadvantages:

- Extra overhead from constructing multiple paths and maintaining QoS tables at each node in the large networks. As a result, no end to end reliability for data delivered is performed which makes this protocol unsuitable for the applications given in this work where both reliability and delay are considered.

2.3.6.2 SPEED

Stateless Protocol for Real-Time Communication in Sensor Networks (SPEED) [126] is an example of a routing protocol which uses a routing technique called Stateless Geographic Non-deterministic Forwarding (SNGF). It is a location based protocol which is designed mainly for applications using WSNs when only delay of data transmission needs to be considered. It aims to reduce the overhead in the network and improves the performance of a WSN. This involves reducing delay and avoiding congestion using both MAC and routing protocols. The SPEED protocol is designed to provide guarantees for the end to end data delivered in a WSN based on the speed of each packet in the network. The SPEED protocol exchanges different beacons in the network such as Neighbours Beacon Exchange, A stateless Non deterministic Geographic Forwarding Algorithm (GFA), Neighbours Feedback Loop (NFL) and Last Mile Processing. These beacons are used to discover neighbours which are proper to be selected for delivering data from source nodes to a sink [127].

Advantages:

- Improves the bandwidth of the data transmission.
- Provides a guarantee for end to end delay for data delivered.
- Good scalability and robustness.
- Can be applied for the applications when only delay associated with the data delivered needs to be considered.

Disadvantages:

- The SPEED protocol does not consider any energy and reliability related metrics when data is transmitted. This shows that it cannot be applied for applications where energy or reliability need to be considered.

2.3.7 Hierarchical-based (Cluster) Routing protocols

Sensors are grouped into clusters prior to operation of the network and use both CSMA and TDMA based schemes [1],[15]. Data is transmitted between nodes belong to different clusters and their cluster head and then between cluster head and a sink. These protocols can enhance the lifetime of the network by distributing the load of energy consumption between nodes using cluster based concepts. In addition, collision with data from other nodes in the network is reduced using allocated TDMA schedules between nodes and their cluster head [128], [129]. Some of the recently proposed cluster based routing protocols are discussed and evaluated, in terms of their suitability to be used for the applications used in this research, in the following sections.

2.3.7.1 LEACH

Low Energy Adaptive Clustering Hierarchy (LEACH) [130] is a self organized adaptive cluster based protocol for WSNs. It uses cluster concepts to distribute the energy load among the sensor nodes in the network and avoid collision. It is the first and most popular energy aware based protocol that is designed generally for saving energy for nodes in the WSN. The LEACH protocol has some assumptions, such as (i) the sink is fixed and located far away from the sensors, (ii) the nodes in the network are homogeneous and energy constrained. (iii) The nodes located near to each other have correlated data, and nodes provided with enough energy to transmit data to the sink via a single hop communication. (iv) Nodes send data periodically. The key idea behind the LEACH protocol is to organize the sensor nodes into separate groups of nodes, called clusters, which are controlled by a Cluster Head (CH) [8].

CHs in the LEACH protocol are selected based on the equation (T(n)) given below and the pre defined percentage of CHs. After CHs are selected, each CH advertises itself to the rest of the nodes in the network to select new members. After CHs advertisement, nodes ask join to different clusters based on the strength of the received signals from different clusters. Then each CH in the LEACH protocol creates TDMA schedule for their members so that each node uses its slots to deal with data transmission. This avoids collisions with data from other nodes in the network and enhances the reliability for data delivered. The data communication from sensors belonging to each cluster is received by a CH and then this data is aggregated and forwarded to a sink using a single hop communication [131].

$$T(n) = \begin{cases} \frac{P}{1-P*(r \ mod \ \frac{1}{P})} & \text{if } n \in G \\ 0 & \text{otherwise.} \end{cases} \tag{2.1}$$

Where *P* is a percentage of cluster head which needs to be selected, *r* is a current round. *mod* is a remainder of $r/(1/P)$ and *G* is a set of nodes that have not been selected as cluster head in the previous *1/P* rounds. Cluster head nodes in the LEACH protocol must have the following characteristics [130]:

1. Enough energy to perform the data aggregation and send data to a sink.
2. The distance between the cluster head and the sink must be within its range for the transmission so that each cluster head can send data using a single hop communication to the sink.
3. Each node should have at least one neighbour to deal with data communication.

Advantages:

- Solves the implosion and overlap problems.
- Uses data diffusion to reduce redundant data transmissions by performing data aggregation.
- Very robust.
- Extends lifetime of the network using cluster based capabilities.

Disadvantages:

- Has hotspot related problems; nodes on the route to a sink may consume their energy faster than others
- The LEACH protocol does not consider cross layer information to select reliable routes using multi hops so makes LEACH an unreliable routing protocol for large WSNs.
- CHs are selected based on equation given in equation 2.1 and then the change of nodes dying in their early stages is high. Based on this feature, the lifetime of the network is short.
- Selecting cluster head will involve extra overhead and consume energy in very dynamic networks.
- No reliability for end to end data delivered is provided. As a result, this protocol cannot be applied to the applications given in this research when both reliability and energy saving are the main issues.

2.3.7.2 PEGASIS

PEGASIS [132] is an improvement on the LEACH protocol, based on the chain using greedy algorithm. PEGASIS is a clustered based protocol like LEACH, nodes in the chain send data to a sink using their direct neighbours. However, the chain in PEGASIS is constructed and one node is selected to send data, while LEACH forms a cluster. Furthermore, nodes in the PEGASIS protocol send data to their local neighbours in the data aggregation phase instead of sending it to the cluster head. The node in the chain that is nearest to the sink is selected to be a leader and takes the responsibility of aggregating and sending data to a sink.

The key idea behind the PEGASIS protocol is that nodes communicate with their nearest neighbours in which leads to extend the lifetime of the network by reducing the path between source nodes and a sink. PEGASIS selects the nearest node based on the strength of the received signals and the least distance to the sink. Nodes in the chain represent nodes involved in the path (route) and close to each other to deliver data to a sink [133].

PEGASIS has the following assumptions [134]:

- All nodes have global knowledge about the network, such as the topology of the network.
- The sink is static and far away from the sensor nodes.
- This protocol does not update users with the regular information about the network. This means that this protocol cannot be applied to periodically collecting data based applications.
- Sensor nodes are static.
- All nodes have the same level of energy.

Advantages:

- Solves the implosion and overlap problems.
- Uses data diffusion to reduce redundant data very efficiently by performing data aggregation.
- Improves the bandwidth of the data transmission.
- Very robust protocol.
- Outperforms LEACH by eliminating the overhead of cluster formation and minimizing the distance for data delivering from source nodes to a sink.

Disadvantages:

- Has hotspot related problems, nodes on the route to the sink could consume their energy faster than others.
- Not a scalable protocol.
- The PEGASIS protocol does not consider cross layer information.
- Mobile nodes are not supported.
- This protocol does not update users with the regular information about the network. This means that this protocol cannot be applied to periodically collecting data based applications.
- Constructing nodes in a chain may introduce extra overheads which decreases the lifetime of the network. In addition, reliability for the data delivered is not offered. As a result, this protocol cannot be applied for applications where reliability and lifetime of the network are crucial.

2.3.7.3 Cluster Overlay Broadcast

COB [135] routing protocol has been designed based on a cluster cover of the network with a constant density of cluster leaders. The COB protocol discovers routes with a doubling radius broadcast on the overlay network of cluster leaders. The COB protocol can be maintained by the Least Cluster Change (LCC) [135]. This protocol has been designed mainly for Mobile Adhoc NETworks (MANETs), and based on this, it has been examined in the context of the AODV [136] routing protocol through simulations.

Advantages:

- The COB protocol has a time complexity that is linear in the shortest source-destination hop distance and a message complexity that is quadratic in the shortest source-destination distance.
- The COB protocol adapts optimally to the mobility of the nodes and has constant storage complexity in the nodes

Disadvantages:

- This protocol does not update users with the regular information about the network. This means that this protocol cannot be applied to periodically collecting data based applications.

- The COB protocol is mainly designed for MANET and hence cannot be applied for WSNs because of limited resources such as limited battery. In addition, no end to end reliability for data delivered is offered. This shows that the COB protocol cannot be applied for the applications given in this work when reliability and energy saving are the biggest issues.

2.3.7.4 MEVI

The MEVI protocol [137] was designed for Wireless Video Sensor Network (WVSN) applications that send real-time videos in case of an event occurrence, e.g., temperature higher than 60 °C. Thus, it is possible to avoid false-positive alarms and show the real impact of the event in the target environment. This protocol is suitable for fire detection in forest areas and smart cities [137]. The MEVI protocol relies on a hierarchical network architecture with heterogeneous nodes to reduce the overall communication overhead, maximize the network lifetime, and improve scalability and reliability. The nodes have heterogeneous capabilities and are divided into the following classes: (i) non-multimedia-aware nodes, restricted in terms of energy supply, processing and memory; and (ii) multi media aware powerful nodes, equipped with solar energy source, video camera and higher memory and processing capabilities.

CHs in the MEVI protocol are used to transmit and receive packets both inside and outside of the cluster, and to perform complex tasks. On the other hand, non-CHs are used for simple tasks, such as detecting scalar physical measurements. A cross layer information based on network conditions such as remaining energy, Receiver Signal Strength Indicator (RSSI) and locations are considered when data is delivered from source nodes to a sink over multi hop communication. This means that reliable routes for transmitting data can be selected and hence the reliability can be optimized [23].

Advantages:

- Uses data diffusion techniques to reduce redundant data very efficiently by performing data aggregation at different levels in the network.
- Improves the bandwidth of the data transmission
- Cross layer information based on network conditions are considered when data is transmitted.
- Cluster head are selected based on the remaining energy and then based on this, the lifetime of the network is extended.
- Good scalability and robustness.
- Can be applied to time critical based applications as it has a short latency.

- Improves the bandwidth of the data transmission.
- Good scalability and robustness.
- Multimedia transmission is supported.

Disadvantages:

- This protocol does not update users with a regular information about the network. This means that this protocol cannot be applied to periodically collecting data based applications.
- Nodes have different capabilities such as powerful camera video (CHs) and normal scalar (members) nodes. Based on this feature, the MEVI protocol cannot be applied to the applications given in this research when all nodes are assumed to have the same capabilities.

2.3.7.5 TEEN

Threshold Sensitive Energy Efficient protocol (TEEN) [138] is a hierarchical routing protocol that is designed for time critical applications in WSNs. Nodes in the TEEN protocol sense the medium continuously, and then use the sensed attribute values to decide when data needs to be to transmitted. The TEEN protocol uses two data threshold values, called Soft Threshold (ST) and Hard Threshold (HT). The ST is used to force a node to send its data when the change happened to the most recent sensed data is equal to this value. However, the HT is used to force a node to send its data when current sensed data is equal to this value.

The TEEN protocol forms several groups of sensor nodes; each group is controlled by a cluster head as in the LEACH protocol [130]. However, nodes in the TEEN protocol deliver data over multi-hop communication between source nodes and a sink, compared to LEACH where data is delivered using a single hop communication [130].

The TEEN protocol outperforms the LEACH protocol in that it can be used for time critical applications and the lifetime of the network can be extended using data thresholds. However, it is not suitable protocol to be used for applications which need to collect data periodically, because the data may not reach the sink if the threshold is not reached. This means users cannot be updated with information about the network periodically. When the threshold value is reached, nodes will start to transmit their sensed data. So a node will transmit its data when one of the following factors is true: (1) the current value of sensed attribute is bigger than the hard threshold, (2) the current value of the sensed attribute is different from the last sensed value by the given soft threshold value. These threshold values are set based on the requirement of the target applications [139].

Advantages:

- Solves the implosion and overlap problems
- Uses data diffusion to reduce redundant data very efficiently by performing data aggregation at different levels in the network.
- Improves the bandwidth of the data transmission
- Good scalability and robustness
- Can be applied to the time critical based applications as it has low latency.
- Extends the lifetime of the network by distributing energy usage between nodes in the network.
- Data is transmitted based on the given data threshold values, this conserves energy and extends the lifetime of the network.

Disadvantages:

- Cannot be used for periodically collecting data based applications. Thus, it is not suitable protocol to be used for the applications given in this research when this is required.

2.3.7.6 APTEEN

Adaptive Threshold Sensitive Energy Efficient protocol (APTEEN) [66] is a hybrid routing protocol that aims to improve the TEEN protocol so that it can be used for periodically data collected based applications. The APTEEN protocol allows sensors to sense data periodically and react to any sudden change in the sensed attribute values by reporting these values to CHs. The APTEEN protocol follows the same techniques as in TEEN for data transmission between sensor nodes and a sink. However, in the APTEEN protocol, the following parameters are broadcast among nodes for the data transmission [7].

1. *Attribute (A):* This is a physical parameter which the user is interested in and is collecting data about. For instance, collecting the temperature of a part of the environment and then sending it back to a sink, in order to make the required decision. Users can define different attributes to collect different parameters from the target environment.
2. *Hard Threshold (HT):* Nodes need to be forced to transmit data when the current sensed attribute is bigger than this value. In this case, nodes only need to transmit data when sensed data has become greater than *HT*, otherwise data is ignored thereby conserving energy.

3. *Soft Threshold (ST):* This value represents the small change that forces nodes to transmit their sensed data.

4. *Counter Time (CT):* When nodes do not send data during this time period, then nodes are forced to send their data anyway. It is the time between two successive reports sent by nodes. It can be a multiple of frames. This parameter allows nodes to share the connection even when they do not have data to be transmitted.

When sensed data from nodes satisfy the given data thresholds as described above, then packets are forwarded to the network layer, otherwise, data needs to be discarded. In this case, only packets with data satisfying the data threshold values are forwarded and transmitted. Hence, the number of transmissions is reduced and both energy consumption and collision are minimized.

If nodes do not transmit their data, because the data does not satisfy the threshold values for a long time, then the APTEEN protocol forces these nodes to transmit their data using *CT*. A *CT* is a period of time during which nodes need to send their data. This means that the user can update *CT* according to the requirement of the proposed applications. As a result, HT, ST and CT thresholds can be updated according to the requirements of the target applications using APTEEN [7].

Advantages:

- Solves the implosion and overlap problems.
- Uses data diffusion to reduce redundant data very efficiently by performing data aggregation at different levels in the network.
- Improves the bandwidth of the data transmission.
- Energy can be conserved and lifetime of the network can be extended by distributing the load of the energy between nodes in the network.
- Good scalability and robustness.
- This protocol can be used for critical and non critical delivered data related applications by using different data thresholds. This allows users to choose data thresholds according to the requirements of the proposed applications.
- Multi-hop communication is considered in the APTEEN protocol and data is delivered based on the strength of the RSSI.
- The APTEEN protocol can be applied for the applications given in this research with some modification such as designing mobility. As a result, the APTEEN protocol is modified by supporting mobile nodes in this research.

Disadvantages:

1. Extra overhead from multi level cluster head selecting related operations.
2. Efficient techniques need to be designed for handling different queries and aggregation related techniques.
3. Extra overhead may raised when designing CT, HT and ST thresholds.
4. Mobile nodes are not supported.
5. Multi hop communication is considered in the APTEEN protocol and data is delivered based on the strength of the RSSI. However, using only the RSSI metric is not good enough to select the reliable routes for delivering data over multi hop communication using WSNs.

   As a result, the APTEEN protocol needs to be modified by supporting mobile node and taking all of nodes' remaining energy, location and RSSI into account when delivering data over multi hop communication using WSNs.

2.4 Conclusion and Research Contributions

Due to the challenges involved in designing different applications using WSNs such as resource limitations and the nature of wireless communication, the design of MAC and routing protocols for such applications has been an exciting topic in recent days. As previously mentioned, energy aware and critical data delivered related applications were considered in this research. It was crucial that energy saving, delay and reliability were all considered at the same time in these applications. Examples of the proposed applications in this work are: healthcare, forest fire detection, flood detection and multimedia related applications.

Based on the advantages and disadvantages of the MAC and routing protocols discussed and evaluated in Sections 2.2 and 2.3, it has been concluded that there is no single protocol which is perfectly suited for use with all the applications looked at in this thesis. This is because of the challenges associated with designing such applications. However, based on the performance criteria for the applications given in this work, schedule based MAC protocols were preferred over both contention and hybrid based MAC protocols. This is because reliability can be improved for all applications looked at in this research as collision is avoided in schedule based MAC protocols using TDMA schedules.

In addition, cluster based routing protocols were preferred over all other routing protocols as both energy and delay for data delivered were reduced by distributing energy usage and reducing the number of uncritical data transmissions.

It is also evident from analysing the work discussed above that multi hop communication together with cross layer information based on network conditions are both required to enhance performance [140]. Cluster based routing protocols and TDMA based MAC protocols can be combined where the selection of cluster head is based on the nodes remaining energy. In addition, data can be transmitted based on data thresholds and different routing metrics [66]. This will extend the lifetime of the entire network and reduce collisions with data from other nodes in the network. Such protocols may successfully improve the overall network performance while minimizing the energy consumption for different applications. Furthermore, the lifetime of the network must be measured based on realistic scenarios.

However, as shown above, current protocols do not take into account all of these important design aspects in order to increase the capability of WSNs for different applications where different requirements can be met. Therefore, it is essential to design a flexible communication protocol using cross-layer techniques which melds common protocol layer functionalities into cross-layer module resource constrained sensor nodes in order to deliver data using the best available paths. This can significantly improve energy conservation for information dissemination in WSNs.

Based on the evaluation and discussion of the MAC and routing protocols given in this section, GinMAC and APTEEN protocols with some modifications were selected to be suitable protocols in this work. This selection was due to the following:

1. GinMAC as a MAC protocol was selected as a most suitable protocol in this work. This is because it was designed to deliver data with a high reliability while consuming less energy than its rivals. This is due to the fact that GinMAC uses a static TDMA schedule based on the topology of the network in order to avoid collisions and save energy. However, GinMAC's scalability reduces when a high number of nodes are involved in the network. This can be improved by designing an efficient routing protocol to increase the scalability of the GinMAC when the number of nodes is high.

2. APTEEN was selected as routing protocol in this work as it is a cluster based protocol designed to save energy by distributing energy usage across nodes. In addition, both energy usage and delay were minimised by reducing the number of unnecessary transmissions based on different data thresholds. However, this protocol cannot provide high reliability unless it is used with an efficient MAC protocol.

3. In both GinMAC and APTEEN, as originally specified, only RSSI as a metric was considered when choosing the best available path. However, this is not enough to guarantee a reliable path to deliver the data. Based on this, it is crucial to consider more routing metrics based on network conditions. Furthermore, both protocols do not support mobile nodes and so they need to be modified to support mobile nodes where required, such as

in healthcare applications. As a result, the work presented in this thesis aims to modify GinMAC and APTEEN protocols to support mobile nodes when required.

All of this led us to the conclusion that a new cross layer protocol based on modified APTEEN and GinMAC protocols could be designed, taking into account actual network conditions. Hence this thesis makes the following two contributions to the body of knowledge in this field:

1. Improve the capability of WSNs by modifying the GinMAC and APTEEN protocols to support mobile nodes without affecting their performance in terms of reliability, delay and the lifetime of the network.
2. Design a new cross layer protocol based on the modified GinMAC and APTEEN protocols to increase performance in different applications. In these applications multimedia or scalar data is transmitted over multi hop communication.

Chapter 3

Proposed MAC and Routing Protocols Using WSNs

This chapter outlines the implementation of the GinMAC, APTEEN and cross layer protocols based on their specifications [65], [66]. These protocols were selected in Chapter 2 based on their suitability for the proposed applications given in this research. However, it was shown that both the GinMAC and APTEEN protocols needed to be modified to add new features which will improve their relevance to applications which require mobility. It is crucial that the lifetime of the network, delay and reliability of the data delivered were considered in such protocols. The Castalia simulator was used in this research because it is able to simulate different protocols using WSNs based on real applications [67]. More details about the Castalia simulator, its features and modules are given in Chapter 5.

As shown in Chapter 2 neither the GinMAC nor APTEEN protocols support mobile nodes and hence cannot be used for applications, such as healthcare applications, where mobile nodes are involved. In addition, it was shown that these two protocols can be combined, taking cross layer information based on network conditions into account, in order to optimize performance for the proposed applications given in this thesis. As a result, the first original contribution this thesis makes is modifying the APTEEN and GinMAC protocols by supporting mobile nodes for different applications such as healthcare related applications. The second contribution is designing a cross layer protocol based on the modified GinMAC and APTEEN protocols to improve WSNs for different applications by increasing energy saving and improving reliability of data delivered. This protocol considers cross layer information based on network conditions for delivering data from source nodes to a sink.

The GinMAC protocol implementation including the proposed mobility module is given in Section 3.1. The APTEEN protocol and its implementation including a mobility module is described in Section 3.2. A cross layer protocol based on the modified APTEEN and GinMAC protocols is designed and its implementation is presented in Section 3.3.

3.1 A GinMAC Implementation

It has been concluded in this research that GinMAC is a possible MAC protocol for use in the proposed applications, where reliability, energy saving and delay can be guaranteed [65]. Challenges and requirements that need to be considered before designing any MAC protocols for such applications have been described [68]. The implementation of GinMAC including a mobility management module is described in this section.

3.1.1 An Overview of the GinMAC Protocol

GinMAC [102] is a TDMA based MAC protocol, so energy saving and reliability with bounded delay can be achieved. However, an efficient synchronization and slot allocation algorithm needs to be designed in order to allocate the required time slot for each node in the network so that the radio of the nodes be turned on only at the allocated time. In this case, each node needs enough time slots to transmit data to a sink, including control messages, such as messages for time slots allocation, mobility and topology control related messages. The published GinMAC protocol [102] does not support mobility while the modified GinMAC protocol does.

The GinMAC protocol uses three different features to deal with data transmission: Offline Dimensioning, exclusive TDMA and delay confirm reliability control [65]. Offline Dimensioning is used to divide the frames into three slots, which are basic, additional, and unused slots. The basic slot is used for forwarding one message to the sink within a frame size F. The GinMAC protocol [102] has been modified in Section 3.1.5 to add new features to improve its applicability to applications which require mobility, such as healthcare applications. Topology management, time synchronization and the proposed mobility module for GinMAC in this implementation are described below.

3.1.2 Slot Allocations in GinMAC

GinMAC assumes that data is forwarded hop by hop to a sink using a tree based topology, consisting of *n* nodes [68]. Time in GinMAC is divided into a fixed length called *Epoch E*. Each E is subdivided by *n**k time slots so that each node allocates *k* slots for transmitting data to its parent until it reaches a sink. Each node is then assigned *k* exclusive slots with four different types. Basic slots are denoted by (*TX, RX*) and used for transmitting and receiving data, additional slots are denoted by (*RTX, RRX*). A broadcast slot is denoted by (*BROD*) and unused slots are denoted by (*U*) and used for saving energy (if any).

Additional slots are used only for re-transmission to achieve the required reliability of the target applications. These slots are used even when no data is available for transmission [65]. Unused slots are used for saving energy when data cannot be delivered using basic and additional slots. This implementation of the GinMAC protocol does not contain unused slots, but they may be used in the future for increasing the lifetime of the network. Broadcasting slots are used for topology control. Slots for each node need to be allocated according to the defined topology so that the required performance can be achieved.

3.1.3 GinMAC Topology Control Management

GinMAC is a tree based WSN topology so that each node transmits its data to a sink in its allocated slots and sleeps for the rest of the time. The current static topology that is proposed [65] is a WSN with a small number of nodes with static slot allocation. Each node has enough time slots to transmit all its own data as well as data from its children, including control messages to a sink.

The modified GinMAC protocol supports mobility between nodes in the network and this will require the design of new topology control and management algorithms to provide connectivity between static and mobile nodes in the network. It is assumed that the BS has adequate power to reach all nodes in the network using down-link slots. However, the sensor nodes cannot always do this because of their limited power supply.

A node being added to the network must first identify the slots during which it must become active, before it can transmit or receive data. After a node is switched on, it must first ensure time synchronization with the rest of the nodes in the network. Both control and data messages transmitted in the network can be used to obtain time synchronization. The node listens continuously in order to overhear a packet from the sink. Once it has overheard, the node knows when the GinMAC frame starts as each message carries information about the slot in which it was transmitted.

As a next step, the node must find its position in the topology which must stay within the defined topology envelope. In order to do this, the new node listens for packets in all slots. Transmitted data packets from a sink include a header field in which a node that is ready for transmission can find its information to deal with data transmission. This information is used to specify when nodes need to start and stop data transmission to their parents.

Based on the published GinMAC [65], a node may be configured with a list of valid nodes or parents that it is allowed to attach to when mobility is supported. This might be necessary to ensure that a node will only attempt to join the network using links that are known to be good. This is determined by measurements taken before the deployment to increase performance, taking into account the requirements of the target applications.

3.1.4 Synchronization Messages for GinMAC

At the start of each frame, the sink needs to broadcast a synchronization packet which is denoted as *SYNCH* into the network. This packet holds the start time, end time and slot numbers for each node in the network. When nodes receive a SYNCH packet from the network, they will extract their information from the SYNCH packet and then discard it. In this case, CSMA is used by the sink to synchronize nodes in the network and nodes use TDMA to transmit their data to their parents. After nodes receive their slot information from the sink, they need to ask data transmission permission from their parents.

After a node uses its allocated slots, it can go to sleep and wake up at the same time in the next frame. Each node in this case will access the channel using its unique slot time. This will avoid any chance of collision with data transmissions from other nodes in the network. As a result, the GinMAC protocol lets nodes and their parents be active at the same time so that data can be transmitted between them. A new synchronization algorithm has been designed to deliver packets with the required performance for the proposed applications.

The core idea behind this GinMAC implementation is to let nodes sleep as much as possible without affecting the reliability of the data delivered and required delay. The static topology is designed to let nodes have enough slots to transmit their data and to sleep during the rest of the frame. The slot allocation and synchronization for the GinMAC protocol can be found in Figure 3.1.

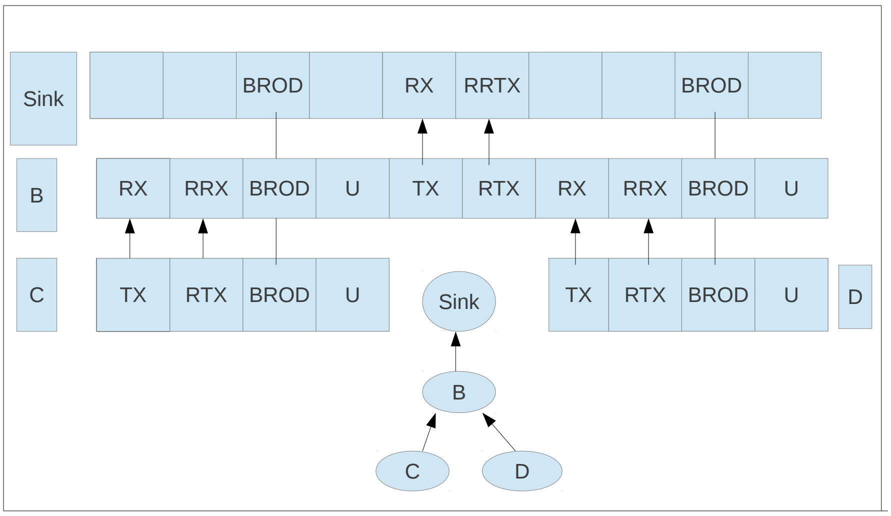

Figure 3.1: Slot Allocations and Synchronizations using the GinMAC Protocol

3.1.5 Mobility Module Using GinMAC

A new challenge is posed when mobility needs to be considered in a WSN. In this case topology control, resource management and performance control need to be designed to provide good connectivity between static and mobile nodes in the network so that the required performance can be provided. Mobility and topology control modules for critical data related applications using WSNs however described [6], [141], [142]. The proposed mobility management module in the GinMAC protocol given in this section uses the same messages as in the above literatures but using different concepts for move detection between mobile and static nodes. The difference is in the way that TDMA schedules between static and mobile nodes based on different attachments using GinMAC are updated when topology of the network is changed. The mobility module for the GinMAC protocol is defined by the algorithm 3.1.1.

3.1.5.1 Mobility Management Module for GinMAC

There may be cases when moving from one location to another in the network affects the connectivity of the network and then re-configuration algorithms are needed. In order to support mobility for the proposed applications, control messages which need to be transferred between static and mobile nodes to find a better attachment have been defined. Some of the possible control messages are (*ADV*), join (*JOIN*), and join acknowledgement(*JOIN ACK*) messages. Static nodes are formed into *Clusters*. When nodes in a cluster (non-mobile nodes) switch on their radios, they need to send ADV messages to the network and then wait.

When mobile nodes receive ADV messages they will ask to join the network. When a static node receives JOIN messages from the mobile nodes they will send back a JOIN ACK message to let the mobile node know that its request to join has been accepted. Through using these control messages, connectivity between mobile nodes and cluster nodes will be established. Non cluster head using the GinMAC protocol are allowed to be mobile and all other nodes are part of a fixed cluster.

Mobile nodes may have more than one cluster (parent) they could join, so they have to decide which cluster will be selected for transferring data to their parents. In this GinMAC implementation, the cluster with maximum Receiver Signal Strength Indicator (RSSI) is considered to be the best one for the new attachment. CNs send ADV including available positions over time and when mobile nodes receive ADV, they compare the RSSI from their current parents to the received RSSI from the new ADV messages. In the case that a new cluster has a better RSSI, mobile nodes need to leave their existing parents and attach to this new cluster which is included in the most recently received ADV message. When a new attachment is selected then a join request needs to be sent to that cluster. Upon receiving the JOIN request from a mobile node, JOIN ACK needs to be sent by the selected clusters.

Slots allocated for mobile nodes must be updated according to the new attachments. Mobile nodes need to release the first tree position after it is attached to the second tree address. So in this case slots allocated for the new clusters need to be increased and slots allocated for the old clusters need to be decreased. A new algorithm for updating slots is needed to balance the allocated slots for nodes in the network according to the different attachments. A new algorithm has, therefore, been designed in this research to update channel allocation according to movements and changes in the topology of the network.

3.1.5.2 Move Detection in the GinMAC Protocol

There are some cases when nodes can move without being detected. For instance, clusters may be unaware of mobile nodes leaving and will then keep allocating space in the channel for those particular nodes. This will consume more energy and reduce the reliability of the network. There may also be cases when clusters are no longer available for attachment without letting mobile nodes know. Because of this, an additional two control messages for the mobility module in the proposed MAC protocol have been used, which are denoted by *KEEPALIVE* and *NODEALIVE*.

The *KEEPALIVE* control message is used by clusters to let their currently attached mobile nodes know that this cluster is still available. The *NODEALIVE* message is used by mobile nodes to let their attached clusters know that they are still available for attachment. Mobile nodes wait for a specific period of time to receive messages from the attached clusters and if they do not receive anything during that interval, a *NODEALIVE* message needs to be sent, to let a cluster know that they still want to use that cluster. If no reply is received then mobile nodes need to search for a new address to make a new attachment (see statements 1 and 2 in

Algorithm 3.1.1).

Algorithm 3.1.1: MOBILITY ALGORITHM(MN, CH)

```
comment: Move detection between Mobile Node (MN) and CH based on RSSI
if MN                                                              (1)
  then switch Message Type
    case ReceiveADV(CH) {
        CH1←MAX_RSSI(MN.oldCH,CH)
        if CH1≠MN.oldCH
          then { P←new JOIN()
                 send P to CH1 }
    }
    case ReceiveKeepAlive(CH) { P←new KeepAliveACK(CH)
                                send P to CH }
    case ReceiveNodeAliveACK(CH) { ACTIVE(CH)←TRUE
                                   Cancel TimeOut(CH) }
    case TimeOut(CH) { ACTIVE(CH)←FALSE
                       delete CH }
    case ReceiveJoinACK(CH) { P2←new ALIVE NODE(CH)
                              send P2 to CH
                              Active TimeOut(CH) }
  else if Cluster Head(CH)                                         (2)
  then switch Message Type
    case ReceiveJoin(MN)
      then { CH.members.add(MN)
             P1←new JOINACK(MN)
             send P1 to MN
             P2←new KEEPALIVE(MN)
             send P2 to MN
             Active TimeOut(MN) }
    case ReceiveNodeAlive(MN)
      then { P1←new NODEALIVEACK(MN)
             send P1 to MN }
    case ReceiveKEEPAliveACK(MN)
      then { ACTIVE(MN)←TRUE
             Cancel TimeOut(MN) }
    case TimeOut(MN)
      then { ACTIVE(MN)←FALSE
             delete MN }
```

3.2 An APTEEN Implementation

3.2.1 An Overview of the APTEEN Protocol

The GinMAC protocol given in Section 3.1 could not offer the required scalability for the proposed applications where a high number of nodes was considered [2], [4]. To address this, new routing protocols are crucial to be designed to increase performance for such applications where various scenarios are involved [3]. As a result, the APTEEN protocol is designed and its implementation is given in this section to offer the required routing and increase performance for the proposed applications considered in this research.

APTEEN [7] is a self-configuration and clustering based routing protocol which has been designed for WSNs. This protocol uses a cluster based technique to distribute energy usage between nodes over time (rounds), thereby conserving energy and reducing collisions. Nodes are joined into a set of different groups when they turn on their radios. Each group is called a *Cluster*. Nodes belonging to each cluster are monitored by the *CH*. CHs are assigned to have more power and energy than other nodes in order to deal with TDMA schedules creation and data aggregation. An example of the topology for cluster based routing protocols is given in Figure 3.2.

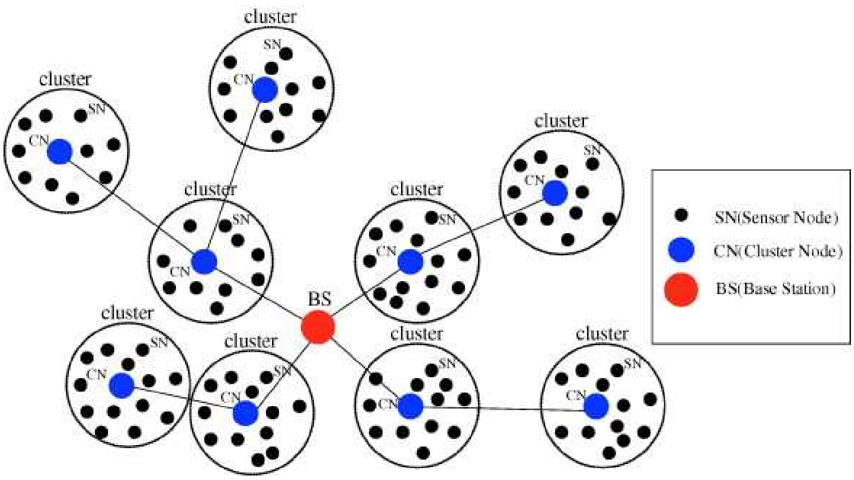

Figure 3.2: Cluster Based Topology [3]

Nodes are deployed and distributed at different levels in the network which are called low based and high based levels. Nodes at the high based levels send their data to a sink via a single hop communication. However, nodes at the low based levels send their data to their cluster head and then go to sleep to save energy and reduce collisions in the network. Cluster head receive and aggregate this data and send it back to higher level based cluster head until this data is delivered to a sink. Since different cluster head are selected in each round, then the chance of nodes dying quickly is low. Data aggregation using the APTEEN protocol needs to be designed according to the requirements of the target applications [7].

The APTEEN protocol lets nodes transmit their data only when the sensed data is in the range of interest, based on the given data thresholds. This will reduce the number of unnecessary transmissions and thereby allowing APTEEN to be used for critical and non-critical related applications. CHs are selected based on the probability that each node has not been selected for a period of time (a number of rounds). When cluster head are selected, they need to advertise themselves to the rest of the nodes in the network [1]. After the CHs advertisement, TDMA schedules are created and broadcast so that the required slots for members can be allocated. After cluster head are selected and TDMA schedules for members are allocated, nodes can transmit their data to their cluster head in which this data is aggregated and then send it back to a sink [10].

3.2.2 Details of the APTEEN Protocol

The operations of the APTEEN protocol are divided into *rounds*, where each round starts with three different phases which are *set-up*,*route discovery* and *data transmission*. In the set-up phase, nodes organize themselves into different clusters, where each cluster needs to be monitored by a cluster head. This is followed by an advertisement phase where cluster head need to advertise themselves to the nodes in the network. Non-cluster head ask to join different clusters, based on the strength of the received signals.

In the route discovery phase, cluster head must find different routes for relaying data from members to a sink. In order to do this, a new algorithm needs to be implemented to select routes between CHs and a sink to take into account different situations. In the data transmission phase, nodes start to send data to their selected cluster head over single hop communication and then go to sleep to save energy. The APTEEN protocol needs to be scalable for different cluster based topologies, for instance single level and multiple levels cluster based topologies.

3.2.3 Cluster Head Selection

As mentioned before, APTEEN uses a Cluster Head selection technique used by LEACH [8], so that when each node turns on its radio, it needs to decide whether or not to become a cluster head in the current round. This decision is based on the suggested percentage of the nodes that needs to be selected as Cluster Head in the network and the number of previous rounds in which this node has not been selected as a cluster head. The selection of the node n to become a cluster head in the current round depends on the probability of a random real number between 0.0 and 1.0 which is denoted by (rn) and $T(n)$ as shown in (2.1). If rn is less than $T(n)$, then the node n is selected to be a cluster head in the current round.

3.2.4 Multi hops Clustering

The algorithm required for selecting routes over multi hops between different nodes in the network is not described in the APTEEN specifications [10], so many options were considered when this version of APTEEN was implemented.

Due to the dynamic nature of the link in WSNs, various link quality estimation metrics, such as RSSI and Expected Transmission Count (ETC), have been proposed to cope with the vagaries of the wireless channel [108], [143]. As a result, a new module was designed to discover routes (better links), taking multi hops between clusters heads and a sink into consideration. RSSI was considered, compared to ETC, in this module due to the fact that the ETC metric requires periodic probe messages to compute the delivery ratio in forward and reverse directions of a link. This means that ETC increases overhead in the network and decreases the lifetime of the network [109].

While the sink has global information about all nodes in the network, such as nodes remaining energy and locations, then in this implementation, the sink is given responsibility for dividing the deployed network into different levels. CHs close to the sink are selected as first level CHs and then these CHs send data to the sink via single hop communication, whereas nodes far away from the sink can be selected as low level CHs. Low level CHs in the network need to select higher level CHs to relay their data to a sink, based on RSSI as shown above. Since only CHs are involved in route selection, then energy consumption can be optimized, simply by forcing the rest of the nodes to go to sleep.

3.2.5 Threshold Values Implementation

The APTEEN protocol saves energy and reduces packet collisions from other nodes in the network by reducing the number of unnecessary transmissions, using pre-defined thresholds. These parameters need to be initialized according to the requirements of the proposed applications. As shown in section 2.3.7.6, after the selection of the Cluster Head, different parameters need to be broadcast in the network. Based on these parameters, the APTEEN protocol lets nodes transmit their data according to (3.1):

$$T(CT, HT, ST, SV, LSV) = \begin{cases} YES & \text{if } CT = 0 \\ YES & \text{if } SV \geq HT \\ YES & \text{if } SV - LSV \geq ST \\ NO & \text{otherwise} \end{cases} \tag{3.1}$$

Where *SV*, *LSV* are most recently and previous sensed values by nodes from the environment, respectively. When sensed data from nodes are satisfy the given thresholds as described above, then packets are forwarded to the network layer. However, if the data received does not satisfy the given thresholds, data needs to be discarded. In this case, only packets with data satisfying the data threshold values such as *HT* and *ST* are forwarded and transmitted. Hence, the number of transmissions is reduced and both energy consumption and collision are minimized.

If nodes do not transmit their data, because the data does not satisfy the threshold values for a long time, then the APTEEN protocol forces these nodes to transmit their data using *CT*.

3.2.6 A Modified TDMA Schedule

After selection, each cluster head needs to allocate different slots for their members using TDMA schedules, to let their members transmit data and handle queries in an efficient way. A sink creates and sends queries to different parts of the network and then nodes reply as soon as they have data matching the queries [66]. So, in some cases, nodes need to have different slots to deal with query and data transmissions. In addition, CHs must have their own slots for aggregating data and finding the required routes for delivering data.

Based on these requirements, a TDMA schedule using the APTEEN protocol is classified into five types of slots: slots for data transmission, slots for answering queries, slots for finding routes, slots for aggregating data and slots for mobility related issues as shown below. A sink should not ask nodes to answer queries at the same time as they are transmitting their own data [66]. In summary, a TDMA schedule using the APTEEN protocol consists of the following fields [10]:

1. **Member Slots:** Each cluster head creates a TDMA schedule for each member using *TX* and *QA* slots. The *TX* slots are used for transmitting data and *QA* slots are used for answering queries. Mobile members should have another slot for mobility control related issues such as move detection when some nodes are mobile.

2. **Aggregation Slots (AG):** Cluster Head use these slots to aggregate data from their members before forwarding this data to a sink.

3. **Route Discovery Slots (RD):** Cluster Head use these slots to discover routes between nodes when transmitting aggregated data from their members to a sink.

4. **TX Slots:** Cluster Head use these slots to transmit their own data to a sink.

In APTEEN, a sink is responsible for sending queries to the nodes in the network when they are not transmitting their own data. Therefore, Cluster Head create a TDMA schedule for each member so that each member has one slot (*TX*) for sending data and another slot (*QA*) for answering queries. When mobility is supported, mobile nodes need another slot for mobility related issues [10].

After the TDMA schedules are created, routes to deliver data from Cluster Head to a sink need to be discovered using the *RD* slots and then *AG* slots are used for aggregating data from members. The allocated TDMA schedules allow members from the different clusters to deal with data communication only in their allocated slots and then go to sleep during the rest of the frame. This saves energy and avoids collisions with data from other nodes in the network. When mobility is required, new algorithms need to be designed to update TDMA schedules according to new attachments. A sink is provided with unlimited power so it can reach all nodes in the network. Sensor nodes, however, have a limited amount of power so they need to reply to queries and send normal data in their allocated slots.

The APTEEN protocol supports three types of queries: *Historical*, *One time* and *Persistent*. A *Historical* query is mainly used for reporting and analysing the historical data about the environment where the WSN is deployed according to the data stored in a sink. A *One time* query is used for reporting and analysing data for a specific part of the network. A *Persistent* query is used to report and analyse data over a period of time[7]. By combining all these factors, a TDMA schedule using the APTEEN protocol can be created as shown in Figure 3.3.

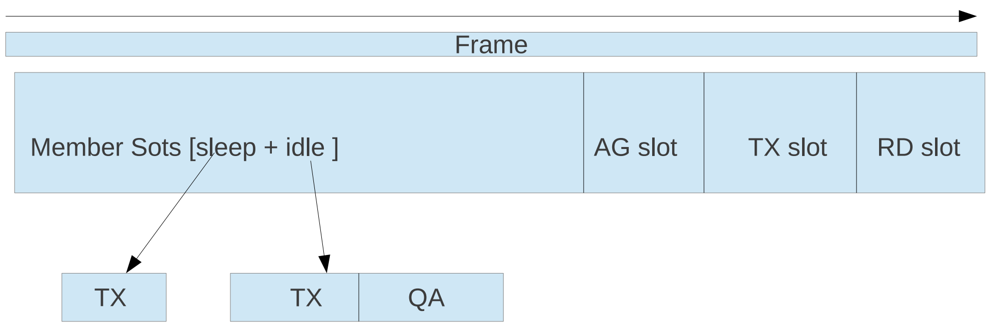

Figure 3.3: TDMA Schedule for APTEEN

3.2.7 Mobility Management Module in Cluster Based Routing Protocols

A new challenge is posed when mobility needs to be considered using the routing protocols in a WSN. In this case topology control, resource management and performance control need to be designed to provide good connectivity between static and mobile nodes in the network and when topology is changed so that the the required performance can be met. APTEEN design [66] does not support mobile nodes and, in order to address this, a new mobility module using the APTEEN protocol has been designed. This section outlines the proposed mobility module for the APTEEN protocol where mobile nodes are supported. This module is based on the mobility module given in Section 3.1.5, but a high number of mobile nodes is assumed to be involved.

3.2.7.1 Mobility Module Using APTEEN

Designing a new mobility module for the cluster based routing protocols is one of the most challenging issues in WSNs. Some mobility modules have already been implemented for the cluster based routing protocols, such as LEACH [8]. However, a mobility module for APTEEN has not yet been designed. To understand how the network behaves under different mobile situations, the node mobility using the APTEEN protocol has to be simulated in a realistic way. The mobility manager is responsible for enabling and controlling node mobility within the simulation area.

A new mobility module has then been designed to fully support mobile applications using the APTEEN protocol. As the APTEEN protocol is a cluster based routing protocol, it is assumed that only nodes belonging to each cluster are allowed to move, so members attach to a different cluster based on RSSI as in the GinMAC protocol.

There may be cases when moving mobile nodes from one cluster to another in the network affects the connectivity of the network and then re-configuration algorithms are needed to ensure the network remains well connected. In order to support mobility for proposed applications using APTEEN protocol different control messages have been defined. These need to be transferred between static and mobile nodes to find a better attachment. Some of the possible control messages are *ADV*, *JOIN*, and *JOIN ACK* messages as shown in Section 3.1.5.

The APTEEN mobility module is based on the mobility module given in the GinMAC protocol. The APTEEN protocol has been improved by adding the mobility module given in Section 3.1.5 so that mobile nodes are supported. Due to the number of nodes in APTEEN being much higher than in GinMAC, the percentage of mobile nodes in GinMAC protocol is too low compared to APTEEN protocol. Based on this feature, the APTEEN protocol is most suited to applications when a high number of mobile nodes is involved.

3.3 A Cross Layer Based Protocol

This section outlines the design of the proposed cross layer based protocol. This protocol combines the GinMAC and APTEEN implementations given in [65] and [10], respectively. A new algorithm has been designed to dynamically select the reliable routes for transmitting data to a sink, considering multi hops communication, cluster based topologies and cross layer mechanisms. More details about the cross layer based protocol and its implementation in this section are outlined below.

In order to minimize energy consumption and increase performance issues such as the reliability of data delivered, extensive research has been reported in the literature related to WSNs, when designing energy efficient protocols for each layer alone [144]. Regarding the MAC layer [68], the most common way to conserve energy consists of putting the transceiver and the processor of a sensor node into a low power, sleep state when it is not being used. As such, the energy wasted due to collisions, overhearing and idle listening is reduced. On the other hand, the network layer addresses the problem by proposing new routing solutions that take into account the sleep state of some nodes [10]. This can be achieved by distributing energy usage between nodes over time which increases the lifetime of the entire network.

However, the majority of proposed communication protocols in WSNs are developed for specific networking layers based on the traditional layered protocol architecture [145]. Such protocols may successfully improve some performance metrics for each specific layer in WSNs communication but they are not linked together to fully optimizing the overall network performance while minimizing the energy consumption for different applications. This is due to the fact that there is no an interaction between different layers that let nodes be active at the same time in order to deal with data transmission [146].

Thus, it is essential to design a flexible communication protocol using cross-layer techniques which melds common protocol layer functionalities into cross-layer module resource constrained sensor nodes. This can significantly improve energy conservation for information dissemination in WSNs [147]. Based on this, a new cross layer protocol based on MAC and routing protocols was designed in this work and its implementation is described in this section.

The cross layer based protocol involves two stages. The first stage starts by using the APTEEN protocol as a network layer, which extends the lifetime of the network by distributing energy usage between nodes using clustering capabilities. Hence this protocol drains energy slowly and uniformly among nodes, leading to the death of all nodes at a similar time. In addition, data is transmitted based on combining cross layer information from different layers in order to select the best routes for delivering data from source nodes to a sink. Section 3.3.5 defines algorithms in the cross layer based protocol which combine cross layer information for data transmission based on the RSSI, remaining energy and location. This lets nodes discover different routes based on various link related metrics to find the best path for data to be transmitted over multi hop communication and thereby increasing the reliability of the data delivered from source nodes to a sink. Furthermore, lifetime of the network increases where the selection of the cluster head is based on node's remaining energy compared to the APTEEN protocol where only a random number is considered. More details about the interaction between GinMAC and APTEEN in the cross layer protocol is given in Section 3.3.2.

The second stage of the cross layer based protocol involves using an algorithm to increase the rate of data delivery for different applications. This uses a retry limit of retransmissions over each wireless link according to its properties and the required packet delivery probability. Usually, the MAC layer retransmits a packet whose transmission was not successful up to *m* retries, where *m* is the same retry limit for all the wireless links. In each retry a sender waits for an acknowledgement from the next hop to make sure that a packet has been received. If there is no reply, then the same packet is retransmitted until either the packet is received or *m* retries are undertaken. In the same way, the next hop uses retry acknowledgements to let a sender know that a packet has been received in order to avoid redundant packets being sent. This algorithm increases the number of successfully delivered packets to a sink, thereby increasing the reliability of the data delivered using the cross layer protocol. More details about this algorithm is described in Section 3.3.3.

This protocol has the same structure and operations as in the APTEEN protocol with some modifications. This shows that this protocol is similar to the APTEEN protocol in most aspects, but new features have been added to increase its performance for different applications as shown below. More details about the cross layer protocol is outlined in the following sections.

3.3.1 An Overview of the Proposed Cross Layer Based Protocol

The cross layer based protocol is a self configured, multi hop clustering and cross layer based routing protocol which has been designed for WSNs. This protocol uses a cross layer related technique to distribute energy usage between nodes over time, which conserves energy and reduces collisions. The aim of designing this protocol is to increase performance of the proposed applications by considering the APTEEN and GinMAC protocols together to improve the capability of WSNs for such applications. The key idea behind the cross layer protocol is considering cross layer information based on network conditions for selecting reliable routes from source nodes to a sink.

Nodes are joined into a set of different groups when they turn on their radios. Nodes send their data to their CHs and then go to sleep to save energy. CHs receive and aggregate this data and send it back to higher cluster head until this data reaches a sink. Since CHs are selected based on their node's remaining energy, then the chance of nodes dying quickly is low compared to the APTEEN protocol when cluster head are selected based on a random number as shown in Section 3.2.

Data aggregation using the proposed cross layer based protocol needs to be designed according to the requirements of the proposed applications. Different types of transmissions are supported such as multimedia and normal transmissions. As a result, the cross layer based protocol can be used for multimedia related applications when multimedia transmission is required to deliver events from source nodes to a sink such as intruder related applications. This protocol lets nodes transmit their data only when the sensed data is in the range of interest, based on the given data thresholds. This will reduce the number of unnecessary transmissions and consequently allow the proposed protocol to be used for critical and non-critical related applications using WSNs.

After CHs are selected, they need to advertise themselves to the rest of the nodes in the network by sending ADVs including different information such as RSSI, remaining energy and location. Upon receiving ADVs messages nodes reply to different cluster head by sending back the JOIN message based on information included in the ADVs received from different CHs as shown in Figure 3.4.

Various link related metrics are considered when selecting cluster head for relaying data compared to the APTEEN protocol when only the RSSI is considered. This means that the most reliable routes are selected in the cross layer protocol based on network conditions [147]. In addition, the lifetime of the network is optimized when selecting CHs by considering remaining energy for nodes, compared to the APTEEN protocol when the selection of cluster head is based on a random number.

After the CHs advertisement, TDMA schedules are created and broadcast so that the required time slots for members can be allocated. After cluster head are selected and TDMA schedules for members are allocated, nodes can transmit their data to their cluster head using their allocated slots. This data will then be aggregated and sent back to a sink over multi hop communication. More details about the proposed cross layer protocol and its operations are outlined in the following sections.

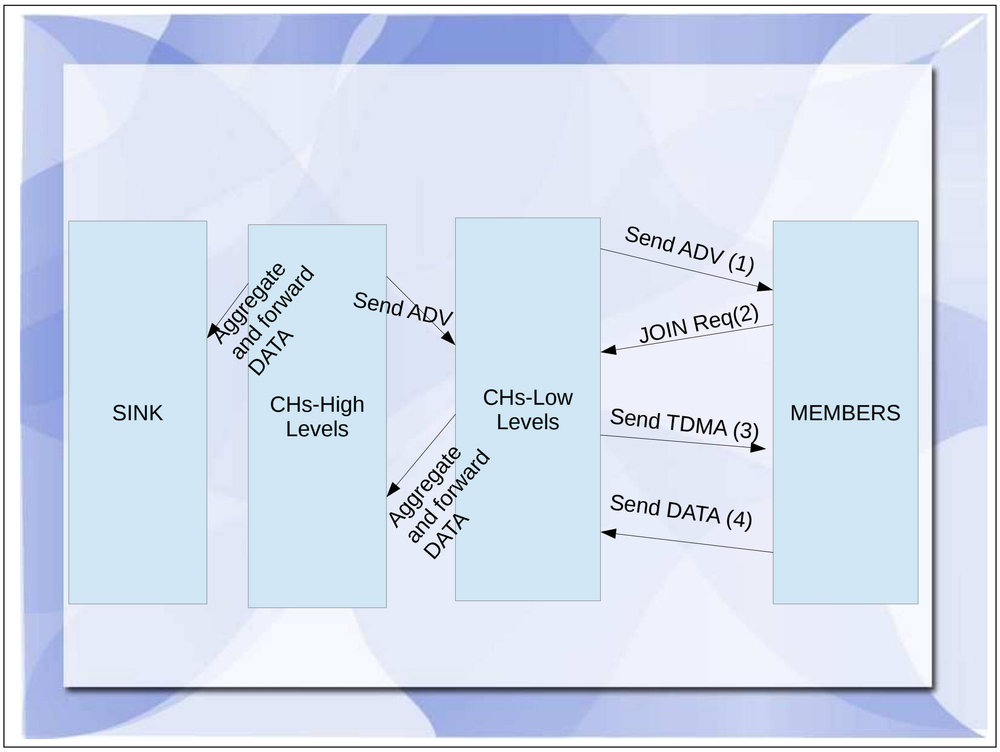

Figure 3.4: Setting-up Operations for the Proposed Protocol

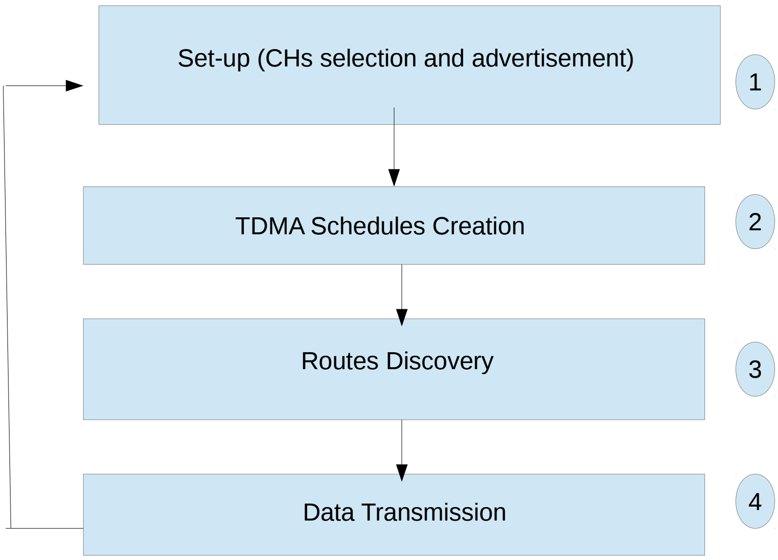

Figure 3.5: Protocol Operations

3.3.1.1 cluster head Selection

The cross layer based protocol uses technique for selecting cluster head which is used by the APTEEN protocol, which considers the node's remaining energy as shown below. When each node turns on its radio, it needs to decide whether or not to become a cluster head in the current round. This decision is based on the suggested percentage of the nodes that needs to be selected as cluster head in the network and the number of rounds that this node has not yet been selected as a cluster head. The selection of the node *n* to become a cluster head in the current round depends on (2.1).

One of the drawbacks of the algorithm used for selecting cluster head given in (2.1) is that the sink does not consider the node's remaining energy when they become cluster head. Hence nodes may be prone to die prematurely. To address this problem, a new approach (3.2) which considers remaining energy for nodes before they become cluster head was designed [148].

$$T(n)_{new} = \begin{cases} \frac{P}{1-P*(r \bmod \frac{1}{P})} * \frac{E\_cur}{E\_max} & \text{if } n \in G \\ 0 & \text{otherwise.} \end{cases} \tag{3.2}$$

Where E_cur, E_max are the current and an initial energy of the node *n*. This algorithm lets the sink select nodes with the maximum energy remaining to be cluster head in each round, thereby extending the lifetime of the network. The selection of cluster head in the proposed cross layer protocol is based on the method given in the equation 3.2.

3.3.1.2 A TDMA Schedule Allocation Algorithm

It has been assumed in the proposed cross layer based protocol that a sink creates and sends queries to different parts of the network and then nodes reply as soon as they have data matching the query. So in some cases, nodes need to have different slots to deal with queries and data transmissions at the same time [10] .

In addition, CHs need to have their own slots for finding routes and aggregating data. Based on these requirements, TDMA schedules for the proposed protocol are classified into five types of time slots: slots for data transmission, slots for answering queries, slots for finding routes, slots for aggregating data and slots to deal with multimedia related traffic (when required). A sink should not ask nodes to answer a query at the same time as they are transmitting their own data [66]. Therefore, a TDMA schedule using the cross layer based protocol consists of the following fields:

1. **Member Slots:** Each cluster head creates a TDMA schedule for each member using *TX,QA* slots. Each member is active only during its allocated slots. A TX slot is used for transmitting data while a QA slot is used for answering queries.

2. **Aggregation Slots (AG):** Cluster head use these slots to aggregate data from their members.

3. **Route Discovery Slots (RD):** Cluster head use these slots to discover routes between nodes when transmitting aggregated data from their members to a sink.

4. **TX Slots:** Cluster head use these slots to transmit their own data to a sink.

5. **Multimedia Slots** (MS): Cluster head use these slots to send data based on multimedia transmissions to a sink.

The allocated TDMA schedules allow members from different clusters to deal with data communication only in their allocated slots and then to go to sleep during the rest of the frame. This saves energy and avoids collisions from other nodes in the network. When mobility is considered, new algorithms need to be designed to update TDMA schedules according to different attachments. By combining all of these factors, a TDMA schedule for the cross layer protocol can be defined as shown in Figure 3.6.

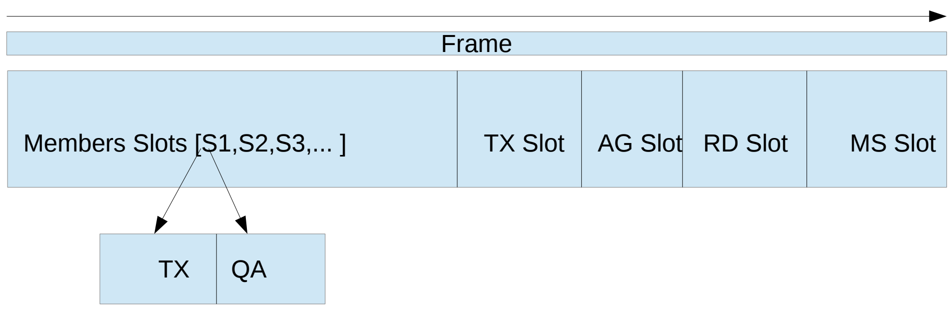

Figure 3.6: TDMA Schedule Structure

3.3.1.3 A Multi hop Clustering and Route Selection

The algorithm required for selecting routes over multi hop communication between different nodes in the network described in the specifications [7] has been modified. This modification includes considering the cross layer information based on network conditions such as RSSI, node's remaining energy and location for selecting routes for data transmission. To achieve this, a new module to select routes considering multi hop communication and different cross layer based information has been designed. This module considers the node's remaining energy, location and RSSI as routing metrics for selecting reliable routes to forward data to a sink.

While the sink has global information about all nodes in the network, such as their remaining energy and location, in this implementation, the sink is additionally made responsible for dividing the network into different levels. Nodes close to the sink are selected as *higher level based nodes*, which communicate with a sink via a single hop communication, whereas nodes far away from the sink are selected as *low level based nodes* as in the APTEEN protocol.

Nodes on the low level in the network must select higher level based nodes (reliable CHs) based on the information received from different CHs using ADV messages to deal with data transmission. It is assumed in all applications looked at in this thesis that sensors are able to find their locations using localization based algorithms [124]. ADV messages for different cluster head include node's remaining energy, distance (location) and RSSI for selecting reliable routes (CHs). Thus ADV and JOIN messages have to include additional fields to report this information. Since only cluster head are involved in the route selection, energy consumption and collision can be minimized, simply by forcing the rest of the nodes to go to sleep.

Route Selection Algorithms New algorithms such as those defined in 3.3.5 and 3.3.1 have been designed to select reliable routes for data transmission after the selection of the cluster head as shown in Figure 3.3. Nodes are classified into 3 different types in the proposed algorithms which are sink (SINK), CHs and Sensor Nodes (SN) as shown in the given algorithms. The proposed route selection algorithms provide valid routes between nodes such as cluster head and a sink, CHs themselves and CHs and members. Nodes check first if there are valid routes before sending data. Where no routes are available, then nodes ask for urgent routes from their neighbours in order to send their data as soon as possible.

$$R(n, CH1, CH2) = \begin{cases} MAX\_RSSI(CH1, CH2) & \text{if CH1.RSSI}\neq\text{CH2.RSSI} \\ MAX\_RE(CH1, CH2) & \text{if CH1.RE}\neq\text{CH2.RE} \\ MIN\_DIST(CH1, CH2) & \text{otherwise.} \end{cases} \tag{3.3}$$

Where CH1 and CH2 are two current available cluster head where node n must select the best one in terms of RSSI, remaining energy (RE) and location as shown in equation 3.3. This equation can easily be changed according to the requirements of the target applications.

3.3.1.4 Data Transmission

After CHs are selected and TDMA schedules for members are allocated, nodes can transmit their data to their cluster head using their allocated slots. This data is then aggregated and sent back to a sink. The cross layer protocol deals with data communication based on scalar data and multimedia related transmissions, compared to the APTEEN protocol where only scalar data is transmitted, when delivering information about the detected events from source nodes to a sink as shown below:

- Nodes which belong to different clusters (non-cluster head) sense the target environments and send their information back to their CHs via a single hop communication and then go to sleep.
- CHs then select a reliable route based on the algorithm given in 3.3.5 before data can be transmitted.
- CHs then aggregate this information and send it back to a sink over multi hop communication. Scalar or multimedia data is transmitted depending on the target applications.
- The sink then extracts this information and replies directly to source nodes which detect the events when needed.

Algorithm 3.3.1: NEXT HOP($N, CH1, CH2$)

---

comment: Finding next hop for node N

comment: RSSI:Receiver Strength Signal Indicator

comment: RE:Remaining Energy

comment: DIST:Distance from CHs to Sink

if CH1.RSSI≠CH2.RSSI
  then return (MAX_RSSI(CH1,CH2))
  else if CH1.RE≠CH2.RE
  then return (MAX_RE(CH1,CH2))
  else return (MIN(CH1,CH2))

Algorithm 3.3.2: MAX_RSSI($CH1, CH2$)

---

comment: RSSI:Receiver Strength Signal Indicator

if CH1.RSSI>CH2.RSSI
  then return (CH1)
  else return (CH2)

Algorithm 3.3.3: MAX_RE($CH1, CH2$)

---

comment: RE:Remaining Energy

if CH1.RE>CH2.RE
  then return (CH1)
  else return (CH2)

Algorithm 3.3.4: MIN_DIST($CH1, CH2$)

---

comment: LOC:Distance from CHs to Sink

comment: Sink (x1,y1): Location of the sink in the Network

comment: CH (x2,y2): Location of a CH in the Network

comment: $LOC = \sqrt{(x2 - x1)^2 + (y2 - y1)^2}$

if CH1.LOC<CH2.LOC
  then return (CH1)
  else return (CH2)

Algorithm 3.3.5: ROUTES DISCOVERY($N, CH[], grid, MaxHop$)

```
comment: Finding routes to deal with data communication for node N
comment: CH[]: is a set of CHs in the network in current round
comment: F is a flag to show if the level of CH is found or not
comment: d is a variable to divide the grid into different levels, d ∈ [0, maxHop]
comment: grid: size of the deployed network
comment: MaxHop: maximum hops
comment: SN: Sensor Node (Member)
if N is SINK
  then { for J ← 1 to CH[].SIZE
           do { F[J]←FALSE
                d[J]←0
                for I ← 1 to MaxHop and not F[J]
                  do { d[J]←d[J]+grid/MaxHop
                       if CH[I].distance≤d[J]
                         then { CH[I].level←I
                                F[J]←TRUE
                                if CH[I].level≠MaxHop
                                  { if CH[I].level == 1
                                    CH[I].nextHop←SINK
                                    P←new ADV(CH[I])
                                    Broadcast P
                       else
                         then d[J]←d[J]+grid/MaxHop
  else if N is Cluster Head (CH)
  then { if ReceiveADV(CH1,CH2)
           then CH.NextHop←NEXT HOP(CH,CH1,CH2)
  else if N is SN (Member)
  then { SN.NextHop←NEXT HOP(N,CH1,CH2)
```

3.3.2 An integration between GinMAC and APTEEN in the Proposed Cross Layer Protocol

The GinMAC implementation [4] has been modified so that it can be combined with the APTEEN implementation given in Section 3.2 to implement the cross layer protocol given in this section.

The GinMAC protocol is no longer responsible for selecting routes between nodes in the network. This means that GinMAC follows information given by the APTEEN protocol which is the network layer in the cross layer protocol. This is to confirm that data is delivered to the next hop over single hop communication. However the APTEEN protocol remains responsible for much of the operations that need to be undertaken in the cross layer protocol. These operations include selecting cluster head, finding available routes and providing the connection between mobile and static nodes.

Information based on network conditions such as RSSI, nodes remaining energy and locations are provided by different layers and are combined at the network layer to select a best link for delivering data. At the MAC layer, GinMAC accesses RSSI and nodes locations from the physical layer and nodes remaining energy from the resource manager and then passes this information back to APTEEN. At the network layer, APTEEN combines these pieces of information and then selects a best link and informs GinMAC which node is selected as a next hop to deliver data over single hop communication. At the MAC layer, GinMAC is then given the responsibility to confirm that a packet is delivered as illustrated in Section 3.3.3.

3.3.3 Reliable Transmission

Reliable data transmission between source nodes and a sink is one of the most important requirements for designing efficient protocols using WSNs. Different applications have different requirements in terms of reliability and consequently a lot of different protocols have been proposed to provide this. However, there are still problems with offering the required reliability for energy-ware and critical delivered data related applications using WSNs [149]. In addition, a further challenge is posed in terms of the reliability of the data delivered when mobile nodes are required.

In WSNs, critical applications, such as healthcare and forest fire related applications, information about events collected by the sensor nodes must be reliably delivered to the sink for successful monitoring of an environment. Therefore, given the nature of error prone wireless links, ensuring reliable transfer of data from resource constrained sensor nodes to the sink is one of the major challenges in WSNs [144]. A reliable transfer of data is achieved when the packet carrying event information arrives at the destination. In WSNs, reliability can be classified into different levels: Event reliability level and hop by hop or end to end reliability level.

Packet or event reliability is concerned with how much information is required to notify the sink of something happening in the target environment. Packet reliability requires all the packets carrying sensed data from all the sensor nodes in the network to be reliably transmitted to a sink. Packet reliability in terms of recovering the lost packets at the hop by hop or end to end level, can be achieved through the use of retransmissions and an acknowledgement [150].

This is simply the retransmission of the lost information which can either be performed on end to end or hop by hop basis.

End to end retransmission requires the source node that generated the packet to retransmit the lost information. Hop by hop retransmission allows the intermediate nodes to perform retransmission of lost information by caching it in their local buffers [151]. The GinMAC implementation [4] has been modified to implement reliable transmission using *ACK* and *SENT* packets over single hop communication.

3.3.4 A Mobility Module for the Cross Layer Protocol

The mobility module for the cross layer based protocol is based on the mobility module given in Algorithm 3.1.5. However, it has been optimized so that RSSI, nodes' remaining energy and locations are all considered when selecting new attachments, compared to mobility modules in the APTEEN and GinMAC protocols where only the RSSI is taken into account. An algorithm for the modified mobility module for the cross layer protocol is defined in 3.3.6. Move detection between mobile and static nodes is also involved in the proposed mobility module.

When mobile nodes receive new ADVs from different CHs then a better attachment needs to be selected (see statement 1 in Algorithm 3.3.6). In addition, mobile nodes need to detect if their CHs are still available for transmission (see statements 1 - 5 in Algorithm 3.3.6). CHs accept mobile nodes when they need to join different clusters and let their mobile nodes know that cluster is till available (see statements 6 - 9 in Algorithm 3.3.6). TDMA schedules for nodes are updated according to the different attachments and topology changes in the network.

Algorithm 3.3.6: MOBILITY ALGORITHM FOR THE CROSS LAYER PROTOCOL(MN, CH)

---

comment: Move detection between Mobile Node (MN) and different CHs

if MN
  then switch Message
- **case** ReceiveADV(newCH) { MN.NextHop←NEXTHOP(MN,currentCH,newCH) (1)
- **case** ReceiveKeepAlive(CH) { P←new KeepAliveACK(CH) (2); send P to CH }
- **case** ReceiveNodeAliveACK(CH) { ACTIVE(CH)←TRUE (3); Cancel TimeOut(CH) }
- **case** TimeOut(CH) { ACTIVE(CH)←FALSE (4); delete CH }
- **case** ReceiveJoinACK(CH) { P2←new ALIVE NODE(CH) (5); send P2 to CH; Active TimeOut(CH) }

  else if Cluster Head(CH)
  then switch Message
- **case** ReceiveJoin(MN) { CH.members.add(MN) (6); P1←new JOINACK(MN); send P1 to MN; P2←new KEEPALIVE(MN); send P2 to MN; Active TimeOut(MN) }
- **case** ReceiveNodeAlive(MN) { P1←new NODEALIVEACK(MN) (7); send P1 to MN }
- **case** ReceiveKEEPAliveACK(MN) { ACTIVE(MN)←TRUE (8); Cancel TimeOut(MN) }
- **case** TimeOut(MN) { ACTIVE(MN)←FALSE (9); delete MN }

In summary, the cross layer based protocol has the following features to improve the capability of WSNs for the proposed applications considered in this thesis:

- By sending queries over time to different parts of the network, users can gain a complete picture of the network, a feature which most of the recently cluster based routing protocols do not have.
- The cross layer based protocol can be used for critical and non-critical delivered data

related applications by using different thresholds. This allows users to select thresholds according to the requirements of the proposed applications.

- The cross layer based protocol supports mobile nodes when different attachments are selected based on network conditions.
- Energy can be conserved by distributing energy usage between nodes in the network.
- Delay can be reduced and energy can be conserved by aggregating and reducing redundant copies of data at the intermediate nodes in the network.
- Nodes in each cluster need only send their data to their cluster head over a single hop communication using their allocated slots, so the lifetime of the network is extended.
- As only cluster head nodes are involved with routing and forwarding data to a sink, the routing complexity in large WSNs is reduced.
- As only cluster head needs to aggregate data from their members thus energy consumption is reduced.
- Data is transmitted to a sink over multi hop communication based on different information about network condition. This information includes a Receiver Signal Strength Indicator (RSSI), node's remaining energy and location. This means that reliable routes for delivering data from source nodes to a sink can be selected.
- The cross layer protocol combines information from different layers such as MAC, Radio (e.g CC2420), physical (e.g IEEE 802.15.4) and routing layers for selecting reliable routes for data transmission from source nodes to a sink. As a result, performance can be optimized.
- Multimedia transmission is supported and only cluster head are involved with multimedia based transmissions.

Chapter 4

Protocol Validation

The APTEEN and GinMAC implementations given in Chapter 3 was validated by replicating and confirming the simulation scenarios and the published results that these two protocols are based on, before designing the required modifications. In order to do this, both the GinMAC and APTEEN protocols have been validated in the following sections, talking simulation scenarios and published results [65], [66] into account using the Castalia simulator. The validation of the GinMAC protocol, simulation scenarios and results are described in Section 4.1. The validation of the APTEEN protocol, simulation scenarios and results are presented in Section 4.2. More simulation results regarding the validation of the APTEEN and GinMAC protocols, talking different parameters into account, are given in Appendix C.

4.1 A GinMAC Validation

The GinMAC protocol is a part of the GINSENG project [65] which was designed to increase performance for automata control related applications using WSNs. GinMAC is a MAC protocol which is given a responsibility for delivering data from source nodes to a sink in order to optimize performance in such applications. The GinMAC protocol was designed to be used for WSN applications where a small number of nodes were involved.

It was concluded in Section 3.1 that the GinMAC protocol could be modified and used to improve WSNs for the healthcare application simulated in this thesis. To do this, the GinMAC protocol must be validated before the required improvements can be implemented. Therefore, this section validates the GinMAC implementation given in Chapter 3 using the published simulation scenarios, parameters and published results [68]. Energy saving, delay and reliability were considered when validating the GinMAC protocol where a small number of nodes and static TDMA schedules were involved. Details about the proposed application and simulation scenario are outlined in this section.

Table 4.1: Simulation Parameters (GinMAC Validation) [68]

Parameter	Value
MAC Protocol	GinMAC
Network Dimensions(in meters)	90 X 90
Distance Between pair of nodes	20 meters
Measurement Metrics	duty cycle, delay and reliability
Packet Rates (packet per seconds)	0.1,0.2,0.5 and 1
Battery Type	AA
Real Radio	CC2420

4.1.1 Simulation Scenarios and Parameters

The GinMAC protocol has been validated in terms of energy saving, reliability and delay in the delivery of data using WSNs with static nodes (mobile nodes are not supported in this case). The simulation scenarios [68] were considered in this section to validate the GinMAC implementation given in section 3.1. The Castalia simulator was used in this research because it is able to simulate different protocols using WSNs based on real applications [67]. More details about the Castalia simulator, its features and modules are given in Chapter 5.

The application requirements given in the following sections using different packet rates were considered for the GinMAC validation. Packet rate is defined as HZp = packet per seconds. As it can be seen from the graphs in the simulation results given below, *HZ1* means nodes send 1 packet in a second. *HZ0.5* means nodes send 1 packet per 2 seconds and so on. More details about the topology of the WSN, MAC protocol and other parameters can be found in Table 4.1.

4.1.2 Quality of Services for Validation and Performance Evaluation

A simple application where all nodes send data to a sink was simulated using different packet rates. Simulation results are given in this Section. The application simulated was healthcare related, where data needed to be collected from the bodies of patients and then sent back to a base station. The GinMAC protocol was simulated according to the specifications [65] with different packet rates as shown in each graph. This GinMAC implementation will be validated according to published results [68] in terms of reliability, energy saving and delay. These parameters will also be considered in the performance evaluation given in Chapter 5.

In order to make sure that this implementation follows the published specifications [65], it is expected that this implementation will offer a similar performance. As a result, the following features were required for validating the GinMAC protocol for the proposed healthcare application:

Reliability: The reliability of given protocols is defined as the ratio between total packets generated and sent by source nodes and total packets received by a sink or a final destination. So Reliability = (Received Packets/Sent Packets). The threshold value for reliability needs to be high enough to meet the requirements of the proposed application. When mobility is supported, this threshold may be reduced. Reliability required, therefore, is highly dependent on an application.

Energy Saving and Network Lifetime: Energy saving is one of the most important challenges which needs to be considered when designing WSNs for any applications. The energy consumption of a node depends on how long the node is active for transmitting and receiving data. Each node has a small battery with a limited power which cannot be recharged very often. This means the energy consumed by nodes needs to be reduced in order to extend the lifetime of the entire network.

The lifetime of a network is the maximum period that a WSN can survive, whilst spending energy at a given rate. Let total energy consumed by each node be denoted by C Joules, initial energy be denoted by *E* Joules and current simulation time by *T* seconds. The lifetime of each node in the network using given protocols has been calculated as follows:

$$Lifetime(n) = ((E/C) * T). \tag{4.1}$$

A lifetime for the network as a whole must be calculated based on the lifetime of the nodes in the network. However, it is not possible to have a lifetime metric which is perfect for all applications using WSNs. The required performance of any WSN is application dependent and hence the lifetime of the network must be defined according to the requirement of the target application. However, in order to have a realistic metric which can be used as a basis for comparison across a number of applications it is proposed that the average energy to all nodes is considered. So, for the purpose of these comparisons, the lifetime of the entire network is defined as the average lifetime of all nodes in the network, as given in (4.2).

$$Lifetime\_network(AVG(All)) = \frac{\sum_{i=1}^{k} Lifetime\_node(i)}{k} \tag{4.2}$$

Where *k* is the number of nodes in the network.

Delay Calculation: Delay is defined as the time that it takes for a packet to be received at its final destination after it has been sent from its source node. Delay in WSN based applications needs to be measured so that all data packets are delivered within a bounded delay. Each packet that is delivered after this delay is considered to be lost and is then ignored. Delay for the end to end data delivered using WSNs in this research has been calculated using histogram graphs where the y-axis records the number of packets delivered to a sink and the x-axis illustrates different ranges of latency where these packets are delivered [67].

4.1.3 Simulation Results for GinMAC Validation

Packet Delivery and Reliability: The published simulation results [68] show that the implementation of the GinMAC protocol [65] delivers all data to a sink with 100% reliability. As shown in Figure 4.1, GinMAC delivers all data to a sink with 99.7% - 100% reliability at various transmission rates. This shows that the GinMAC protocol performs similar to the published results in term of reliability of data delivered. As a result, the GinMAC protocol is validated in terms of reliability of the data delivered from source nodes to a sink.

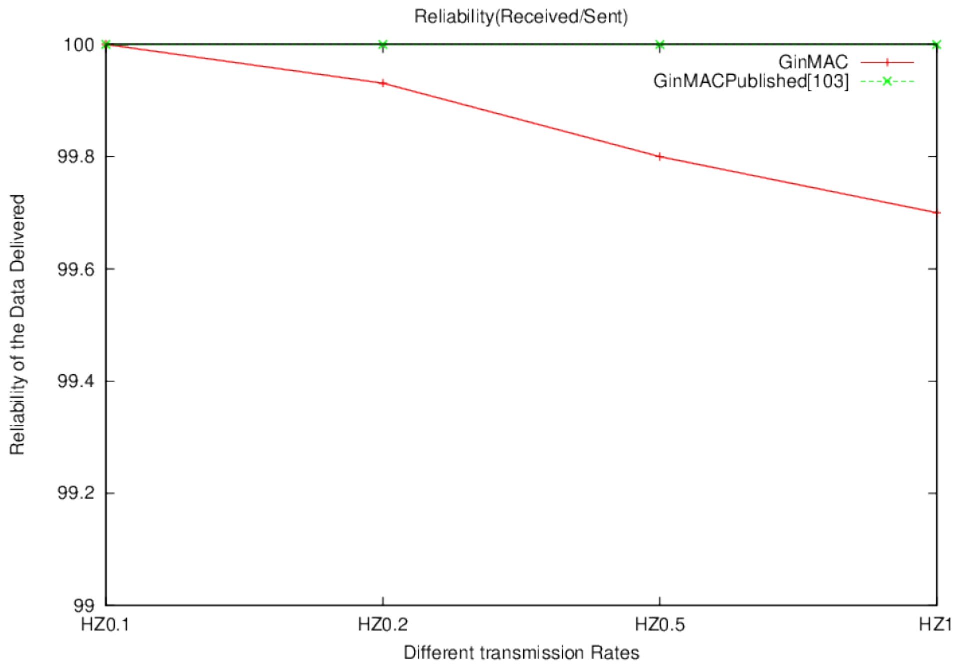

Figure 4.1: Reliability of Data Delivered using the GinMAC Protocol (Validation)

Energy Saving and Network Lifetime: The published simulation results [68] show the performance of the GinMAC protocol according to the specifications [65] in terms of energy saving. In the published GinMAC, energy is consumed based on the allocated TDMA slots so that data can be delivered using a single frame. This shows that GinMAC duty cycle is allocated based on the topology of the network.

Based on the published results [68] and Figure 4.2, nodes in this GinMAC implementation consume energy in the similar way to the published results using their TDMA allocated slots based on the topology of the network.

In addition as shown in Figures 4.2 and 4.3, it can be seen that nodes at different levels in the tree topology of the simulated scenario, as shown in Figure 4.4, consume energy according to their levels in the network. For instance, nodes at low levels consume less energy than nodes at high levels. This is because nodes at high levels need more time slots than nodes at low levels in order to transmit their own data to a sink as well as data from their children. This means that both implementations consumed energy based on time slots allocated for each node using static TDMA schedules. This leads us to the conclusion that nodes consume their energy in a similar way in both implementations. As a result, GinMAC is validated and it is ready to be modified according the modifications given in Chapter 2.

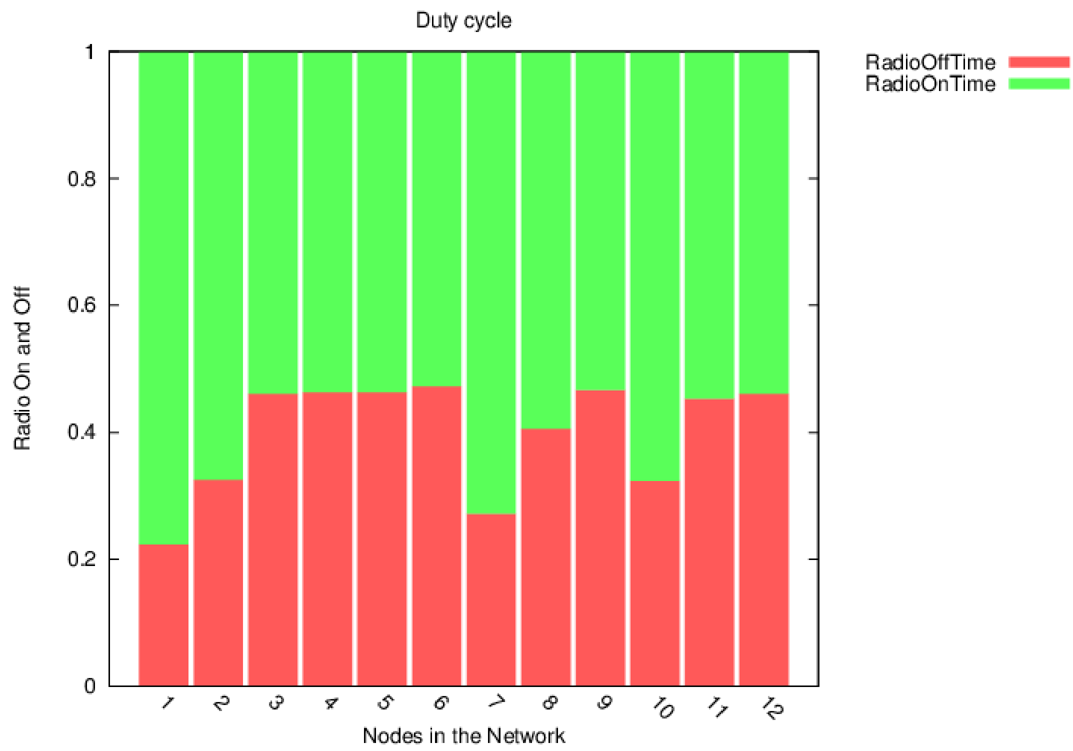

Figure 4.2: Energy Consumption using the GinMAC Protocol (Validation)

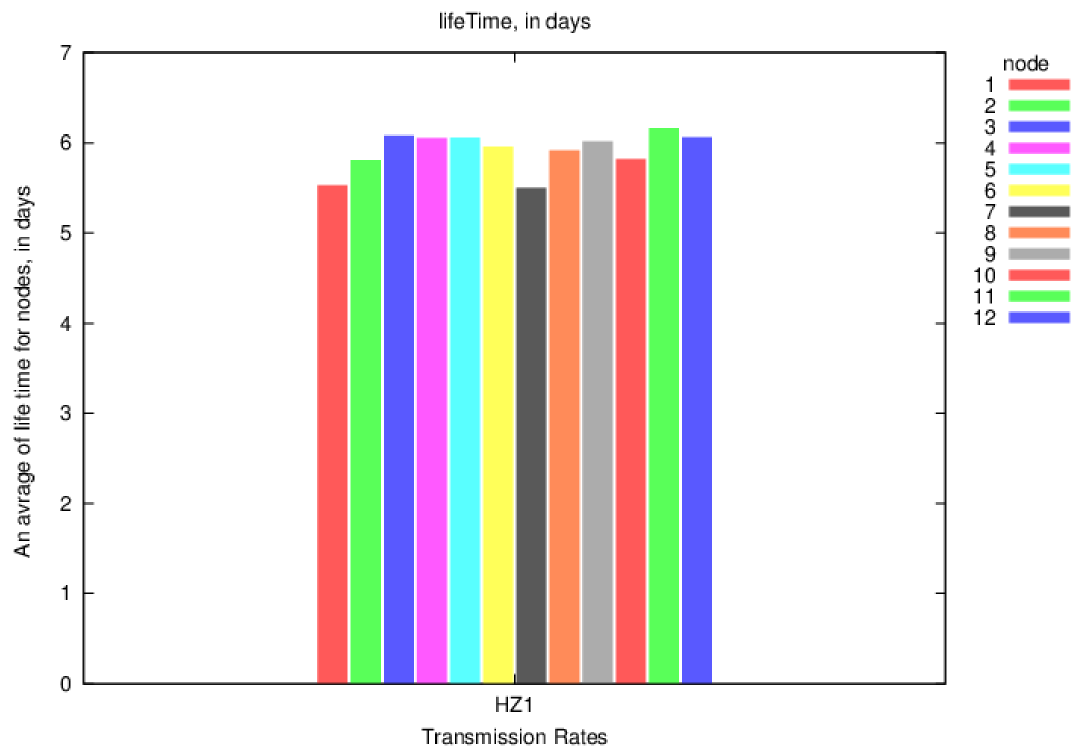

Figure 4.3: Lifetime of Nodes in the Network using the GinMAC Protocol (Validation)

It is believed that this implementation could be improved by designing efficient routing protocols, thereby increasing the lifetime of nodes in the network. One way of doing this is

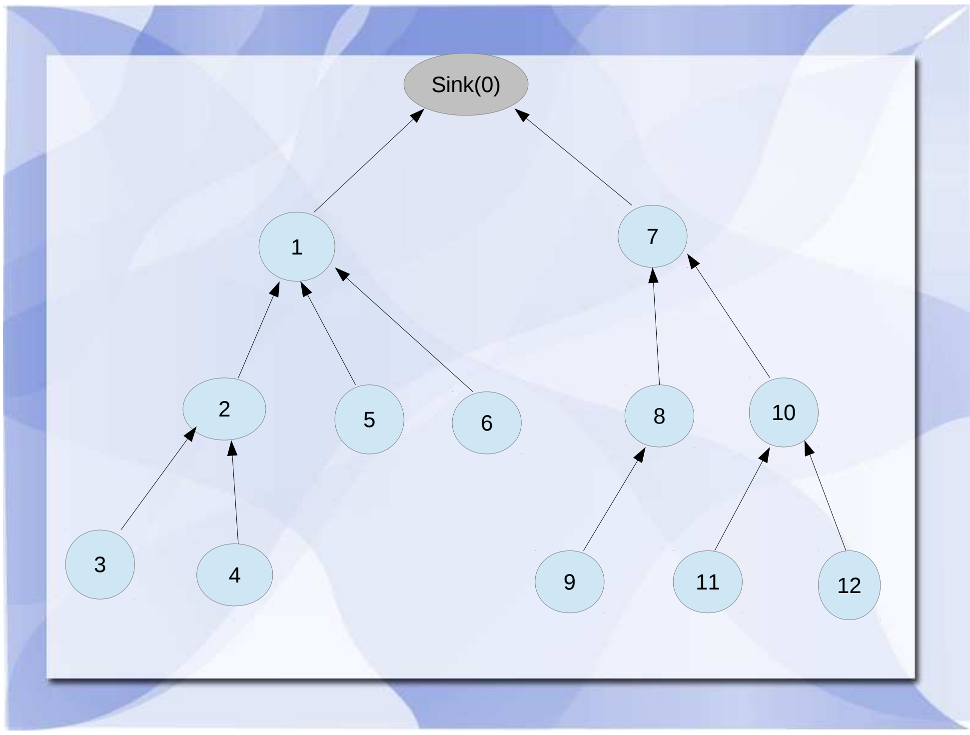

Figure 4.4: Topology of the WSN (GinMAC Validation) [102].

by using data threshold based routing protocols so that nodes are only allowed to transmit data when needed based on given data thresholds. This decreases the number of transmissions and consequently increases the lifetime of the entire network.

Delay in the Delivery of Data: The published results [68] show that GinMAC protocol delivers data within one second. This GinMAC protocol delivers data packets to a sink within a minimum delay. More than 99% of the data successfully received at the sink is delivered within the first second (1000 ms) which similar to the published results when all data is delivered within a second as shown in Figure 4.5.

This shows that this implementation offers a similar performance compared to the published result in terms of delay for data delivered from source nodes to a sink. As a result, GinMAC has been validated in terms of delay in the delivery of data.

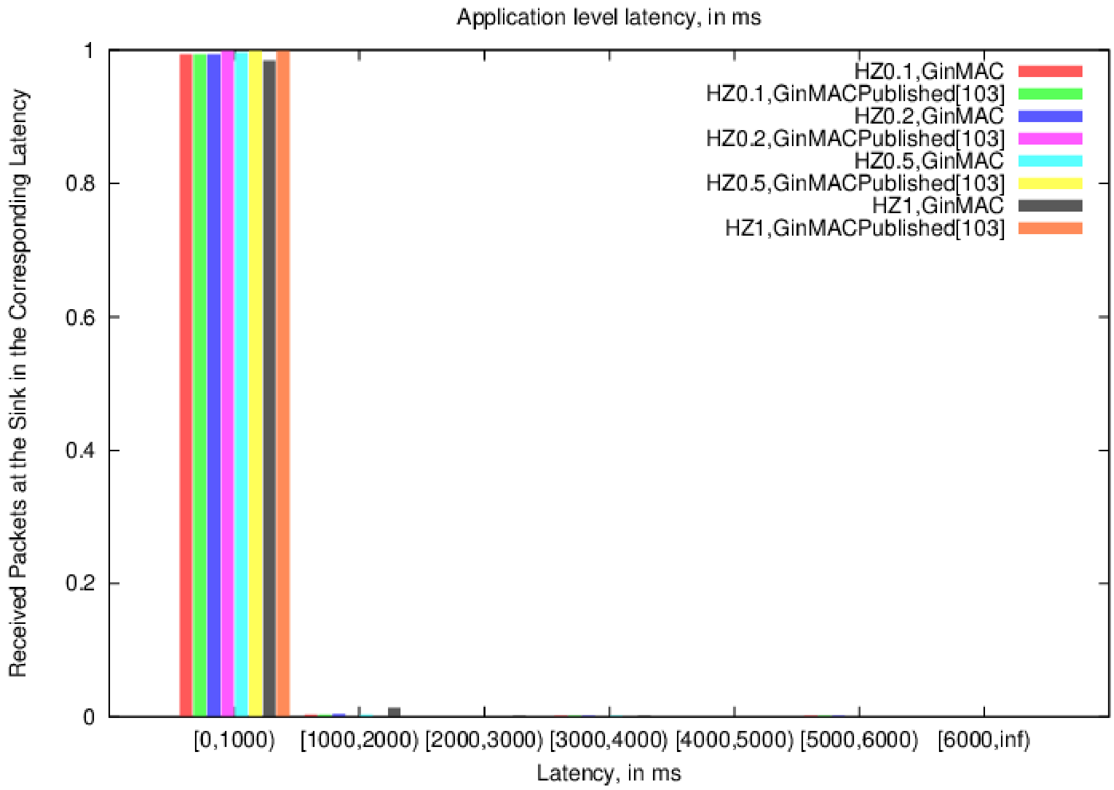

Figure 4.5: Delay of the Data Delivered using the GinMAC Protocol (Validation)

4.2 APTEEN Validation

4.2.1 Simulation Scenario

This section outlines the scenarios and simulation results for validating the APTEEN protocol 3.2, taking into account the published simulation scenarios, parameters and results [66].

Different scenarios with various numbers of nodes were required for validating the APTEEN protocol considering both static and mobile nodes. Energy saving, data delivered and delay were all considered in scenarios given in this section. In addition, the proposed mobility and route discovery modules including multi hop communication and different parameters for WSNs using the APTEEN protocol were involved. Details about simulation scenarios and other specific parameters are given in Table 4.2. More simulation results regarding the APTEEN protocol validation are given in Appendix C.

Table 4.2: Simulation Parameters (APTEEN Validation) [66]

Parameter	Value
Routing Protocols	APTEEN and LEACH
Network Dimensions	100m X 100m
Round length	20 seconds
Validation Metrics	Lifetime, delivered data and delay
Number of CH	5 -20
Number of Nodes	100 - 400
Packet Rates (packet(s) per second)	1
Mobility model	Random way-point mobility model
mobility speed(meters in seconds)	5
mobility interval(in minutes)	1
Advertisement interval (in seconds)	15
Initial Energy(in J)	2
Multi-hops	3-5
Real Radio	CC2420

The APTEEN protocol was simulated and results were compared to the published results [66] to validate this implementation before undertaking the required improvements and modifications. These modifications are: (i) designing new algorithms to select reliable routes for delivering data to a sink based on network conditions. (ii) Proposing a mobility module when mobile nodes are considered. In this section, both the APTEEN protocol [10] and the required modifications such as mobility module given in Chapter 3, taking different scenarios into account, were validated.

4.2.2 Simulation Results

An implementation of the APTEEN protocol based on the specifications [66] including the proposed route discovery and mobility modules were simulated, taking energy saving, received data at the sink, delay and mobility into consideration. Simulation results are discussed in the following sections. As mentioned before, different scenarios were considered where static and mobile scenarios with different numbers of nodes using different parameters were simulated as shown in Table 4.2.

4.2.2.1 Data Received at the Sink

The APTEEN protocol was simulated in terms of delivering data at the sink compared to the LEACH protocol [130]. Figure 4.6 show the performance of the APTEEN and LEACH protocols compared to the published results [66], [130]. It can be seen that APTEEN and LEACH performed slightly different than the published results due to different simulators were used. However, both protocols perform in a similar way to the published results as shown in Figure 4.6. This shows that both APTEEN and LEACH have been validated in terms of delivering data to a sink.

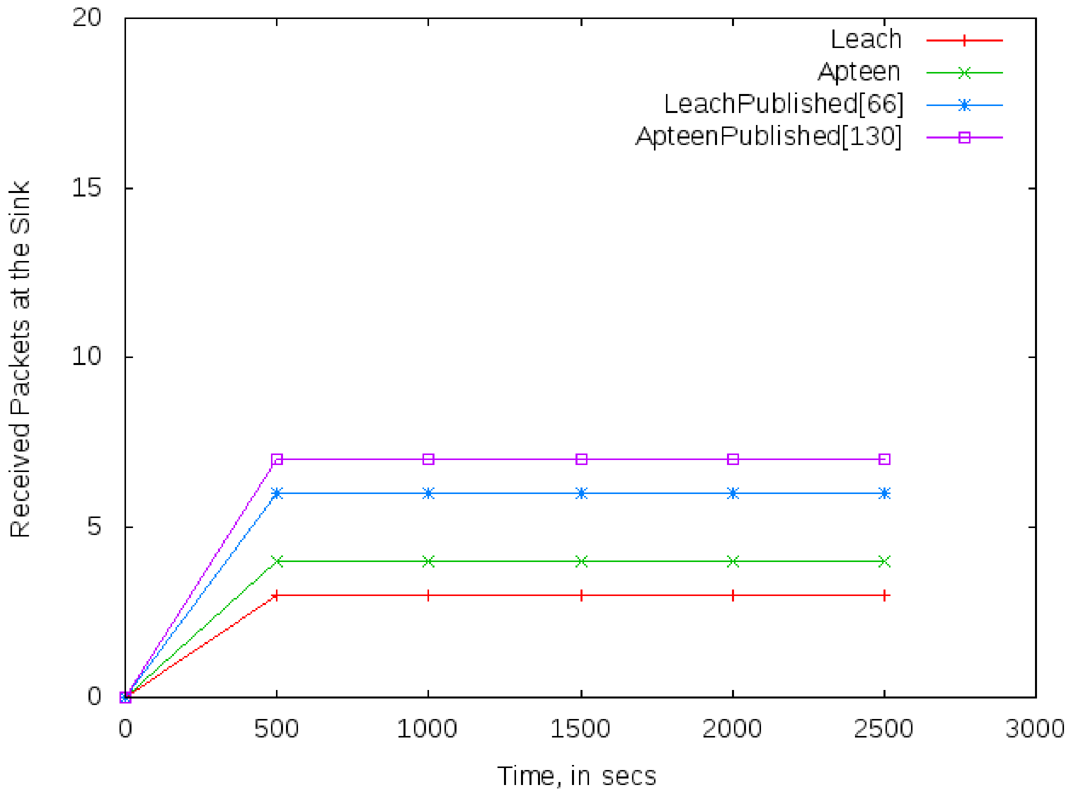

Figure 4.6: Total data received at the Sink over time (Validation)

4.2.2.2 Energy Saving and Lifetime of the Network

The APTEEN protocol was simulated in terms of energy saving compared to the LEACH protocol [130]. Figures 4.7, 4.8 show the performance of both the APTEEN and the LEACH protocols in terms of energy consumption and lifetime of the network. These results show that the APTEEN protocol saves energy compared to the LEACH protocol. This performance is due to that the APTEEN protocol reduces the number of data transmissions (non critical transmissions) when data does not need to be sent using different thresholds (HT and ST). This lets nodes in APTEEN consumes less energy, thereby extending the lifetime of the network.

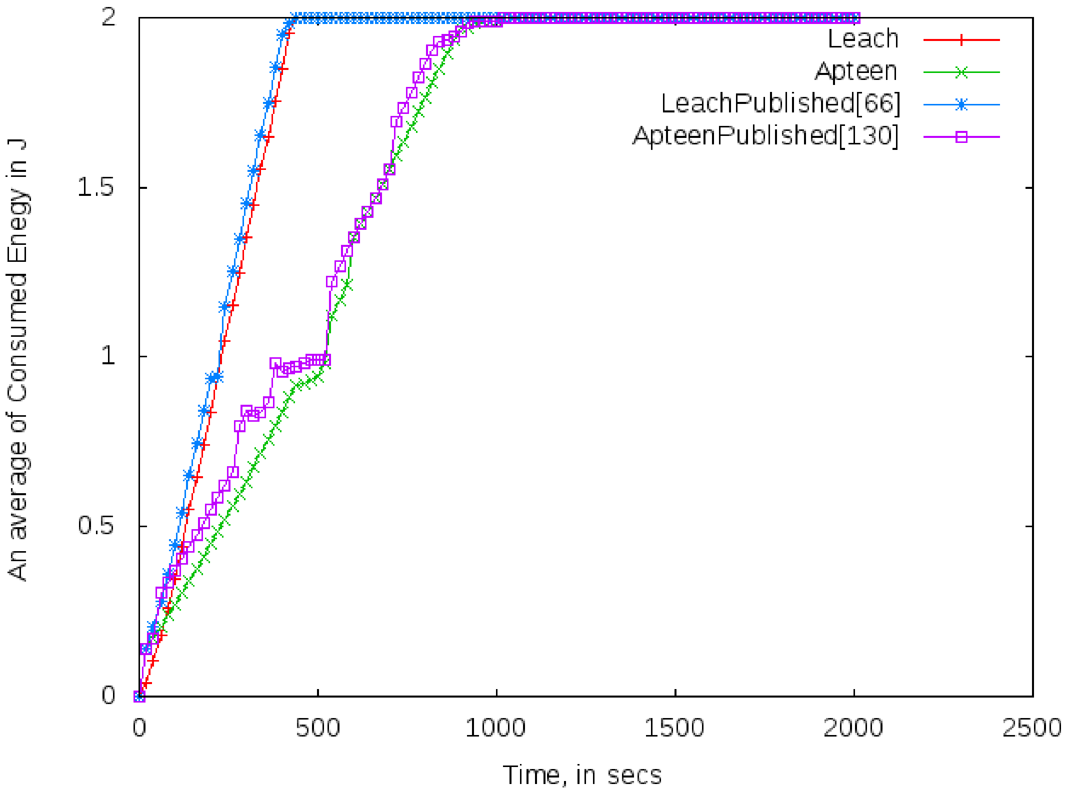

Figure 4.7: Energy Consumption using the APTEEN and LEACH Protocols (Validation)

However, because the LEACH protocol forces nodes to send their data in all cases, energy consumption increases and lifetime of the network decreases. As a result, the APTEEN protocol is better than the LEACH protocol in terms of energy saving and extending the lifetime of the entire network. In addition, based on the simulation results given in Figures 4.7 and 4.8, it can be seen that both LEACH and APTEEN perform similar to the published results [66], [130] in terms of energy saving when data was delivered to a sink.

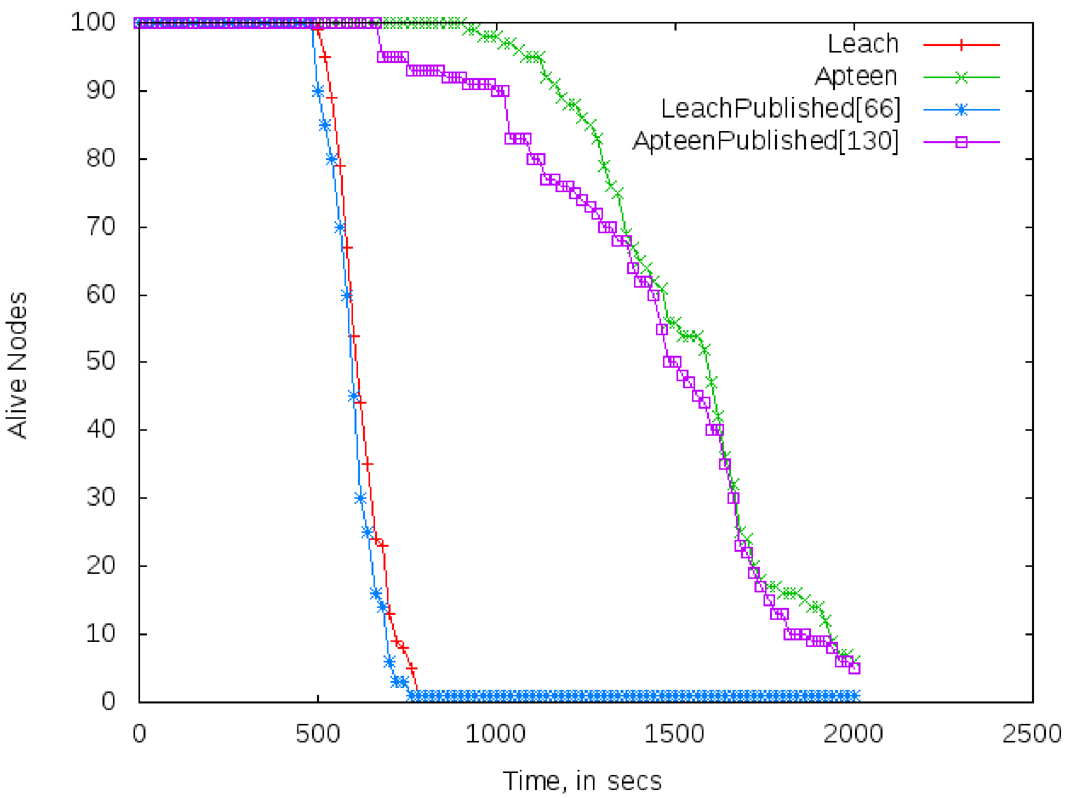

Figure 4.8: Lifetime of the Network Based on Rounds When First and Last Nodes Die using the APTEEN and LEACH Protocols (Validation)

4.2.2.3 Simulation Results using Routes Discovery Module

After the selection of cluster head using the APTEEN protocol, each CH must find reliable routes to deliver their own data, as well as data from their members, to a sink. To do this, a new algorithm was implemented as shown in the algorithm 3.3.5. Simulation results from the proposed route discovery module are discussed below using different simulation parameters. Energy consumption and data delivered are both considered when measuring the routes discovery module.

Figure 4.9 shows the average energy consumed by all nodes in the network where different percentages of CHs and multi hop communication were used. This figure shows that more energy is consumed when the percentage of CHs is high. This is to be expected as CHs consume more energy than the other nodes due to their additional tasks of aggregating and relaying data from source nodes to a sink. This means that when the number of CHs is high then energy consumption increases and the lifetime of the entire network decreases.

Figure 4.10 shows the number of data packets successfully delivered to a sink using simulation parameters given in Table 4.2. It can be seen that the number of packets delivered can be increased by having more CHs and lower numbers of multi hop. This is also to be expected because data is delivered using different reliable routes when the percentage of CHs is high. However, when the number of multi hop is high, there is a higher likelihood of packets being lost before they are delivered to a sink.

4.2.2.4 Mobility Module Results Using the APTEEN Protocol

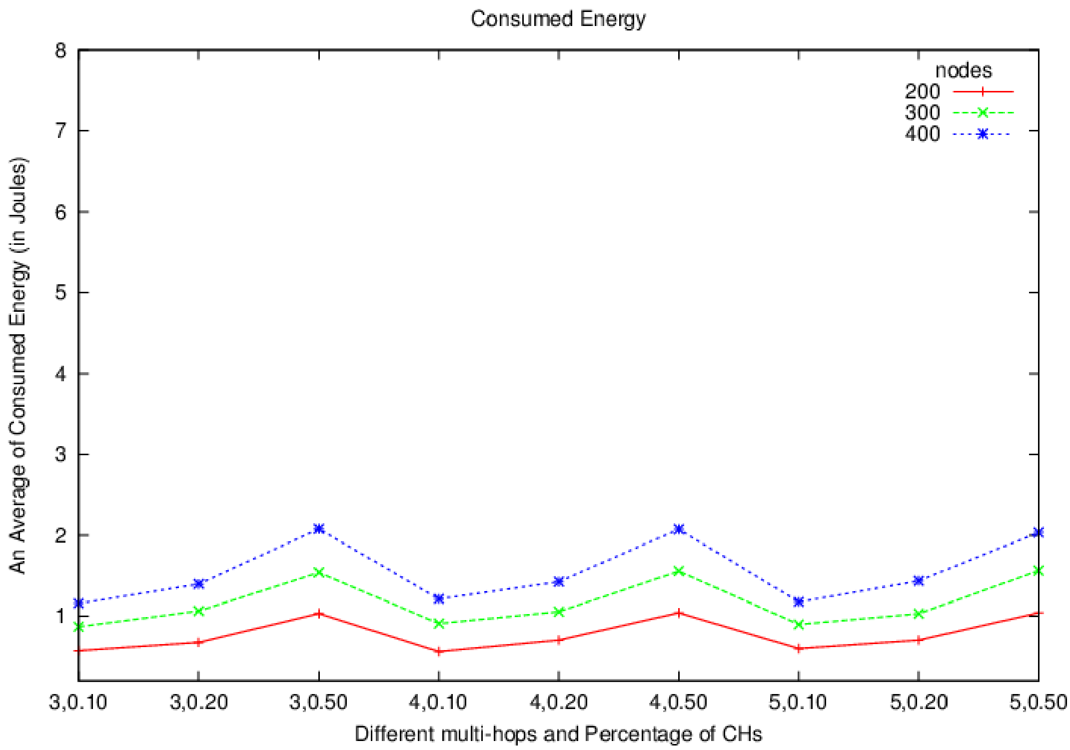

Figure 4.9: Proposed Routes Discovery in terms of Energy Consumption (Validation)

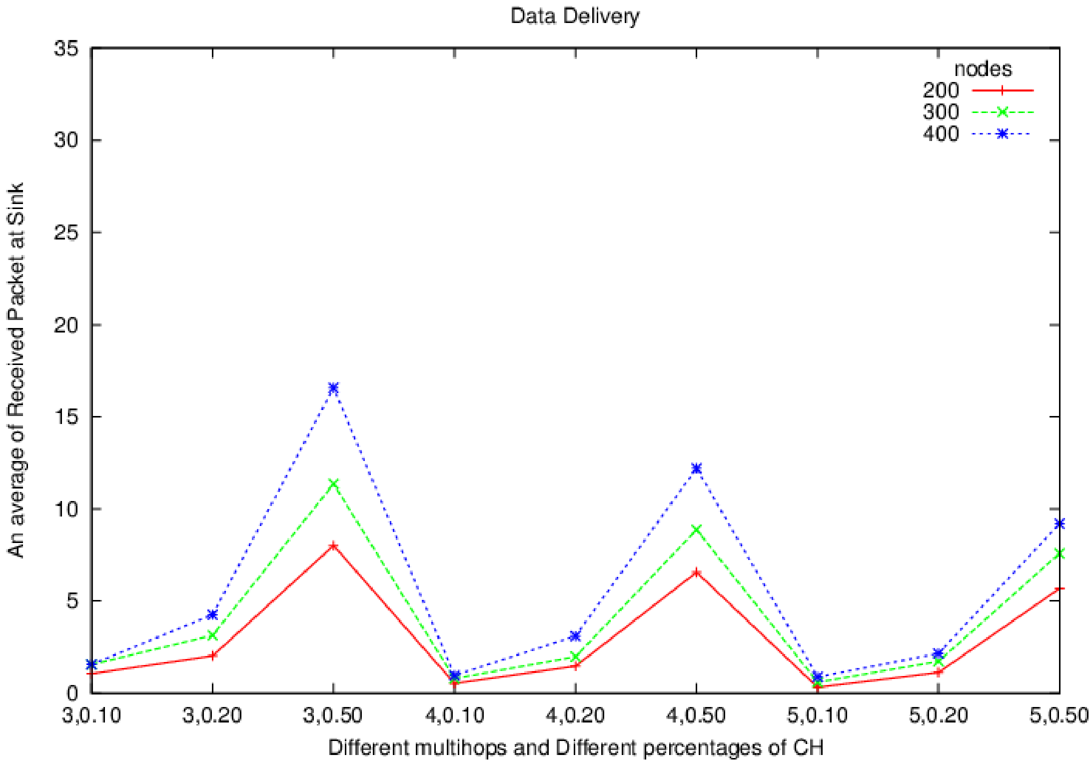

Figure 4.10: Proposed Routes Discovery in Terms of Delivered Packets (Validation)

Figure 4.11 describes the rate of successful and failed connections between mobile nodes and their cluster head in different attachments. It shows that the proposed mobility module provides good performance in terms of connectivity between mobile and static nodes in a network.

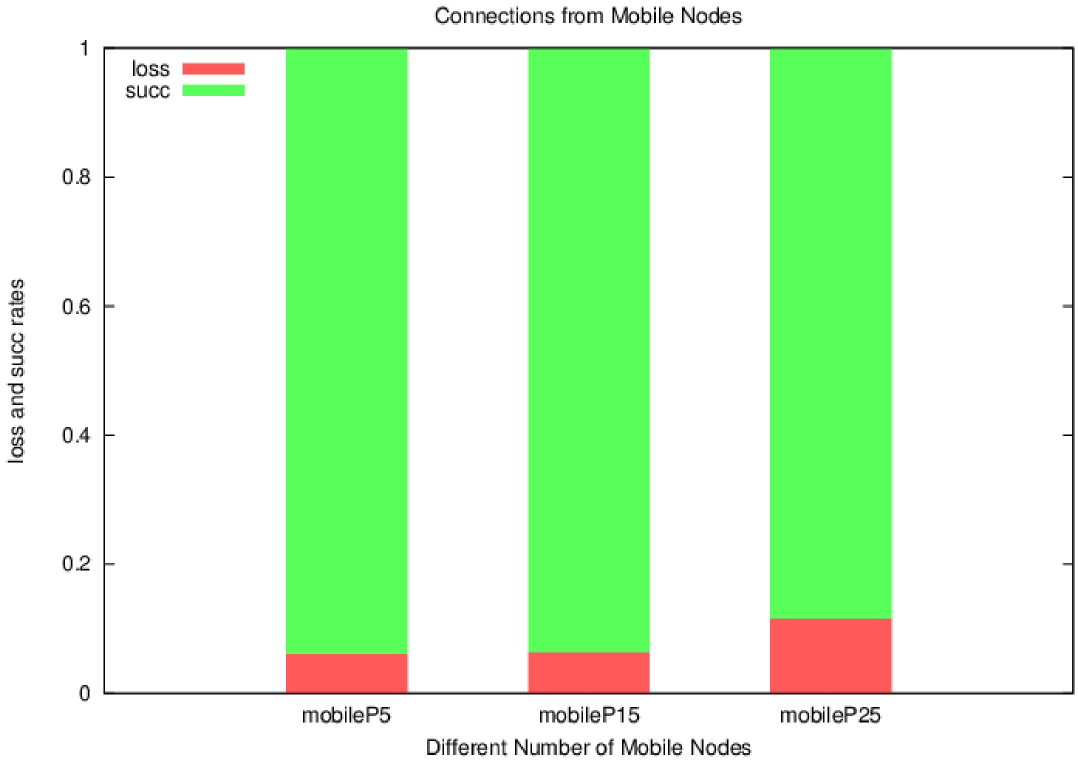

Figure 4.11: Connectivity Detection Between Static and Mobile Nodes (Validation)

4.2.3 Analysis of the Results

In the above results, the APTEEN protocol and the required modifications such as route selection and mobility modules have been validated [66]. Thus it has been concluded that the APTEEN protocol could be used for improving WSNs of different applications to increase performance where the lifetime of the network and delay of data delivered are crucial. The key ideas behind this performance for the APTEEN protocol are as follows:

- By sending queries over time to different parts of the network, users can gain a complete picture of the network, a feature which most of the recent cluster based routing protocols do not have.
- The APTEEN protocol can be used for critical and non-critical delivered data related applications by using different thresholds. This allows users to select thresholds according to the requirements of the proposed applications.
- Energy can be conserved by distributing energy usage between nodes in the network.
- Delay can be reduced and energy can be conserved by aggregating and reducing redundant copies of data at the intermediate nodes in the network.

- Nodes in each cluster need only send their data to their CHs over a single hop communication using their allocated slots, so the lifetime of the network is extended.
- As only CHs are involved with routing and forwarding data to a sink, the routing complexity in large WSNs is reduced.
- Only cluster head needs to aggregate data from their members thus energy consumption is reduced.
- Data is transmitted to a sink using the best available links based on RSSI.

Chapter 5

Performance Evaluation

This chapter describes the performance evaluation of the protocols proposed in Chapter 3. Simulation was the sole method used for measuring the proposed protocols for the applications given in this section. This is due to the flexibility of using simulators for testing protocols, compared to real test-beds using WSNs due to a high number of nodes and various parameters can be involved in the performance evaluation to test proposed protocols. Each application was simulated with different scenarios using different parameters and situations.

The APTEEN [66], TMAC [82] and LEACH [130] protocols were selected as comparison protocols in this Chapter as they are designed to save energy using WSNs.

The following applications are considered in this research:

1. Healthcare application when data from patients and their environments were considered in order to improve the health of patients as shown in Sections 5.2, 5.3 and 5.4, respectively. Different scenarios based on a realistic application were considered and the GinMAC and the cross layer based protocols were used to increase performance. This application including its simulation results has been published [2], [3], [4].

2. Monitoring application based on multimedia transmissions such as multimedia related applications, when different scenarios and parameters were considered as shown in Section 5.5, was simulated using the proposed protocols. Details of this application along with its simulation results has been published [152].

3. More applications about the environment monitoring using the protocols proposed in this research are bounded in Appendix D.

5.1 Simulation Models

5.1.1 An Overview of the Castalia Simulator

Castalia [67], [153] is a simulator for WSNs, Body Area Networks (BANs) and generally networks of low-power embedded devices. It is based on the OMNeT++ [154] platform and can be used by researchers and developers who want to test their distributed algorithms and protocols in realistic wireless channel and radio models.

The Castalia simulator was designed right from the beginning so that the users can easily implement their algorithms and protocols using proper modules. The modularity, reliability, and speed of Castalia is partly enabled by OMNeT++, an excellent framework to build event driven simulators. This helps users to define their own protocols very easily and integrates them into the rest of modules [155], [156]. More details about the Castalia simulator, its features for WSN and BANs can be found in the literature [67].

Therefore, after a great deal of research related to simulators for WSNs and because of the features listed below, the Castalia simulator was used in this research. The core idea behind evaluating protocols using the Castalia simulator is to enable the design of proper messages and modules as well as designing techniques to use these messages and modules as required.

5.1.2 Castalia Features for WSNs

Castalia is a highly parametric simulator and can simulate a wide range of platforms [67]. This means that the Castalia simulator can be used to measure the performance of different protocols in a WSN taking data from real applications into consideration.

In summary, the following sections outline the most important models within the Castalia simulator taking WSNs and BANs into consideration [157].

5.1.2.1 Advanced Wireless Channel Models Based on An Empirically Measured Data

The Castalia simulator has a very advanced wireless channel model based on real data and supports static and mobile nodes in the network. Path loss and variation models are implemented for BANs based on real data using different applications, such as healthcare related applications [82], [158]. In summary, the wireless channel model implemented in the Castalia simulator supports the following features:

- Defines a map of path loss (define topology of the network), not simply connections between nodes [159]. One important aspect of the wireless channel modelling is to estimate the average path loss between two nodes. For WSNs, where the separation of nodes is from a couple of meters to a hundred meters, the lognormal [158] gives accurate estimates for average path loss. For BANs modelling, Castalia defines path loss map. For example average path losses using a testbed and provide these as input to Castalia.

- Defines a complex model for temporal variation of path loss in the BANs based on different activities. This model could be driven from a real application while a person is in his/her daily activities such as walking [160].
- Fully supports mobility of the nodes.
- Interference is handled as received signal strength, not as separate features.

5.1.2.2 Advanced Radio Models Based on Real Radios for Low-power Communication

The radio model in the Castalia simulator is another feature that is preferred for use in different applications using WSNs. This involves different states such as SLEEP, Transmission (TX) and Receiving (RX) for switching nodes from one state to another based on different radios such as CC2420 and CC1000 [67]. These radios have been used for many applications using WSNs in recent years.

In summary, radio models used in the Castalia simulator support the following [159]:

- Data reception is based on packet size, modulation type such as PSK, FSK and custom modulation.
- Multiple TX power levels with individual node variations allowed.
- States with different power consumption and delays switching between them.
- Realistic modelling of RSSI and carrier sensing.
- Cross layer control is supported between different modules.

5.1.2.3 A Link Error Model Using Castalia

Errors in packets are determined and modelled by bit errors and how many bit errors can a packet endure based on given encoding. In Castalia if 1 bit error happens then there is a packet error. Bit errors are determined by Signal-to-Interference-plus-Noise Ratio (SINR) and the modulation type that the radio is using. Note that the SINR is dynamic for the lifetime of a packet (i.e., can change for different parts of the packet) and Castalia is capable of taking these changes into account. Therefore, if SINR > 0 then packet is received [67].

5.1.2.4 Physical Process and Sensing Models

Physical and sensor managers models can easily be designed according to the requirements of the proposed applications using WSNs and BANs. This allows users to design their physical and sensor manager models based on their input data. Physical and sensing manager modules in the Castalia simulator have the following features:

- Highly flexible physical process model.
- Sensing device noise, bias, and power consumption.

5.1.2.5 A realistic Energy Consumption Module Using Castalia

Energy consumption in the Castalia simulator depends on the state of radio and the time it spends in different states. So the MAC and routing protocols become very important as they influence this directly. If a MAC or routing protocol is used and it does not put the radio to sleep, then sending a few more packets, or using a lower TX power has negligible effect. This is due the fact that the radio is just listening for the majority of the time anyway. This means that the power consumed by nodes when listening vs actually receiving is virtually the same (for the low power radios that Castalia is concerned). However, receiving can actually be less power hungry if the SINR of the received frame is very high [153].

Therefore, a lot of factors need to be considered when designing energy efficient protocols for WSNs. Energy can be saved using MAC or routing protocols by turning the radio of nodes off as much as possible without affecting the overall network performance. Castalia is the best simulator in which can be used for simulating BANs and WSNs because of [67]: (i) advanced channel and radio modules based on the real data from real manufacturers. (ii) Energy consumption taking realistic scenarios into consideration.

In addition, as shown in Tables 5.1 and 5.2, nodes use different models and parameters when data is delivered based on realistic radios such as CC2420 and BANs [23]. A power transmission to deliver data needs to be selected based on the requirements of the target applications. However, it is not possible to have a power transmission which is perfect for all applications using WSNs. The required performance of any WSN is application dependent and hence the power transmission and other specific parameters of the network must be selected according to the requirement of the target application.

In order to have a realistic selection which can be used as a basis for comparison across a number of applications it is proposed that the power transmission for single hop based routing protocols for these applications be more than in multi hop based routing protocols [161]. So, for the purpose of these comparisons, a power transmission for LEACH is defined to be 0dBm and for APTEEN and the proposed cross layer protocols is defined to be -3dBm, -5dBm and -

10dBm, taking into account the requirements of the target applications. Furthermore, the power transmission and other specific parameters for nodes in BANs used in applications given in this work were assumed to be different than in WSNs as shown in Tables 5.1 and 5.2.

Table 5.1: Radio Parameters and Energy Consumption Models for WSNs and BANs [67]

RX Modes	CC2420 Radio (WSNs)	BAN Radio (BANs)
Name	Normal and Ideal	Low
Data Rate(kbps)	250	512
Modulation	PSK and IDEAL	DIFFQPSK
BitsPerSymbol	4	1
Bandwidth(MHz)	20	20
NoiseBandwidth(MHz)	194	1000
NoiseFloor (dBm)	-100	-104
Sensitivity (dBm)	-95	-91
Power Consumed(mW)	62	3.1

Table 5.2: Transmission Power Consumption Model for WSNs and BANs, in mJ

TX LEVEL	Value for WSNs (dBm)	Value for BANs(dBm)
1	0	-10
2	-1	-12
3	-3	-15
4	-5	-20
5	-7	-25
6	-10	-
7	-15	-
8	-25	-

5.2 A Healthcare Application

Because of the rapidly increasing number of elderly people, the cost of medical care is increasing day by day. Recent advances in technology have led to the development of small, intelligent, wearable sensors capable of remotely performing critical health monitoring tasks using WSNs. This involves transmitting the patient's data back to health care centres using a wireless medium. Such health monitoring platforms aim to continuously monitor mobile patients needing permanent surveillance. However, to set up such platforms, several issues need to be resolved along the communication chain [61].

The healthcare field is always looking for more efficient ways to provide patients with the best and most comfortable care possible. Providing proper monitoring can be expensive for their family and may force them to move from their homes because living alone will be too much of a risk for their health. It has been assumed [61], that a WSN could be used to monitor and treat patients remotely, based on data collected from the patients themselves.

One way to approach this task is to use an application to monitor the health of patients that allows caregivers or relatives to monitor patient's health status at a much lower cost. In this case, families are not forced to move the patients into unfamiliar environments such as hospitals. Furthermore, these applications can be helpful to elderly people who suffer from poor memory by providing them with advanced features such as helping them to take medicine and locate important objects in their homes [64].

In this section, an application based on a prototype [64] has been used to remotely monitor the healthcare of patients in their homes where mobility and reliability are the biggest issues. As there is a large amount of data to be managed, an efficient protocol needs to be designed in order to provide the performance required from the proposed application.

Based on the above criteria, the GinMAC and cross layer based protocols, given in Chapter 3, are used to improve the health of patients using WSNs, taking different scenarios into account. These scenarios have been carried out to evaluate the performance of both GinMAC and the cross layer based protocols compared to TMAC, APTEEN and LEACH. Energy saving, delay, reliability and mobility are crucial in this application. Details about the healthcare application and its structure are outlined below.

5.2.1 Structure of the Healthcare Application

The proposed healthcare system consists of four different parts [64] and illustrated in Figure 5.1. The first of these is the home monitoring part where sensor nodes are placed on the patients and around the home to get multiple sets of data about the patients. This includes the patient's activities, health status using a BSN and living environment information via a HSN. The HSN sensors are installed in the living room, bedroom, kitchen, bathroom and corridor. BSN and HSN sensors need to be attached to the patients themselves and to the environment that these patients are living in, but must not affect their daily activities.

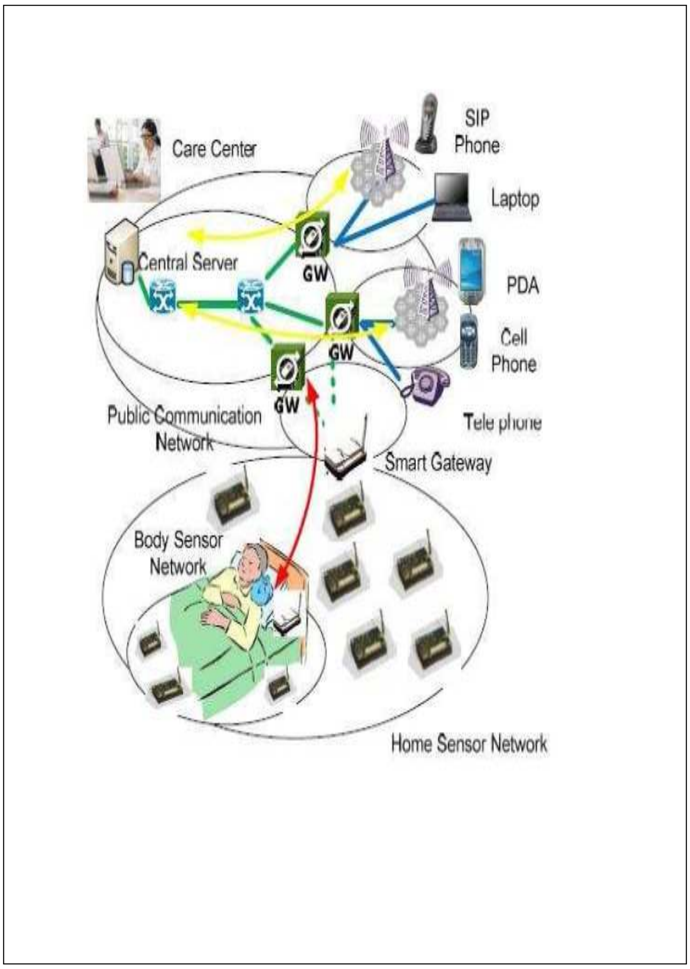

Figure 5.1: Structure of the Proposed Healthcare Application [61]

The second part is the decision. This is the most important function in the application because the performance of the whole application depends on the decision made here. The required medical decisions are made depending on the data collected from the home, the data from the body of the patient and the previous status of the patient. The BS is responsible for collecting data from both the HSN and BSN and forwarding it to the Health Centre (HC) or caregivers (doctors and relatives). Therefore, the BS must deal efficiently with collecting data from different parts of the network and sending it to the medical centre for future decisions.

The third part involves caregivers, including doctors or nurses in the hospital and possibly relatives. They are responsible for dealing with the medical report messages (normal or alarm messages) that are sent to them. In the proposed application relatives should be able to check the patient's current health status through online web pages using authentication techniques.

The fourth part is the Public Communication Network (PCN) including the Internet, Global System for Mobile Communication (GSM)/ General Packet Radio Service (GPRS), Ethernet, Gate Way (GW), and WI-FI. The PCN delivers generated messages from the BS to the caregivers so that patients can be given the required medical services in real time.

5.2.2 WSNs in the Healthcare System

The first part of the healthcare system using WSNs is simulated in a home to monitor and collect data from both the home and the bodies of the patients themselves. Each patient is monitored by a WSN divided into two sub networks which are a BSN and an HSN. A BS receives data from both the BSN and HSN and then gives commands to the corresponding network.

5.2.2.1 Design of Body Sensor Networks (BSNs) for a Healthcare Application

Sensors for each BSN need to be deployed according to the physical condition that the system is aimed at monitoring, for example, heart rate sensors. In the proposed healthcare application only one physical medical parameter is considered for monitoring which is body temperature. So, the BSN consists of one sensor attached to the body of the patient. Data that represents temperature needs to be collected from this sensor. This data must then be combined with data from the sensors in the environment that these patients are living in and finally be sent back to the BS, to enable any necessary medical decisions to be made. The number of sensors for each BSN can be increased based on the requirement of the proposed applications.

In order to provide a comfortable system that does not affect the patient's daily activities, there will be challenges which need to be considered, such as the size of the sensors that need to be attached to the body of the patient. Each sensor needs to be as small as possible so that it can easily be attached to the body of the patient without affecting their daily activities, whilst still providing the required quality of service and performance.

5.2.2.2 Design of Home Sensor Networks (HSNs) for the Healthcare Application

HSNs in the WSNs for each patient need to be designed to monitor the environment that the patient is living in. In this case, each room will have a number of sensors to provide the data that needs to be collected. This data must cooperate with the BSNs, when the patient is in that room. The data collected then needs to be forwarded to the BS for future analysis. An efficient mobility module needs to be designed to provide the required connection between BSNs and HSNs when patients are moving from one room to another.

5.2.2.3 Design of Base Stations (BSs) for the Healthcare Application

Data from each patient needs to be collected and forwarded to the BS before it is transferred to the caregivers. Hence, in the proposed application, the BS is the core of the healthcare system. As a result, the proposed healthcare application needs an intelligent module at the BS to deal with data collected from the application before sending back any medical reports to caregivers. This involves dealing with data collected from patients, for instance, patient's activities, their behaviours as well as the required reports, such as normal and emergency alarms. This information must be combined intelligently by caregivers in order for appropriate decisions and diagnosis to be made.

In the proposed healthcare application, each patient needs to be registered with at least one doctor in the medical centre so that all reports related to this patient can be forwarded to his or her caregivers. In addition, each patient needs to have at least one other contact in case there is an emergency. Therefore, the BS needs to include a database to store information about all the patients in the system including their close relatives and doctors such as names, addresses and phone numbers.

Regular (not emergency) reports about the health status of the patient can be be sent to their relatives over time. One way this can be done is using online personal web pages for each patient with access requiring an authentication process. Two types of reports are provided by the application; regular and healthcare reports. Regular reports record the health status of each patient over time, while health reports show what medical operations and other necessary care have been carried out by doctors or relatives within a given time frame.

5.2.3 Data Communication in the Healthcare Application

Each sensor node has a limited energy supply to cater for the sensing, data processing, data storage and transceiver and has little capability to recharge. The majority of its energy is consumed by the communication system, so an efficient energy conserving communication protocol must be used. The bandwidth is limited and must be shared among all the nodes in the sensor network, but reliable and efficient communication of the acquired data is crucial, to avoid any loss of vital information during diagnosis. This can only be achieved by implementing efficient MAC and routing protocols to deliver information reliably from source nodes (BSNs and HSNs) to a BS.

Sensor nodes in the BANs and WSNs used in this application have different parameters and models such as data rate, battery, sensor type, link error models, energy consumption models as well as wireless channel models as shown in Section 5.1. All of these parameters and models were considered where this application was simulated using the protocols proposed in this research. More information about these models using Castalia can be found in the literature [67].

Based on the required criteria for the healthcare application given in this section, the GinMAC protocol and the cross layer based protocols given in Chapter 3 were used to increase performance of this application. This involved energy saving, reducing delay and reliability for data delivered as well as improving mobility between nodes in the network. Different scenarios with various parameters were considered to simulate this application using the proposed protocols. Simulation results and conclusions about these protocols for the healthcare system demonstrate that these protocols are suitable, and are discussed below.

5.3 GinMAC for Healthcare Applications

The GinMAC protocol given in Section 3.1 was simulated and compared with the TMAC protocol [82] in order to improve performance for the healthcare application given in section 5.2. TMAC was selected as a comparison protocol in this section as it is designed to save energy using adaptive related techniques. Reliability for the data delivered was considered the most important factor which needed to be considered for the healthcare application. Then energy, delay and mobility were also considered when simulating the given MAC protocols for the proposed healthcare application. Simple scenarios, where the number of nodes was low, were simulated using the GinMAC and TMAC protocols including the proposed GinMAC mobility module with different parameters. More details about the simulation parameters and scenarios are given below.

5.3.1 Simulation Scenarios and Parameters

A simple application where all nodes send data to a sink using different packet rates was used to measure the proposed application using the GinMAC and TMAC protocols. The TMAC [82] protocol was selected in this application as a comparison protocol because it is designed to save energy for WSNs using adaptive techniques based on ongoing traffic rates.

The Castalia simulator was selected for this work because of its ability for simulate protocols for WSNs based on real data [67]. Both the TMAC and GinMAC protocols were simulated according to the application requirements given above, using different sensing intervals. Sensing interval is defined as Ii = one packet per *i* second. It can be seen from the graphs in the simulation results given in section 5.3.2 that I1 means the nodes sense the environment and send data at rate of one packet per second. I2 means the nodes sense and send data at rate one packet every 2 seconds and so on. Energy consumption, wireless channel and radio models used in this application were described in Section 5.1. More details about the MAC protocols and other parameters can be found in Table 5.3.

5.3.2 Simulation Results and Discussion

Simulation results from Section 5.3 are discussed below; static and mobility scenarios were considered. Based on these results, a number of conclusions are made about using the GinMAC and TMAC protocols for the healthcare application given in Section 5.2.

Table 5.3: Simulation Parameters (GinMAC for Healthcare Application)

Parameter	Value
MAC Protocols	ModifiedGinMAC and TMAC
Distance Between pair of static nodes	25 meters
Measurement Metrics	Lifetime, delay and reliability
Sensing Intervals (packet per second(s))	1,2,5,10
Mobility Model	Random way-point
Mobility Speed (meters in a second)	1
Initial Energy(BANs)	AA battery
Initial Energy(WSNs)	D battery
Real Radio (WSNs)	CC2420
Real Radio (BANs)	BAN Radio

5.3.2.1 Results from the Static Scenarios

Data Delivered and Reliability: Figure 5.2 shows that the GinMAC protocol can meet the application requirements given in Section 5.2 in terms of reliability taking various parameters into consideration. This is due to the fact that GinMAC delivers more than 98% of packets from source nodes to a sink. TMAC cannot offer a reliability of more than 96% in either high or low sensing intervals using the same parameters as shown in Figure 5.2. Thus, it can be said that GinMAC performs better than TMAC for the proposed application when reliability is the main criterion.

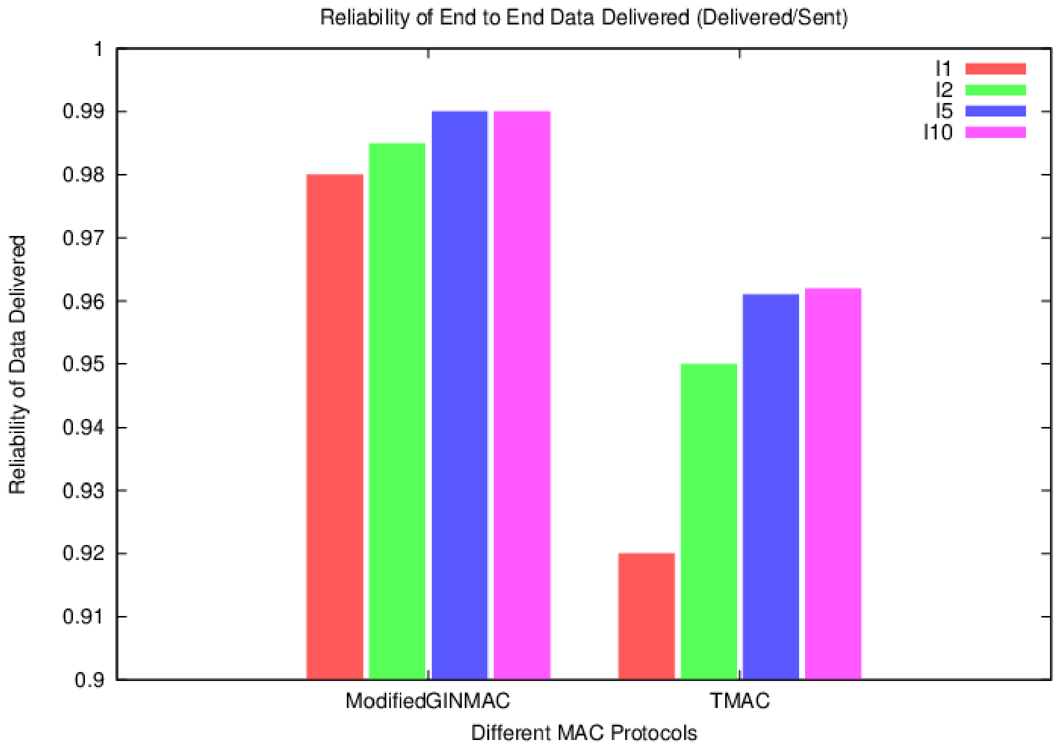

Figure 5.2: Reliability of Data Delivered using TMAC and GinMAC Protocols for the Static Scenario Using Different Sensing Intervals.

This improvement is due to the fact that the GinMAC protocol uses static slot allocation and no interference can occur. However, the TMAC protocol uses contention based techniques making collisions more likely to happen.

Energy Saving and Lifetime of the Network: Figure 5.3 shows the average lifetime of nodes in the network using the GinMAC and TMAC protocols at different sensing intervals. It can be seen that GinMAC performs worse than TMAC in terms of energy saving and the lifetime of the entire network for all given sensing intervals. This improvement is due to the fact that the adaptive-related techniques of TMAC results in nodes being active only when they have data to send or receive and therefore greater energy efficiency, compared to the GinMAC protocol which does not have this feature. A WSN using GinMAC can survive more than 7 days at low sensing intervals and around 8 days at high sensing intervals as shown in Figure 5.3.

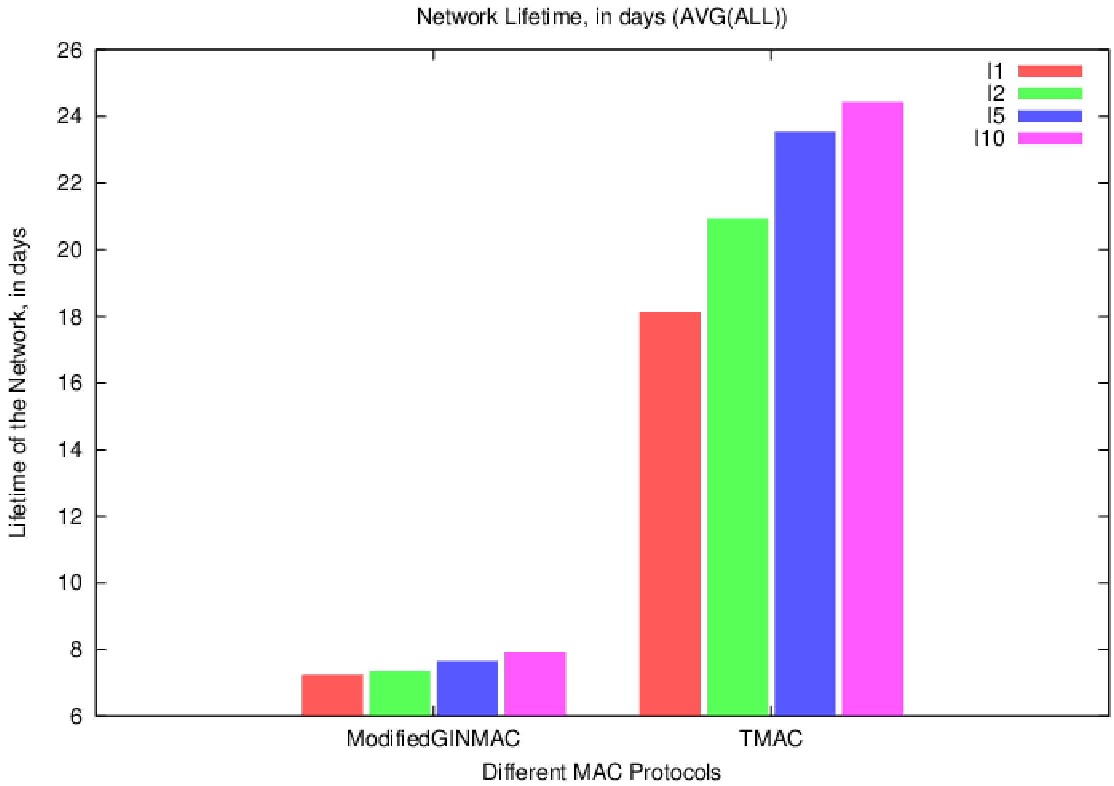

Figure 5.3: Lifetime of the Network using the GinMAC and TMAC Protocols for the Static Scenario Using Different Sensing Intervals.

Delay in the Delivery of Data: According to the results in Figure 5.4, most data packets are delivered to a sink within the first 5 seconds at high sensing intervals using both protocols. The remaining data packets are delivered within the next 5 seconds at low sensing intervals. Hence all packets are received within 10 seconds. This performance is due to the fact that GinMAC uses static TDMA schedule allocations. This allows nodes to deliver their data to a sink with only a short delay.

5.3.2.2 Results from the Mobility Scenarios for the GinMAC Protocol

The mobility module for the GinMAC protocol considers the RSSI for selecting better attachments when some nodes are mobile as shown in 3.1.5. Figures 5.5 and 5.6 show that GinMAC offers the same performance in terms of reliability and network lifetime for both static and mobility scenarios. However, because of overhead from the mobility detection related messages, such as Node alive and keep alive, GinMAC's performance in terms of reliability when mobile nodes were considered is a bit worse than in the scenarios when no mobile nodes were involved.

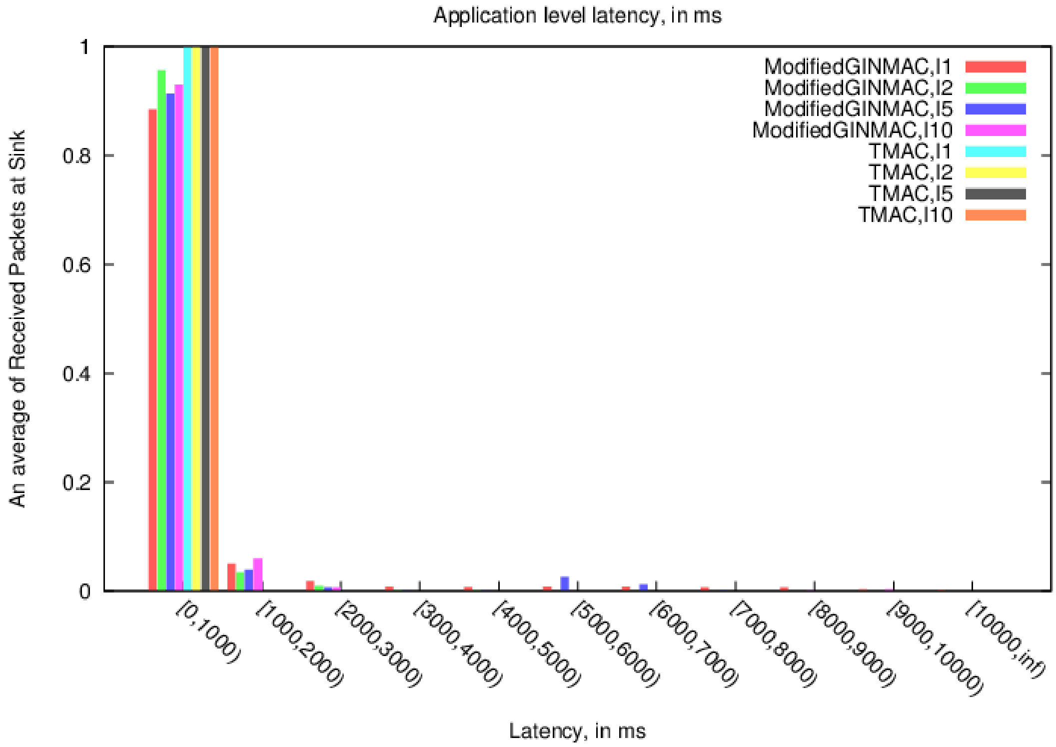

Figure 5.4: Latency for Data Delivered Using the GinMAC and TMAC Protocols for Static Scenario

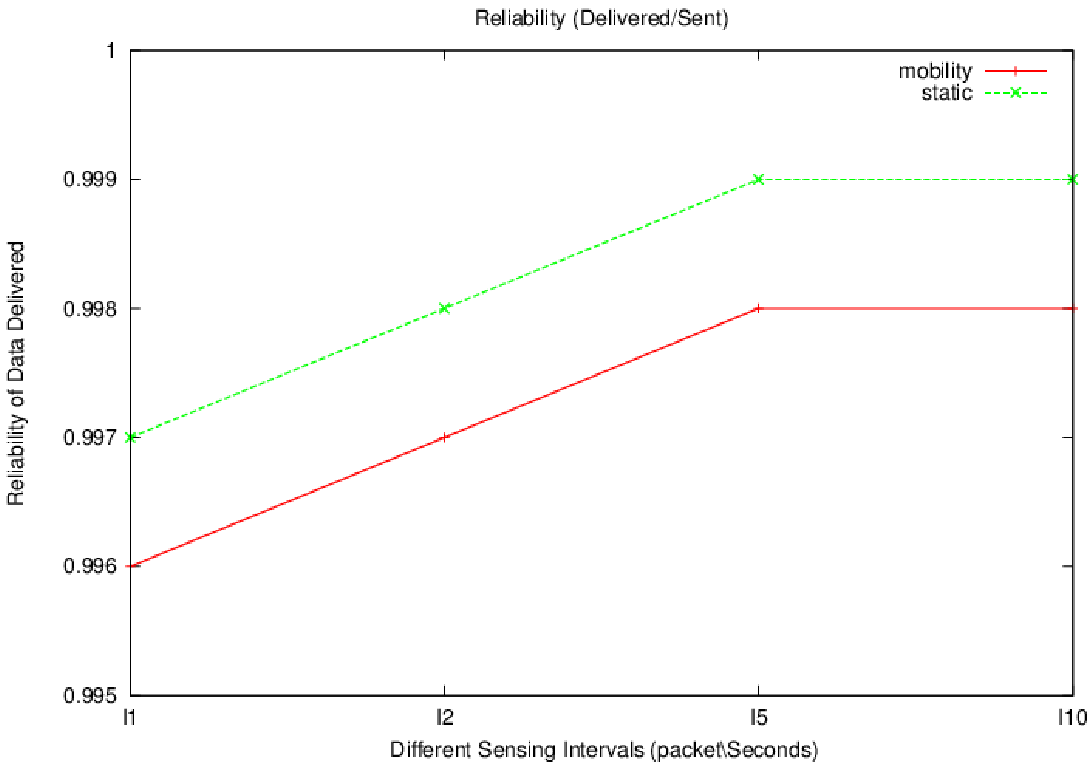

Figure 5.5: Reliability of Data Delivered When Some Nodes are Mobile Using GinMAC

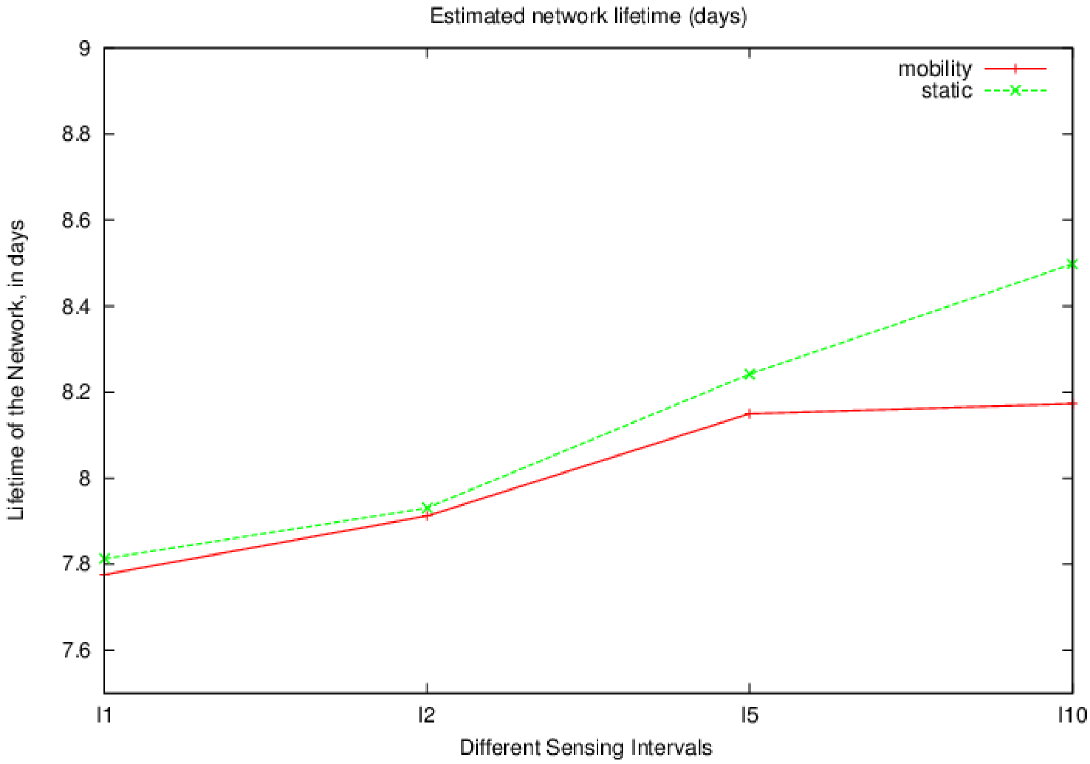

Figure 5.6: Lifetime of Nodes in the Network Using Both Mobility and Static Scenarios for GinMAC Using Different Sensing Intervals.

Figure 5.7 shows that a mobility module using GinMAC performs similarly in terms of latency for delivering data compared to static scenarios when no mobile nodes were involved. This means that the proposed mobility module provides good connectivity between nodes compared to the static scenario when there were no mobile nodes in the network.

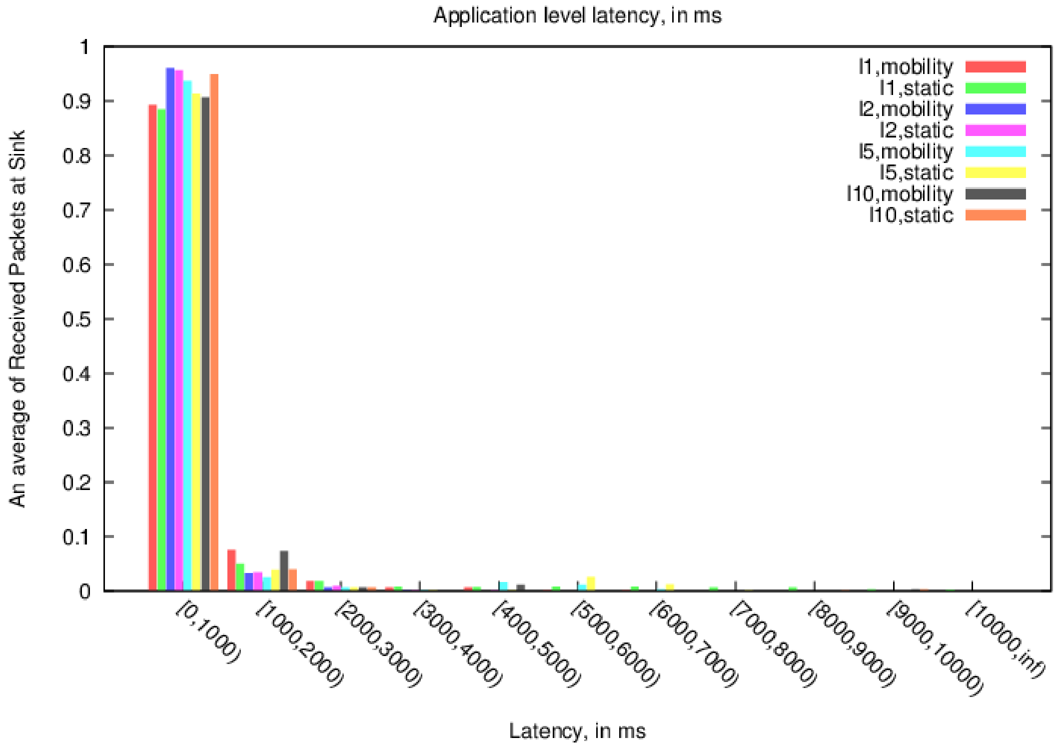

Figure 5.7: Latency for the Delivered Packets Using both Mobility and Static Scenarios for GinMAC Using Different Sensing Intervals.

5.3.3 Analysis of the Results

In this Section, reliability was considered the most important performance criterion needed in the healthcare application. The GinMAC protocol achieves excellent performance in terms of reliability using both mobile and static scenarios. Thus the GinMAC protocol could be used to improve WSNs of the proposed healthcare application when the number of nodes is low. However, efficient routing protocols needed to be designed to improve WSNs by extending the lifetime of the network when the number of nodes is high. As a result, the APTEEN protocol [66] was designed and subsequently a cross layer protocol based on the modified GinMAC and APTEEN protocols was designed using WSNs where energy saving, delay and reliability were all are optimized. This cross layer based protocol will be used for simulating different applications, with a high number of nodes, in the following Sections.

5.4 Cross Layer Based Protocol for Healthcare Applications

The cross layer based protocol given in Chapter 3 was simulated for the proposed healthcare application given in Section 5.2. Reliability of data delivered was considered the most important factor which needed to be guaranteed for this application, although energy consumption, delay and mobility were also measured. Three different scenarios, where the number of nodes was high, were simulated using the cross layer protocol and LEACH protocols across different parameters. More details about simulation models and other specific parameters for the healthcare application simulated in this section were given in Section 5.1.

It was assumed in the healthcare application given in this section that locations of caregivers within the target environments were also monitored. This means that urgent help and treatment could be given to patients based on the patient's and caregivers locations. As a result, the reception or sink selects caregivers who are close to the patients who needed help urgently. Further details about the simulation parameters and scenarios are given below.

5.4.1 Simulation Scenarios and Parameters

Three different scenarios for the proposed application were simulated. The first was a simple scenario, where the number of nodes was 50 (25 mobile nodes (patients), 24 static nodes (environments) and 1 sink (reception)). The second scenario was 2 wards having the same information as in the first scenario, but in this case, patients assumed to be being monitored by both wards. The third was a complex scenario which it involved 8 wards, with each ward having the same information as in previous scenarios.

A cross layer based protocol given in Chapter 3, APTEEN as well as LEACH were simulated all for the proposed healthcare application given in this section. The LEACH and APTEEN protocols were selected in this section as they are cluster based routing protocols which aim to save energy for different applications using WSNs. Details about the proposed healthcare application are given in section 5.2. Energy saving, reliability for data delivered and delay were tested to measure the performance of the proposed cross layer based protocol, APTEEN and LEACH. Based on this, a number of conclusions have been reached concerning applying the modified cross layer protocol to the proposed healthcare application.

Table 5.4: Simulation Scenarios (Healthcare Application)

Parameter	Value
Number of Nodes	50, 100 and 400
Number of beds(in each ward)	25
Number of sinks (receptions)	1,2 and 8
Number of sensors in an environment	24
Number of wards	1,2 and 8
Network Dimensions (meters in squares)	50, 150 and 250
Distance Between pair of static nodes	25-30 meters
Routing Protocols	Cross Layer, APTEEN and LEACH
Physical Parameter	Temperature
Temperature range	30 – 40
Temperature Hard Threshold	38
Counter Time (Frames)	5
Power Transmission for LEACH	0dBm [161]
Power Transmission for Cross Layer (WSNs)	-3dBm or -5dBm [161]
Power Transmission for APTEEN (WSNs)	-3dBm or -5dBm [161]
Power Transmission for Cross Layer (BANs)	-10dBm [161]
Power Transmission for APTEEN (BANs)	-10dBm [161]
Measurement Metrics	Network lifetime, delay and reliability
Mobility Model	Random way-point
Initial Energy(in J)	AA battery (BANs), D battery (WSNs)
Real Radio	CC2420 (WSNs), BAN (BANs)
Slot Length (in ms)	80
Round Length (in sec)	50
Percentage of CHs	5 - 15
Multi hop	4

5.4.2 Analysis of the Results

Delivered Packets and Reliability: Figure 5.8 shows that the cross layer based protocol performs better that both LEACH and APTEEN for the target application in terms of reliability across various scenarios. This improvement is because nodes using the cross layer protocol relay packets based on the cross layer information from network conditions such as RSSI, as well as node's remaining energy and location when data is delivered. Based on this, a number of delivered packets to a sink increases and then reliability of the data delivered improves.

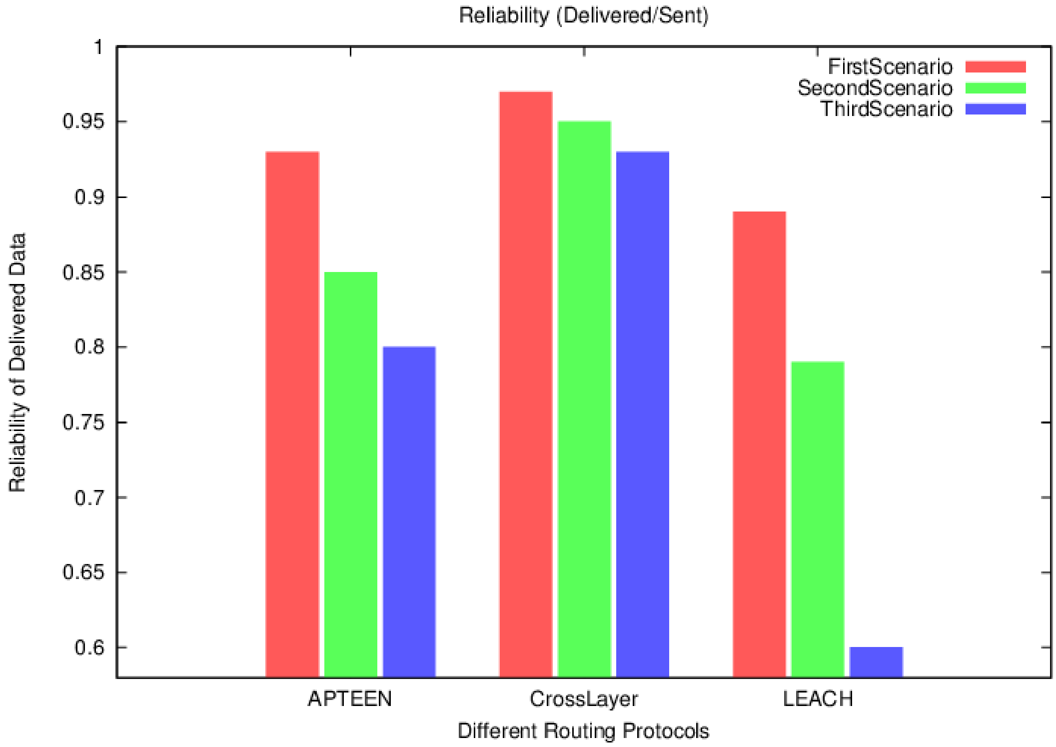

Figure 5.8: Reliability of Data Delivered for Healthcare Application

However, both LEACH and APTEEN do not consider cross layer information when data is transmitted and then number of delivered packets reduces and reliability of the data delivered decreases.

On the other hand, the APTEEN protocol performs better that the LEACH protocol in term of reliability as the APTEEN protocol delivers data across multi hop communications, compared to LEACH where only single hope communications is used. Furthermore, nodes in the APTEEN protocol send data based on different data thresholds compared to LEACH where data is sent in all cases. This makes LEACH unreliable routing protocol for large WSNs where data cannot be delivered to a sink via single hop communication. Results from the second and third scenarios from Figure 5.8 confirm this.

Thus, the designed cross layer protocol could improve WSNs used for the proposed healthcare application when reliability is the main issue.

Energy Saving and Lifetime: Figure 5.9 shows the average lifetime of the network using the cross layer protocol, APTEEN and the LEACH protocols across different scenarios. It can be seen that the cross layer based protocol performs better than the APTEEN and LEACH protocols in terms of saving energy. In addition, APTEEN performs better than LEACH in terms of energy saving. The reasons behind this performance are as follows:

- The selection of CHs in the cross layer based protocol is based on the nodes' remaining energy and, as a result, the probability of nodes dying in their early stages is low, thereby extending the lifetime of the entire network. However, in the LEACH and APTEEN protocols the selection of CHs is based on a randomly selected number [90] which results in a decrease in the lifetime of the network.

- Energy is conserved using the cross layer based and APTEEN protocols by aggregating and reducing redundant copies of data at the intermediate nodes in the network based on different data thresholds. However, in the LEACH protocol, nodes do not consider thresholds when data is delivered.
- Nodes in the LEACH protocol use maximum transmission power (i.e., 0 dB) to deliver data to a sink in all given scenarios using single hop communication. However, in both the cross layer based and APTEEN protocols CHs use low power transmission (i.e., -3dBm or -5dBm) when delivering data to a sink using both multi hop and single hop communications. Low transmission power consumes less energy and this then extends the lifetime of the network.

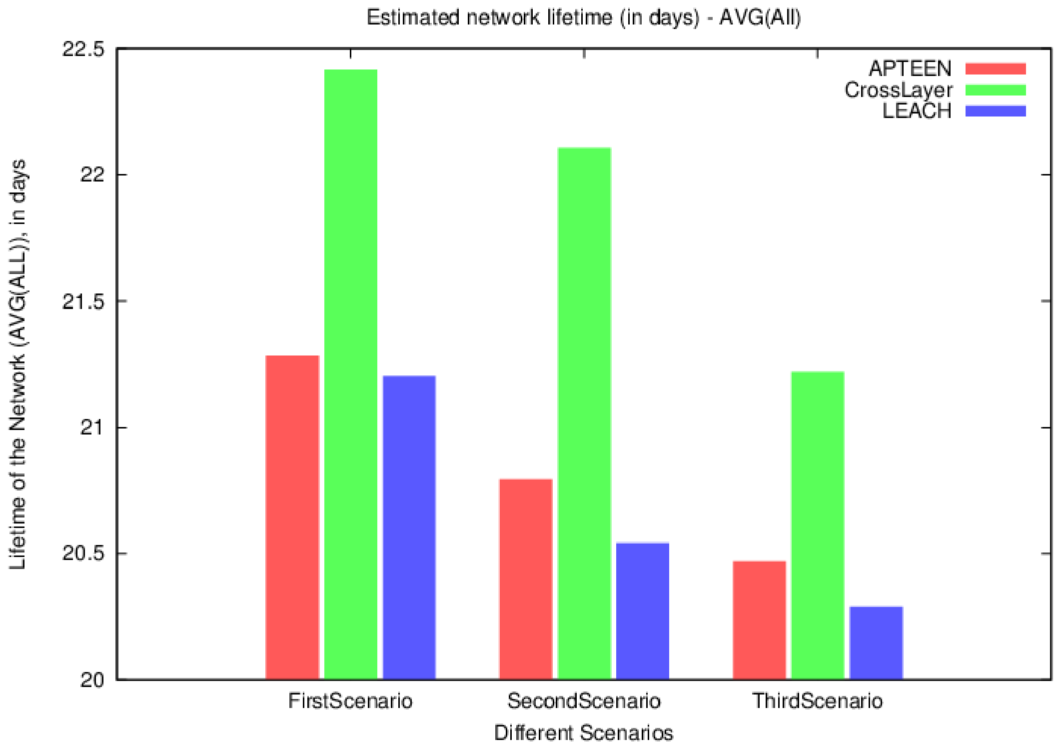

Figure 5.9: Lifetime of the Network for the Healthcare Application

It can be seen that a WSN using the proposed cross layer protocol can survive for more than 21 days using the third simulated scenario and between 22 and 23 days using the first and second simulated scenarios. However, a WSN using the LEACH and APTEEN protocols using all simulated scenarios last between 20 and 22 days. This means that the cross layer protocol performs better than the LEACH and APTEEN protocols for the proposed application in terms of extending the lifetime of the network.

Delay in the Delivery of Data: Figure 5.10 shows the performance of the cross layer protocol, APTEEN and LEACH protocols in terms of delay in delivering data to a sink. It can be seen that all three protocols deliver data from source nodes to a sink from all given scenarios with a minimal delay. This performance is due to the fact that these protocols aggregate data at intermediate nodes before forwarding it to a sink.

According to the results in Figure 5.10, an average of 80% of packets from the network using all given protocols are delivered within the first minute. The remaining data packets from all scenarios are delivered within 3.3 minutes. This shows that some delay is produced when the second and third scenarios were considered using both APTEEN and the proposed cross layer protocols. This is due to the fact that in such protocols data needs to be delivered over mutil hop communication between source nodes and a sink.

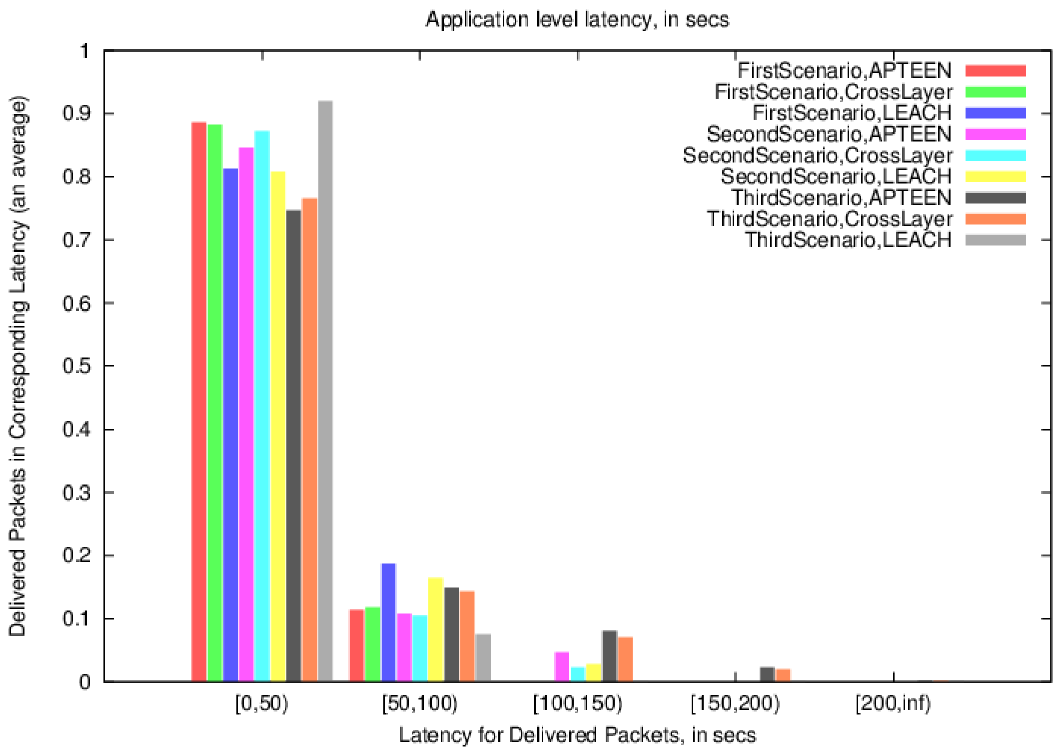

Figure 5.10: Latency for the Data Delivered for the Healthcare Application

5.4.3 Analysis of the Results

Reliability and energy saving were considered the most important performance criteria which needed to be guaranteed in the proposed healthcare application given in this Section. The cross layer based protocol achieved a high performance, in contrast with the LEACH and APTEEN protocols, in terms of both reliability and energy saving across numerous scenarios. Therefore, the cross layer based protocol could be successfully used to improve WSNs used in the proposed healthcare application.

5.5 Wireless Video Sensor Network and Multimedia Evaluation

5.5.1 Wireless Video Sensor Networks

A WVSN is a WSN where each node is equipped with a small video camera to capture the environment. A Field of View (FoV) for each node defines the area and direction in the network where a node can sense the environment to detect an event. This means that each video sensor senses the environment within its FoV to detect events and then informs its neighbours when it is required to as shown in Figures 5.11 and 5.12.

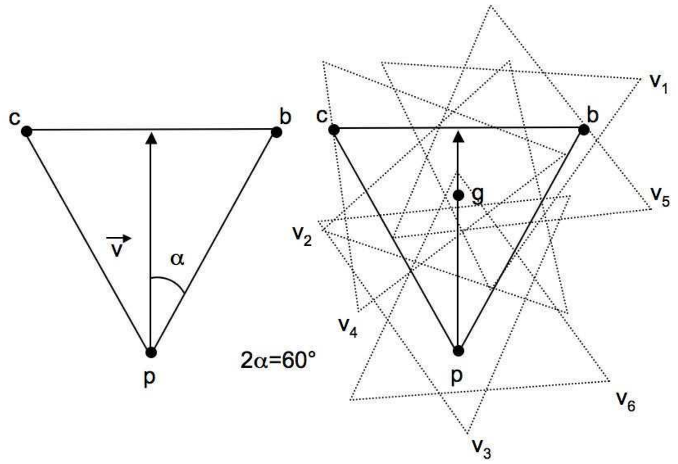

Figure 5.11: Field of View for Sensor Camera Nodes having one Gravity Point (g) [162]

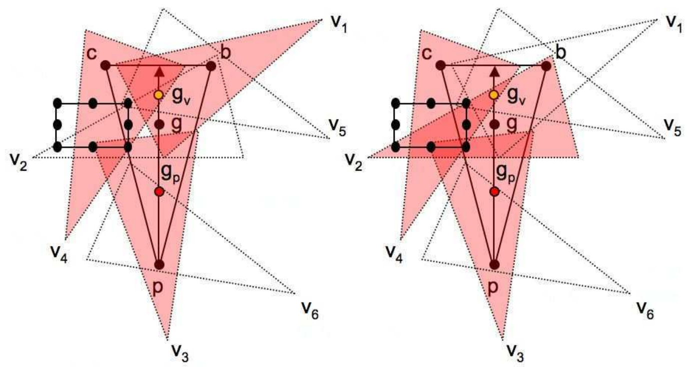

Figure 5.12: Field of View for Sensor Camera Nodes having Alternative Points (g,g_v,g_p) [162]

A WVSN may need a lot of energy to deliver multimedia related contents from source nodes to a sink over multi hop communication. This means that some energy aware algorithms must be designed in order to save energy in the absence of events. As a result, the notion of cover set has, therefore, been introduced to define the redundancy level of a sensor. Thus, a video sensor must use its maximum capture rate just in case it is needed. In order to do this, new techniques which allow sensors to use their capture rates as desired based on the requirements of the proposed applications must be implemented. A higher capture rate consumes more energy [23], [53].

In addition, different parts of the area of interest may have different levels of risk depending on the pattern of observed events such as the number of detected events in a specific area in the network. Sensors placed in the network must be identified with one of the two available levels of criticality which are *low critical* and *high critical*. A low criticality level indicates that nodes in the target application do not require a high video frame capture rate to save energy while a high criticality level does [55]. More details about the cover-set calculation and level of criticality related issues are described below.

5.5.1.1 Video Sensor Coverage Model

There are a lot of challenges involved in designing new protocols for WVSNs due to resource limitation, such as limited energy, and network topology changing. In randomly deployed sensor networks, provided that the node density is sufficiently high, sensor nodes can be redundant (nodes that monitor the same region). This may lead to overlapping among the areas being monitored while some parts of the network may not be covered. One possible solution for this issue is to let some nodes go to sleep when there are other nodes which can cover their sensing area [162]. This means that efficient scheduling algorithms must be designed to enable nodes to go to sleep and change their capture rates based on the number of their neighbours which are available.

An efficient solution for the issues described above for a node n is called a covered set [162] and it is denoted by CoV(n). It is calculated as follows: *CoV(n)* = $\{v_1, v_2, v_3, .., v_m\}$, where FoV for each node in the set $\{v_1, v_2, .., v_m\}$ covers different parts of the FoV of the node n as described in Figures 5.11 and 5.12. Nodes must calculate cover sets and then decide to become active or not based on the availability of their neighbours.

When mobile nodes are involved, cover sets for each node must be updated periodically. To do this, nodes can calculate their cover sets and then decide when they need to become active [55]. Video sensor nodes use their capture rates based on the length of their cover sets. Nodes with maximum cover sets use their maximum capture rates. As a result, a Bezier curves algorithm has been designed as shown in Figure 5.13 and given in [162]. More details about WVSNs, the Bezier algorithm and issues relating to calculating cover sets can be found in the literature [163].

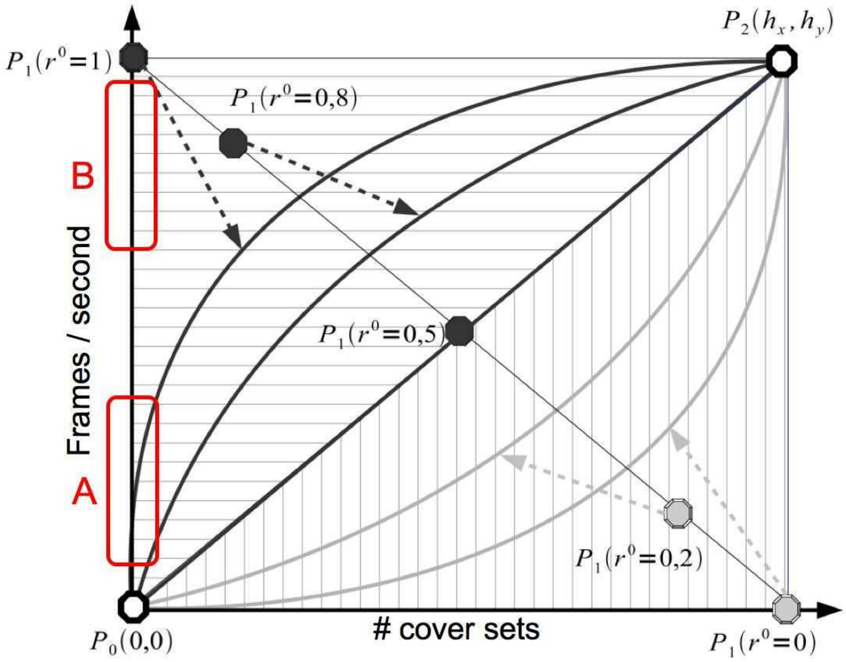

Figure 5.13: Critically Based Schedules in WVSNs [162]

5.5.1.2 Critically Based Schedules in WVSNs

Recent studies in WVSNs have suggested novel methods regarding the critically based schedule related issues which enable nodes to use their capture rates based on their neighbours and critical levels of different parts of the target environments [162]. This decision can be made based on the Bezier curve as described in Figure 5.13. Most sensor nodes move to a so-called hibernate mode or sleep mode in the absence of events in order to save energy. However, it is also highly desirable that some sensor nodes still keep a relatively high capture rate to better detect intrusions/events and to alert other active nodes to move to an alerted mode. This is due to the fact that these nodes can be replaced by their cover sets in case they are damaged or have died [55]. With video sensors, the higher the capture rate, the better relevant events can be detected and identified.

A common approach with the Bezier algorithm using WVSNs is to select a subset of the nodes to be active while the other nodes can go to sleep. This means that when a node has several covers (neighbours), it can use its maximum frame capture rate because if it runs out of energy, it can be replaced by one of its covers. Consequently depending on the application's criticality, the frame capture rate of nodes with a large number of cover sets can be dynamically changed [163].

As shown in Figure 5.13, Bezier curves [55] can be used to compute the level of criticality for different parts of the interested area dynamically. This curve is defined using three different points (P0, P1 and P2) and the level of risk (r), where $r \in [0..1]$. The level of criticality for the proposed application is defined using two levels which are high criticality (when $r > 0.5$) and low criticality ($r \leq 0.5$). These levels are defined by P0, P1, and P2 as shown in Figure 5.13. The Point P0 (0,0) is the origin point and P1 (bx, by) is the behaviour point. The P2 (hx,hy) is the threshold point where hx is the highest number of cover sets which nodes could have and hy is the maximum frame capture rate determined by the sensor node hardware capabilities [53]. The P1(bx,by) is calculated for each node based on the equations given in [53]. Therefore, based on P0, P1 and P2 the Bezier curve is then calculated and is defined by B(t) [162]. As a result, nodes dynamically increase or decrease their capture rates according to the level of risk (r) for the proposed application using the above calculation.

When video sensor has maximum cover sets, it can use its maximum capture rate (when r = 1 as shown in Figure 5.13) for better detection. The lowest capture rate (when r = 0) is used to save energy when no events are happening. This means that capture rates for video sensors can be changed from the lowest rate to the highest rate using the Bezier curves based on the criticality (r) of the proposed application (from rectangle A to rectangle B, as shown in Figure 5.13). Some examples which show how the **Bezier** curve enables video sensor nodes to increase their capture rates based on the level of detected events and numbers of their cover sets are given in [162].

5.5.2 Multimedia Management and Evaluation using WVSNs

5.5.2.1 Multimedia Management

Applications involving multimedia transmissions over WVSNs must evaluate the video quality from the user's perspective as well as video related characteristics such frames with different priorities (I, P and B) when testing different protocols for such applications. The loss of high priority frames causes video distortion from the human's perspective. Some of these frames have a direct impact on the quality of the multimedia delivered while others have a smaller effect [53].

If an I-frame is lost, the errors propagate through the rest of the Group of Picture (GoP) because the decoder uses the I-frame as the reference frame for all other frames within a single GoP. When this occurs, the video quality recovers only when the decoder receives an unimpaired I-frame. If a P-frame is lost, the impairments extend through the remaining GoP. The loss of a B-frame only affects the video quality of that particular frame [162].

Multimedia flows enable the end users (systems) to visually determine the real impact of the detected event, performing object/intruder detection and analysing the sensed events based on the visual information from the WVSNs. However, the Castalia simulator [67] and its extensions do not enable the transmission control and evaluation of real video sequences. Therefore, a new framework which is called *M3WSN* [164], has been designed for multimedia management and evaluations over WVSNs based on the Evalvid framework [165].

The Evalvid framework [165] provides video related information, such as frame type, received/lost data, delay, jitter and decoding errors for the received or distorted videos. This information enables the creation of new assessment and optimization solutions for fixed and mobile nodes involving multimedia related scenarios. The Evalvid framework can be used for video transmission and quality evaluation based on videos sequence and different traces. Thus, before transmitting a real video sequence, video sources, for example from the video library [166] must be given in advance.

5.5.2.2 Encoding and Decoding Multimedia Contents

Once the video is encoded, trace files must be produced on both sender and receiver sides. These files contain all relevant the information for transmission and the evaluation tools which provide routines to read and write these traces for multimedia evaluation. Therefore, three kinds of trace files are involved in multimedia evaluation over WVSNs [164]. Two of them are created on the sender side, namely video and sender traces. On the other hand, the destination node creates the receiver traces. Both sender and receiver trace files are required to evaluate multimedia contents over multi hop communication using WVSNs. These trace files and original videos are combined at the final destination in order to reconstruct the videos delivered.

The video trace is created once and contains all the relevant information about every frame that comprises the video. Sender traces for the transmitted video are created using the framework given in [164] as it includes a module to let nodes retrieve a video based on detected events. However, the receiver trace is created at the final destination to receive the multimedia packets and reconstruct the delivered video at the final destination (sink). This framework can be used for measuring the different QoSs regarding the delivered videos at the final destination. This includes an overall rate of the delivered videos, a delivered/loss rate of the transmitted frames and delay for delivered videos. As a result, this framework can be used for evaluating and analysing different applications involving multimedia transmission using WVSNs.

5.5.3 A Multimedia Based Application

5.5.3.1 A Security Application based on Multimedia Transmission

Security related applications based on multimedia transmissions [53] are typical surveillance and monitoring related applications using WVSNs. Events from target environments can be detected by sensors and the information sent back to a sink enabling the required decisions to be taken. A WSN is the best solution for these applications because of the following features: (i) Capabilities of a WSN for sensing and collecting data from its environment and then sending this data back to a sink. (ii) The low cost of individual sensors; when some nodes die other nodes can replace them. However, a WSN must be able to reconfigure itself when some nodes run out of energy in order to keep the network well-connected.

Cluster based WVSN architecture of different levels for an event detection application is considered in this section as it is more suitable for the proposed application given in this Section [161]. An example of the proposed application is given in Figure 5.14 and consists of two types of nodes, scalar and camera nodes. Scalar sensor nodes perform simple tasks, such as detecting scalar physical measurements within their sensing ranges. Resource rich camera sensors are given responsibility for doing complex tasks, such as sending the multimedia from the detected events to a sink when this is required.

The scalar sensor nodes have a limited sensing range to sense the environments and detect events. On the other hand, camera sensors nodes are given the responsibility for capturing the detected events using their equipped video cameras in the positions where these events were detected. This information is then sent back to a sink via multimedia transmission. This means that scalar sensors have to wake up the camera nodes when any events were detected.

In the proposed application, nodes are multi-featured, for example, nodes can sense the environment and carry out the surveillance at the same time. This means that nodes sense the environment using temperature measurements and also carry out surveillance by sensing vibrations from objects moving around (tracking intruders). Information about this must be delivered to a sink using camera nodes in order for the required actions to be taken [167].

Target intruders in this application were mobile and can move randomly in the environment being monitored. Source sensor nodes then sense the environment and wake the camera nodes up when events are detected as previously discussed. Camera sensor nodes capture the targets after receiving alert messages from scalar nodes using their FoVs. This shows that, depending on the direction of the video camera and its features for angle and depth of view, events in the environment can be captured and monitored [168].

Many approaches have been used to show how intruders can be detected considering different points of the FoV for camera nodes when sensing the target environments. As a result, two approaches have recently been proposed using WVSNs [53], [162]. The first approach [53] considers a camera node with an FoV covering only one gravity point (g) with different angles. In this approach, an FoV with wider angles can detect more intruders as shown in Figure 5.11. However, the second approach [162] involves an FoV with several alternative gravity points ($g_1, g_2, .., g_m$) as given in Figure 5.12. The second approach is often preferred because an FoV with more alternative points can cover more nodes (neighbours) and therefore detect more events. Based on this, the second method was used in this application [162].

When a camera node receives wake up messages from scalar sensors, it should change the direction of its FoVs to the locations where the events have been detected. The nodes then retrieve multimedia or video from the alarmed target area as shown in Figure 5.14. The captured multimedia for the detected events can provide users (control staff) with more precise information and allow them to decide on suitable actions in real time. In addition, the transmitted videos are useful for detecting and predicting the intruder's movements and direction so that appropriate decisions can be taken. An example of an intrusion detection based application using WVSNs is given in Figure 5.14, which details the application proposed in this section.

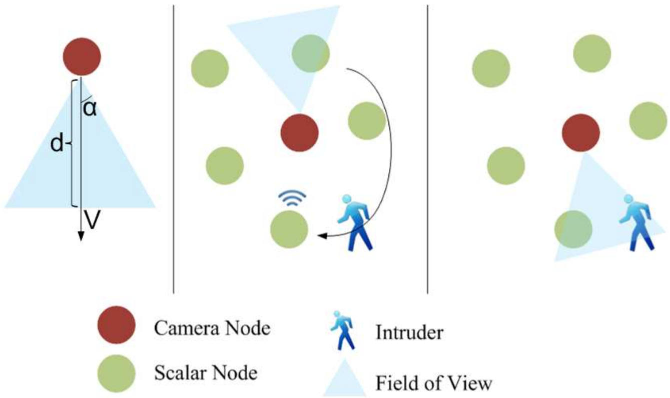

Figure 5.14: Typical Scenario for the Security Related Applications using WVSNs [55]

Multimedia related applications using WVSNs require high video quality from the user's perspective, scalability, energy efficiency and low network overheads. In order to efficiently transmit video packets under certain application level requirements over multi hop communication, efficient routing protocols must be designed. To do this, the cross layer based protocol given in Chapter 3 was tested and simulated for the application proposed and the results are presented in this Section.

The cross layer based protocol can provide suitable communication architecture for the application scenario described above. A multi-hop communication with cross layer information to select different routes for delivering data based on network conditions is considered in the proposed protocol. Camera sensor nodes are CHs and scalar sensor nodes are members belonging to different clusters. This means that each CH has basic information about their members such as location and remaining energy. This information can be used by CHs when receiving wake up messages from their members to change their FoVs to the target and alarmed area in order to capture pre detected events. This information is maintained during wake-up periods of the camera sensor nodes.

5.6 Cross Layer Protocol for Multimedia Based Applications

5.6.1 Simulation Scenarios

Both cross layer based protocol and the LEACH [130] protocol were simulated in this Section using different scenarios for the proposed application. The simulation consisted of four different scenarios for the environment being monitored considering different parameters. Simulation parameters for all scenarios are given in Table 5.5. Each video sensor node is defined by its position (x,y), a depth of view (d) for the camera, a line of sight (V) for the camera and an angle of view (AoV), as shown in Figure 5.14. The field of view of a sensor is then represented by a triangle as shown in Figure 5.11.

The LEACH protocol was selected in this section as it is a cluster based routing protocol designed to save energy using WSNs. The LEACH protocol was modified to manage multimedia transmissions when required. This modification included implementing a new aggregation technique at the CHs nodes to extract useful information from received data before forwarding it to a sink. In addition, a new technique was designed to retrieve multimedia contents from the locations where events were detected and send them back to a sink. More details about simulation models and other specific parameters for the application simulated in this section were given in Section 5.1.

This simulation was conducted to analyse the performance of the cross layer based protocol and LEACH protocols for the multimedia management using the given framework [164]. This framework is designed to evaluate the transmitted videos over WVSNs using different protocols. The M3WSN framework efficiently defines a model to find subsets of nodes covering a given area in the network as well as managing the sensing range for each node by a FoV as shown in Section 5.5. The EvalVid framework [165] provides support for the transmission, control and evaluation of real video sequences in simulation environments as shown in Section 5.5.2. The critical sensor management and cover sets discovering modules are implemented in the same framework. This lets video sensors capture the environment and send multimedia content to a sink when required.

The application architecture given in Figure 5.14 was considered in this section in order to show the impact of different routing protocols for delivering the captured multimedia or video from the detected events to a sink. In this application, the quality of videos transmitted, delay and the lifetime of the network were crucial. For this application, the video sequence was chosen from the Video Trace Library [166]. This video uses the Quarter Common Intermediate Format (QCIF) as it is more suitable format for transmitting and measuring small sized videos using WVSNs [162]. Long-normal Shadowing and MPEG-4 models were selected in this application as they have been used for measuring multimedia over WVSNs for different applications as shown in the literature [161].

Table 5.5: Simulation Parameters for the Multimedia Based Application

Parameter	Value
Routing Protocols	Cross Layer, LEACH
Number of nodes (Scenario1)	50
Number of nodes (Scenario2)	100
Number of nodes (Scenario3)	200
Number of nodes (Scenario4)	500
Percentage of CHs	5 - 15
Round duration	20 seconds
Duration of each slot	1 seconds
Location of Base Station	(0,0)
Number of Intruders	1 - 4
Temperature Threshold	48
Transmission Power for LEACH	0 dBm [161]
Transmission Power for Cross Layer	-5 or -3 dBm [161]
Radio	CC2420
Radio Propagation Model	Log-normal Shadowing
Video sequence	Hall
Video encoding	MPEG-4
Number of frames for each Video	300
Video format	QCIF (176 x 144)

The hall monitored video sequence was chosen from the Video Trace Library [166] for this application as it is a most suitable for multimedia related applications such as intrusion detection. The hall video sequence is considered to be a high movement video which is most proper video sequence for the proposed application given in this section. This video characteristic is expected for many WVSNs applications, such as environmental monitoring [137], [162]. The hall video contains two targets moving in the hall and, based on this movement, different routing protocols can be measured and simulated.

Routing protocols are usually evaluated from a network and packet level point of view by using QoS metrics, e.g., delay, jitter or loss. However, QoS metrics do not reflect the user's perception and, consequently, fail to capture subjective aspects of the human's experience when multimedia need to be considered [161]. As a result, Quality of Experience metrics (such as Peak Signal to Noise Ratio (PSNR), Structural Similarity (SSIM) and Video Quality Metric (VQM)) a long with their approaches have been designed. These techniques were designed to overcome the limitations of current QoS aware routing schemes regarding human perception and subjective related aspects [23].

Therefore, to highlight the impact of using the routing protocols given in this section, from the user's point of view and to measure the quality of the delivered videos, the simulation scenarios evaluate the transmitted videos. Both PSNR metric [161] and the rate of the delivered frames [164] were considered in this application. The EvalVid and M3WSN frameworks [137] were used for measuring the quality of the delivered videos at the final destination. The PSNR metric has values ranging from 0 to 41 dBm. A higher value means a better video quality as shown in Table 5.6.

Table 5.6: PSNR Evaluation Values (dBm) [161]

Number	Value
40.0 - 41.0	Excellent
37.0 - 39.9	Very Good
30.0 - 36.9	Good
20.0 - 29.9	OK
0 - 19.9	Bad

Four different scenarios for the proposed application were considered in this section. The first scenario consisted of placing nodes in a small field (a one floor-based security environment) so that all the nodes can communicate with a sink using a single hop communication. The second scenario was a network where source nodes were looked away from the sink and where multimedia contents could not be delivered using a single hop communication (two floor-based security environments). The third and fourth scenarios were large scenarios where data needed to be delivered over long routes between source nodes and a sink (multi-floor based security environments). In all given scenarios, the cross layer based protocol and LEACH protocols were measured in terms of delivering the multimedia contents from different parts of the network to a sink. Quality of service and simulation results are discussed below.

5.6.2 Quality of Service for the Proposed Application

In this application, the target environment is monitored by sensing the temperature in different parts of the environment and carrying out the surveillance at the same time. Target Intrusions for the proposed application are mobiles and then move randomly to different locations automatically. Information about the detected event (intruders or high temperature) must be delivered to a sink with a high accuracy while consuming a small amount of energy. As a result, the following features are crucial for the proposed application:

1. **Lifetime of the Network:** The lifetime of the network for this application can be defected by total number of nodes active during a period of time. Nodes need to be active only when required in order to extend the lifetime of the network. The lifetime of the network can be extended using cover set related algorithms. Nodes with shared cover sets with other nodes can simply go to sleep [163]. However, the lifetime of the network has been defined recently using different concepts based on realistic scenarios [3].

Therefore, in this application, the lifetime of the network is the maximum period of time that a WSN can survive, whilst spending energy at a given rate. The lifetime of each node in the network for this application can be calculated as shown in (4.1) and the lifetime of the entire network can be defined as shown in (4.2).

2. **Reliability of the Delivered Videos:** When an event is detected in the target environment then the multimedia representing this event must be delivered to a sink with an acceptable level of accuracy. Some applications may accept low quality for the received videos while others accept only videos with a high quality. In this application, the received videos must be clear enough so that the required actions can easily be taken. As a result, the quality of the delivered videos for this application based on PSNR and delivered frames was calculated as shown in (5.1) and (5.2), respectively.

$$Quality(PSNR) = \frac{\sum_{v=1}^{V} PSNR(v)}{V} \tag{5.1}$$

$$Quality(Frames) = \frac{\sum_{v=1}^{V}(v\_I + v\_B + v\_P)/3}{V} \tag{5.2}$$

Where V is the number of delivered videos at the final destination (sink) and v_I, v_B and v_P are frames for the delivered video (v) with corresponding types, respectively. $PSNR(v)$ is psnr value for the transmitted video (v).

3. **Delay in the Delivery of Videos:** Videos for the detected events must be delivered to a sink within a minimal delay so that events can be captured and identified in order to avoid further risks and damage. Delay for end to end videos delivered at a sink can be calculated as shown in Section 4.1.2.

5.6.3 Analysis of the Results

Different scenarios for the proposed application using the cross layer based protocol and LEACH where the lifetime of the network, quality of the delivered videos and delay were crucial, were simulated in this section. Simulation results are discussed below.

Quality of the Delivered Videos: Figures 5.15 and 5.16 show the performance of the cross layer based protocol as well as the LEACH protocol using different scenarios for the proposed application based on the PSNR metric and delivered frames, respectively. The video quality varies depending on the distance between the locations of detected events and the sink.

As shown in Figures 5.15 and 5.16, both the LEACH and the cross layer based protocols deliver multimedia from source nodes to a sink with high reliability when small networks are considered (first scenario). The reason behind this is that for single hop communication the camera nodes or CHs send multimedia packets using a single hop transmission. The sink is in the transmission range of the nodes and the packets are received with a high reliability and the quality of the delivered videos is good. As a result, both the LEACH and the cross layer based protocols deliver multimedia with a good quality and high reliability (an average of 100% of frames and PSNR = 40 dB) from the detected events to a sink.

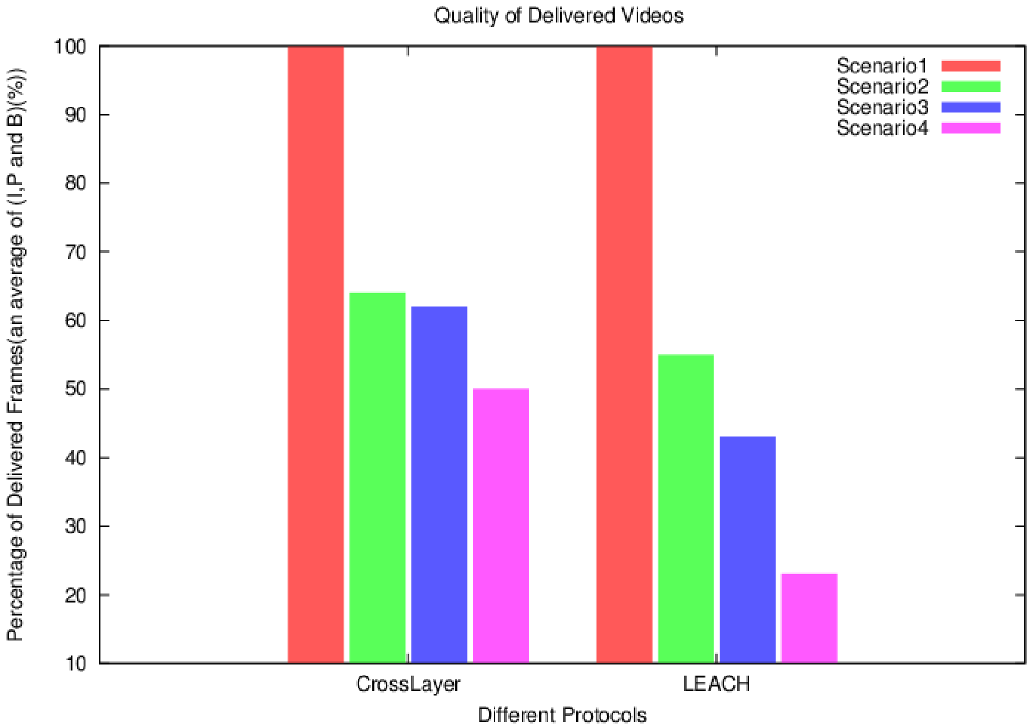

Figure 5.15: Reliability of the Transmitted Videos Based on an Average of the Delivered Frames

However, as shown in the same figures, the cross layer based protocol performs better than the LEACH protocol in terms of delivering multimedia from source nodes to a sink. This occurs specially when data cannot be delivered from source nodes to a sink using a single hop communication (second and third scenarios). The cross layer based protocol, however, uses multi hop communication with a cross layer solution to select reliable routes for delivering packets holding the multimedia contents to a sink based on network conditions. This involved using RSSI, remaining energy and number of hops as routing metrics when delivering data from source nodes to a sink. This decreases packet loss and increases the quality of the delivered videos.

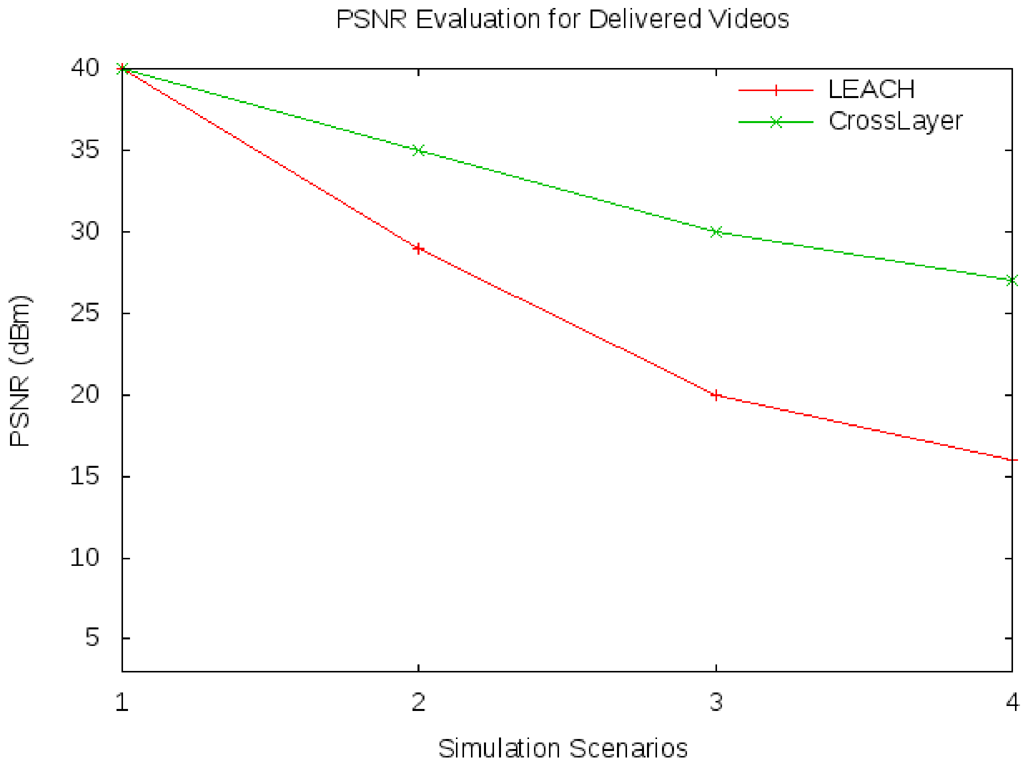

Figure 5.16: Quality of the Transmitted Videos Based on PSNR Metric

On the other hand, CHs using the LEACH protocol could not deliver data to a sink with acceptable rates when large scenarios were considered as shown in Figures 5.15 and 5.16. This is because the sink is not in the transmission range of the nodes and the LEACH protocol does not use cross layer information to select reliable routes using multi hop communication. CHs using the LEACH protocol consider only a single hop communication and this makes LEACH an unsuitable routing protocol for large WVSNs. As a result, the number of discarded packets is higher and then the reliability of the delivered videos at the final destination is lower. In addition, a very large and complex scenario was simulated (fourth scenario) to test both protocols where a high number of nodes was placed in a large network. In this case, the cross layer based protocol can still deliver data to a sink.

As a result, the cross layer based protocol offers a good performance in terms of the quality of the delivered videos based on PSNR and delivered frames for all given scenarios. As shown in Figures 5.15 and 5.16 the performance of the cross layer based protocol in terms of reliability for delivering videos is decreased in the second and third scenarios, compared to the first scenario. This is because multimedia contents, holding the information about the detected events, require a huge amount of data which must be delivered over multi hop communication from source nodes to a sink.

If it is crucial that performance exceeds that given in Figures 5.15 and 5.16, the cross layer based protocol must be improved. One way to do this is to modify the proposed cross layer based protocol by adding new video encoding related techniques [23], so that data can be discarded depending on the types of frame. In this case the number of delivered frames with type I-frame must be assigned as high priority as this directly affects the quality of the delivered videos [161].

Lifetime of the Network: Figure 5.17 shows the lifetime of the network using the cross layer and the LEACH protocols for the proposed application, taking different scenarios into account. As shown in Figure 5.17, the cross layer based protocol extends the lifetime of network compared to the LEACH protocol in all given scenarios. The reasons for this are as follows:

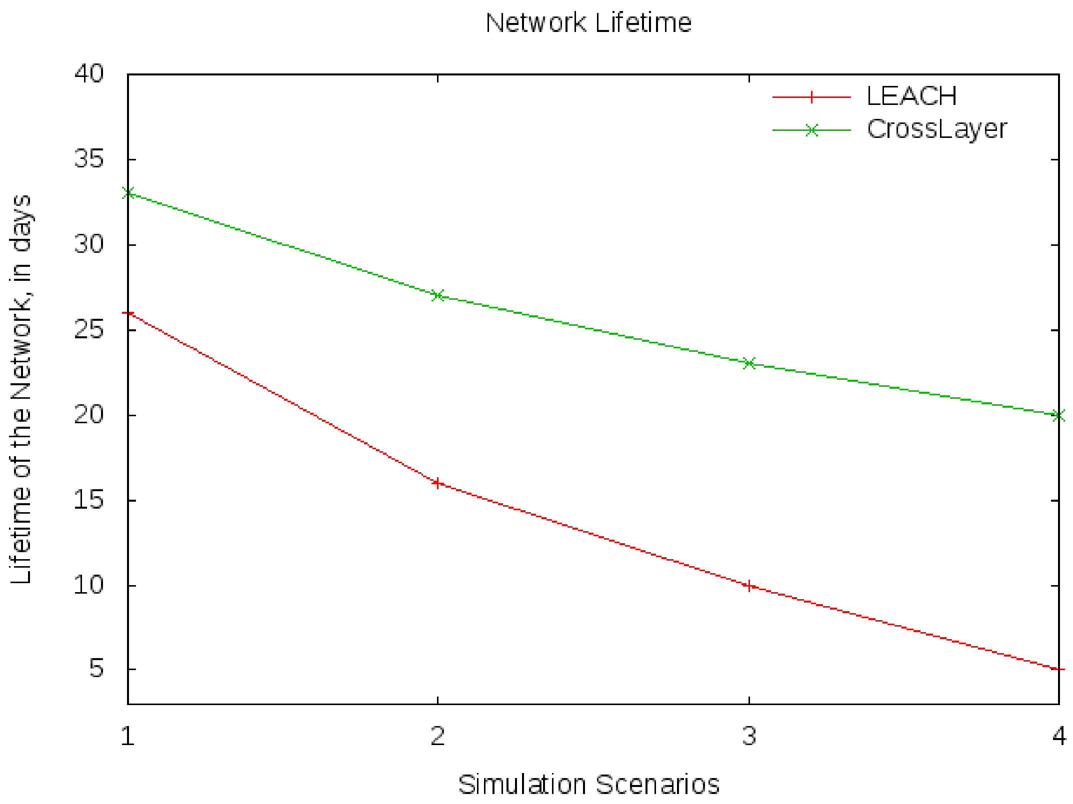

Figure 5.17: Lifetime of the Network for the Multimedia Based Application

- The selection of CHs in the cross layer based protocol is based on the nodes' remaining energy and, as a result, the probability of nodes dying in their early stages is low. Because of this, the lifetime of the entire network is extended. However, in the LEACH protocol the selection of CHs is based on a randomly selected number as shown in the literature [90], which results in a decrease in the lifetime of the network.

- Nodes in the LEACH protocol use high transmission power (0 dB) to deliver videos to a sink in all given scenarios using single hop communication. However, in the cross layer based protocol CHs use low power transmission in both multi hops and single hop communications. Lower transmission power means low energy consumption and this extends the lifetime of the network.

Therefore, as shown in Figure 5.17, a WSN for all given scenarios using the cross layer based protocol can survive for between 20 days and 33 days, compared to the LEACH protocol where a WSN can remain alive for between 5 days and 26 days. This concludes that the cross layer protocol performs better than LEACH for the proposed application where the lifetime of the network is crucial.

Delay in the Delivery of Videos: Multimedia contents from source nodes from different parts of the network using both the LEACH and the cross layer based protocols were delivered within a short space of time as shown in Figure 5.18. This means that both the cross layer based and LEACH protocols give a similar performance in terms of delivering data from source nodes to a sink when nodes can deliver data to a sink using a single communication.

However, in the cross layer protocol some delay was experienced because of multi hop communications between source nodes and a sink when large networks were considered (second and third scenarios). This is due to the fact that nodes in the LEACH protocol use only a single hop communication for delivering data, thus minimising delay, compared to the cross layer protocol where some delay occurs because of multi hop communications between source nodes and a sink. Data from the detected events from all scenarios using the LEACH protocol were delivered within the first 30 seconds while in the cross layer based protocols all data were delivered within a minute as shown in Figure 5.18.

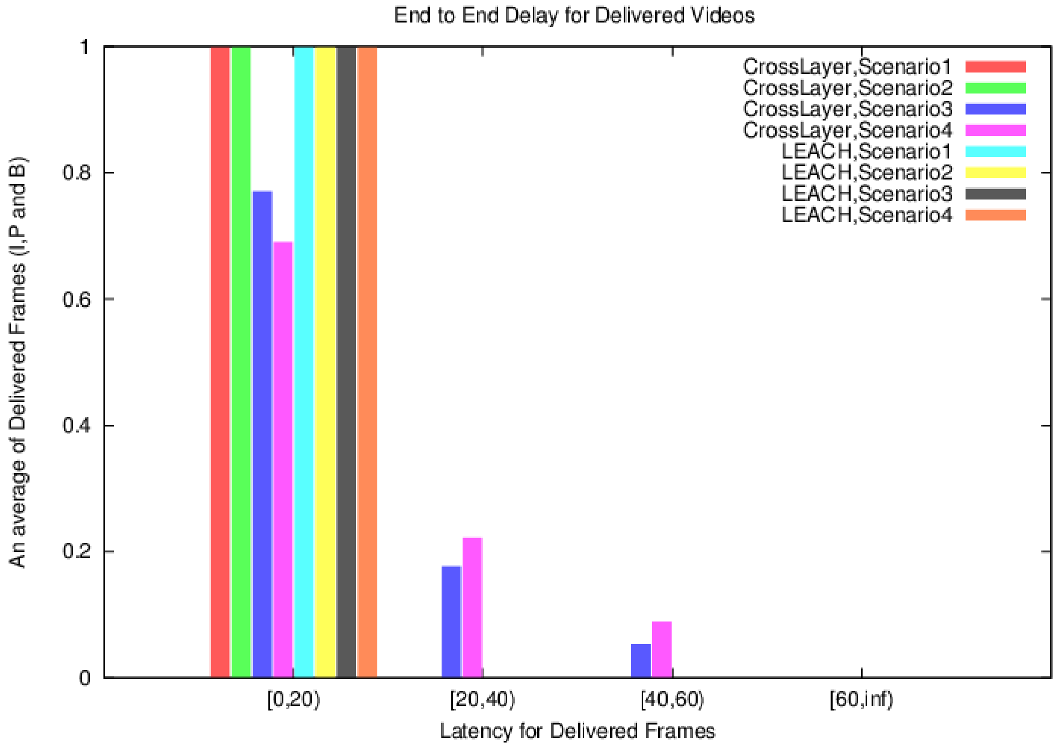

Figure 5.18: Delay of the Delivered Videos for the Multimedia Based Application

The reasons behind the performance of both the cross layer based protocol and the LEACH protocols in terms of reducing delay associated with delivering multimedia contents to a sink are as follows: (i) only CHs are involved in routing and forwarding data to a sink. This reduces the routing complexity in large WVSNs and consequently also the delay into delivery of data. (ii) The ability of the CHs to aggregate and reduce redundant copies of data at the intermediate nodes in the network which results in reducing the delay associated with delivering videos.

Chapter 6

Conclusion and Future Work

This chapter concludes the research background and literature review, and discusses the implementation and main findings. In addition, research contributions, the research limitation and possible future work are discussed.

6.1 Conclusion

Recently WSNs have attracted a great deal of attention from researchers both in academia as well as industry. This is primarily due to their unique capabilities and promising application in areas like health care, sports, military and security. Although sensor nodes are expected to be on most of the time, it is not required to be working all the time. As a result, the design and implementation of WSNs pose several challenges, mainly due to limited resources and the limited capabilities of sensor nodes, in matters such as power and storage. To accomplish their task, sensor nodes are required to communicate with each other and act as intermediate nodes to forward data on behalf of others so that this data can reach the sink, which is responsible for making any necessary decisions. Different applications using WSNs have different requirements so a generic package cannot be used.

6.1.1 Background and Required Literature Reviewed

Based on the literature reviewed and the evaluation given in Chapter 2, the GinMAC and APTEEN protocols were modified to improve WSNs by supporting mobile nodes. In addition, a cross layer protocol based on the modified GinMAC and APTEEN protocols has then been designed to improve the capability of WSNs by increasing performance of different applications. This included improving reliability, extending the lifetime of the network and reducing the delay in the delivery of the data.

6.1.2 Proposed Protocols and Performance Evaluation

Based on the literature and background given above, the GinMAC and APTEEN protocols were selected in this research as they optimize the performance for the proposed applications using static TDMA and cluster based capabilities. These two protocols were validated by the existing literature evidence, before they were modified for this research. This research showed that the cross layer protocol based on network conditions can improve performance for different applications in a number of different scenarios.

Therefore, in this research, the GinMAC, APTEEN and cross layer based protocols were modified and designed to include mobility and routes discovery modules for different applications using WSNs. The key idea behind these protocols was combining TDMA schedules and the cross layer information based on network conditions when data needed to be delivered. In addition, the node's remaining energy was taken into account when cluster head were selected in order to extend the lifetime of the network. It has been shown that these protocols including a mobility module improve WSNs for different applications where different scenarios were considered.

As simulation was the only method used for performance evaluation of the proposed protocols, different applications were considered with various scenarios and particular focus was given to energy saving, delay and reliability of the data delivered. The proposed protocols were used for the following applications:

1. Healthcare; when data needs to be collected from patients and then sent back to a health centre for future decisions. Three different scenarios were considered for this application using different parameters [3], [4].

2. Multimedia based applications, based on multimedia transmissions considering different scenarios. Four different scenarios with different parameters were applied [152].

3. More applications about the environment monitoring using the protocols proposed [169] in this research are given in Appendix D.

6.2 Contribution to Knowledge

The following is a discussion of the contribution made by this work to the body of knowledge in this field:

1. Improving the ability of WSNs to support mobile nodes through enhancements to the MAC layer protocol [2], [4].

2. Improving the ability of WSNs to support mobile nodes through enhancements to the Network layer protocol [3].

3. Improving the ability of WSNs to increase the performance of different applications through combining the MAC and network protocols [152], [169].

6.3 Main Findings

The performance evaluation and simulation results showed that the cross layer protocol based on the modified GinMAC and APTEEN protocols improved the performance of WSNs for different applications and various scenarios enabling the following requirement to be met:

1. Supporting mobile nodes was required such in healthcare applications.

2. Reliability of the data delivered over multi hops using WSNs can be increased by considering cross layer information based on network conditions, such as RSSI, nodes' remaining energy and location.

3. Extending the lifetime of the network by distributing energy usage between nodes.

4. The delay in data transmission can be minimized and energy can be saved by reducing the number of non-critical data transmissions.

Based on these findings, the questions for this research have been answered. A list of publications arising from this thesis is given in Appendix A. In addition, thesis related awards are given in Appendix B. Furthermore, all papers are bounded in Appendix D.

6.4 Limitations and Suggestions for Future Work

6.4.1 Limitations

In this research during the simulation of the applications, cluster head nodes were not allowed to be mobile in the proposed protocols. This means that these protocols could not be applied to applications where all nodes are mobile, such as military related applications using WSNs. In addition, security related algorithms, where data can be protected from attackers, were not designed for the proposed protocols, as this was beyond the remit of this research.

6.4.2 Future Work

Data collected from the target environments in this research, was very sensitive and must be maintained properly as this data is required by the control system for future diagnosis. Sensor nodes are provided with a small storage capacity and data collected from the sensors cannot be managed by control staff who are invited from abroad to handle critical cases. An example of this is when doctors who are specially invited from abroad need to handle critical cases for their patients.

This problem can be solved by forming a cloud where data collected from the target applications using WSNs can be stored. This allows a control system to access data and take appropriate from the distance. As a result, this research could be expanded to deal with this issue if it was a crucial requirement for the target applications. In the light of the limitations and contributions given above, this work could be extended in the following areas:

- Modify the mobility module given in the proposed protocols so that all nodes can be mobile.
- Simulate the modified protocols for applications using WSNs where all nodes need to be mobile such as military related applications.
- Design security related modules for the proposed protocols, based on key encryption algorithms, allowing the security and privacy of the data transmitted in given applications to be protected.
- Combine WSNs with cloud computing when it is crucial to share and analyse real time sensor data from a distance.
- Perform test-bed experiments using a small WSN to confirm the simulation results.

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Appendix A

List of Publications

Publications arising from this thesis are the following with corresponding chapters and sections:

A.1 International Conferences

1. Muhsin Atto and Chris G Guy. Wireless sensor networks: MAC protocols and real time applications. In The 13th Annual Post Graduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting (PGNet2012) , Liverpool, United Kingdom, June 2012. (Chapter 2, section 2.2, MAC protocols)
2. Muhsin Atto and Chris Guy. Wireless sensor networks: MAC protocols and mobility management module for real-time applications. In The Ninth International Conference on Wireless and Mobile Communications (ICWMC 2013), pages 1–6, Nice,France, July 2013. (Best paper awarded)
http://www.iaria.org/conferences2013/AwardsICWMC13.html). (Chapter 3, section 1).

A.2 International Journals

1. Muhsin Atto and Chris Guy. MAC Protocols and Mobility Management Module for Healthcare Applications Using Wireless Sensor Networks . International Journal On Advances in Networks and Services, Volume 7, Number 1, June 2014, ISSN: 2079-8407. (Chapter 3, section 1 and Chapter 5, section 1).
2. Muhsin Atto and Chris G Guy. A cross layer protocol based on MAC and routing protocols for healthcare applications using wireless sensor networks. In International Journal of Advanced Smart Sensor Network Systems (IJASSN), volume 4, April 2014. (Chapter 3, section 2 and Chapter 5, sections 5.2, 5.3 and 5.4)

3. Muhsin Atto and Chris Guy. A Cross Layer Protocol for Energy Aware and Critical Data Delivered Applications Using Wireless Sensor Networks. In Journal of Emerging Trends in Computing and Information Sciences, volume 5, Number 4, April 2014.

4. Muhsin Atto and Chris Guy. Routing Protocols and Quality of Services for Security Based Applications Using Wireless Video Sensor Networks. In Network Protocols and Algorithms, volume 6, Number 3, August 2014. (Chapter 5, sections 5.5 and 5.6).

5. Muhsin Atto and Chris Guy. Routing Protocols for Structural Health Monitoring of Bridges Using Wireless Sensor Networks. In Network Protocols and Algorithms, volume 7, Number 1, April 2015.

Table A.1: Publications and corresponding Chapters and sections in this Thesis

Chapter	Section	Paper
Chapter2	Section 2.2	[4]
Chapter3	Section 3.1	[2]
Chapter3	Section 3.2	[3]
Chapter5	Sections 5.2, 5.3 and 5.4	[3]
Chapter5	Sections 5.5 and 5.6	[152]

These papers are bounded in Appendix D.

Appendix B

Research Related Awards

B.1 Best Paper

Muhsin Atto and Chris Guy. Wireless sensor networks: MAC protocols and mobility management module for real-time applications. In the Ninth International Conference on Wireless and Mobile Communications (ICWMC 2013), pages 1–6, Nice,France, July 2013.
Details can be found in http://www.iaria.org/conferences2013/AwardsICWMC13.html

B.2 Invited Paper

Muhsin Atto and Chris Guy. MAC Protocols and Mobility Management Module for Healthcare Applications Using Wireless Sensor Networks. In the International Journal On Advances in Networks and Services, Volume 7, Number 1, June 2014, ISSN: 2079-8407.
Details can be found in http://www.iaria.org/conferences2013/AwardsICWMC13.html

Appendix C

Simulation Results

More simulation results regarding the validation of protocols given in Chapter 4 and applications described in Chapter 5 are presented in this Appendix. Simulation results regarding the GinMAC validation scenarios given in Chapter 4 are outlined in Section C.1. More simulation results regarding the APTEEN validation, given in Chapter 4, are discussed in Section C.2. More simulation results for the multimedia application using the cross layer protocol are given in Section 5.5.2. Simulation results regarding the healthcare application are given in C.3.

C.1 GinMAC Validation

This section outlines the simulation results from the GinMAC validation where different data threshold values were considered. These results include latency of the delivered queries and duty cycle for saving energy using different sensing intervals.

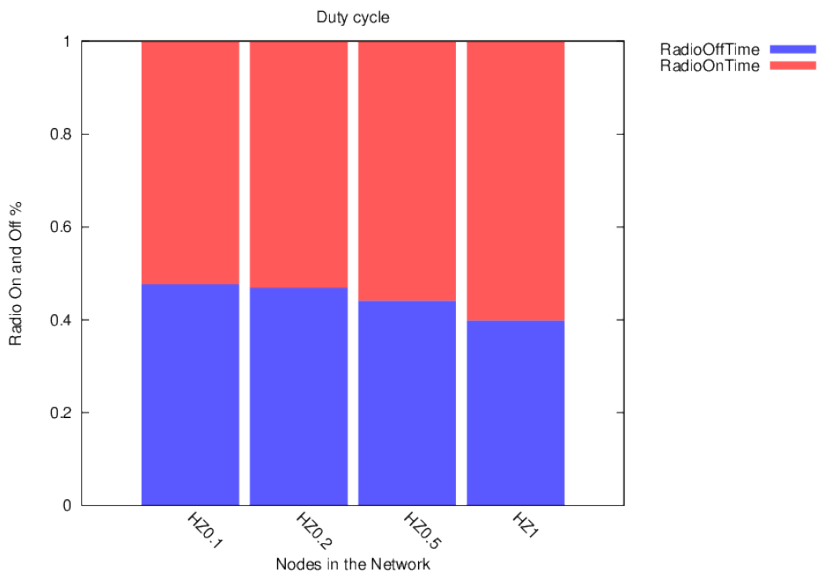

Figure C.1: Duty Cycle Using GinMAC

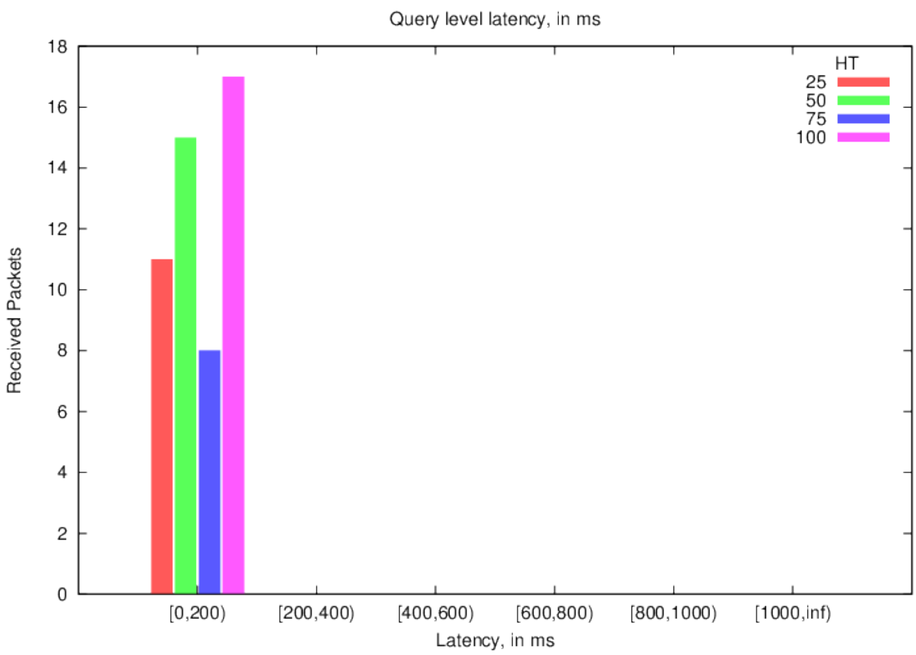

Figure C.2: Latency of Query Delivered Using Different Data Threshold Values

Figure C.1 shows that nodes in GinMAC turn off and on their radios based on different sensing intervals. Figure C.2 shows that GinMAC delivers data from source nodes to a sink with a short delay. This is due to using a static TDMA schedule allocation for nodes where collision is reduced, thereby reducing the delay associated with the delivery of data from source nodes to a sink.

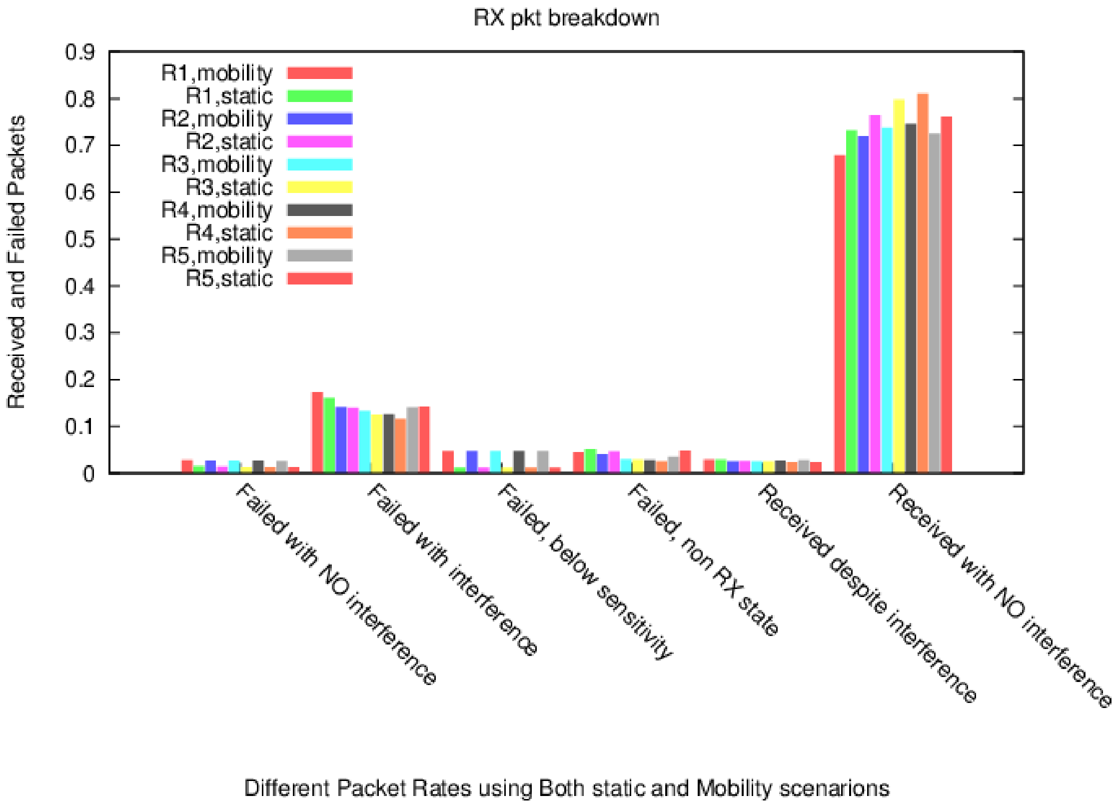

Figure C.3: Mobility Module in GinMAC Using Different Data rates (R1,R2,...)

Figure C.3 shows the number of delivered and failed packets due to the different reasons when data is delivered taking static and mobility scenarios into account using GinMAC. This shows that the mobility module in GinMAC gives a good performance in terms of connectivity between static and mobile nodes taking the different attachments into consideration.

C.2 APTEEN Validation

C.2.1 Data Packets for Different Number of Nodes

This section outlines more simulation results from the APTEEN validation given in Chapter 4. Different parameters were considered such as different number of nodes, different hops and data threshold values. These results are data delivered, energy consumption and the lifetime of nodes where both APTEEN and LEACH were simulated.

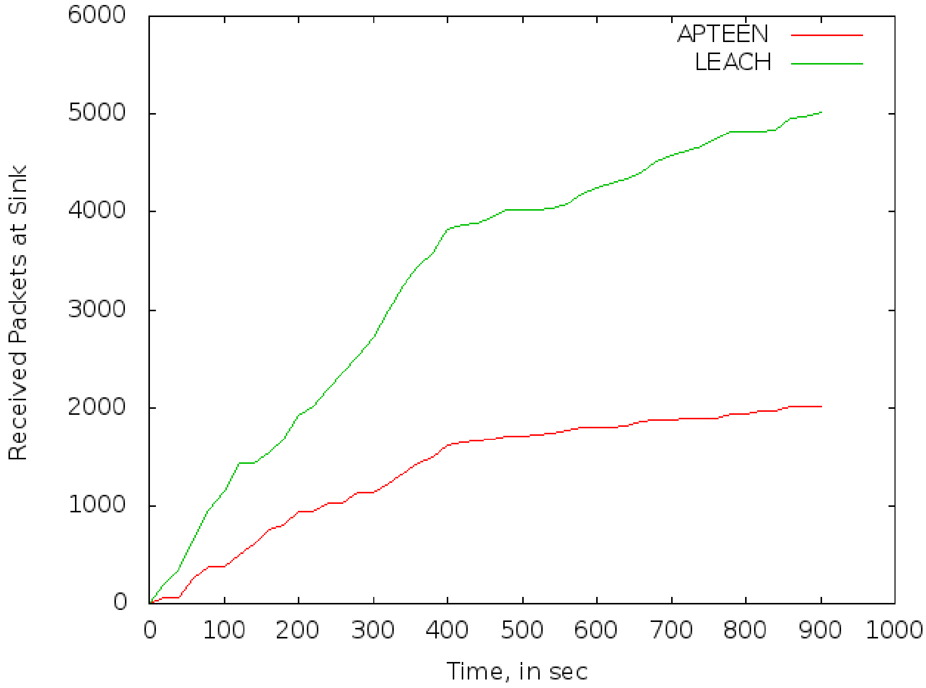

Figure C.4: Data Packets When Nodes = 100

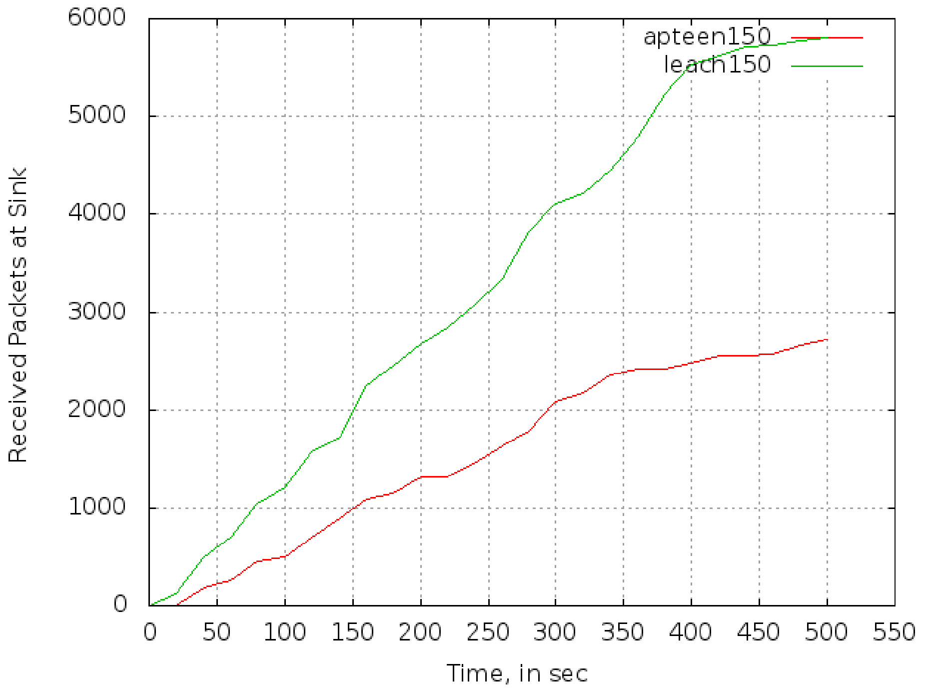

Figure C.5: Data Packets When Nodes = 150

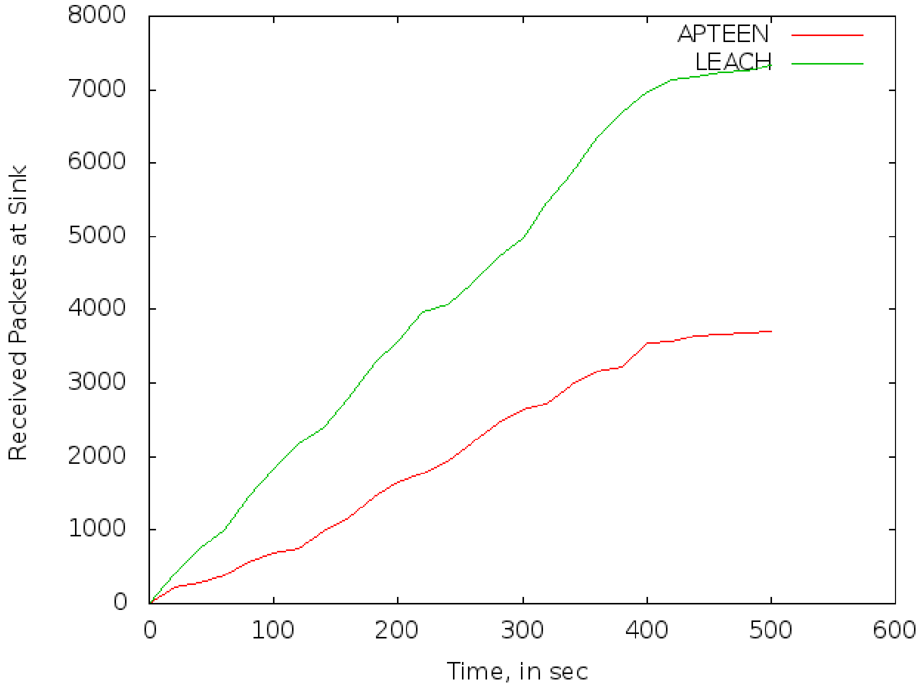

Figure C.6: Data packets when number of nodes = 200

Figures C.4, C.5 and C.6 show that the APTEEN protocol reduces the packets delivered to a sink taking different threshold values into account, compared to the LEACH protocol where data is sent in all cases. This means that data threshold values using the APTEEN protocol can be updated according to the requirements of the proposed applications using WSNs. Based on this feature, APTEEN can be used for critical and non-critical applications using WSNs.

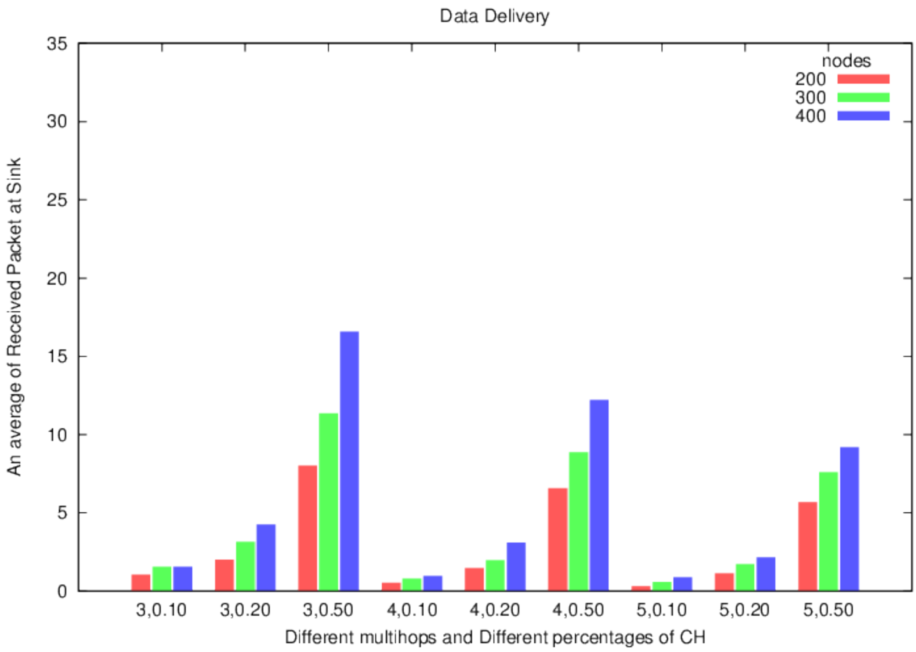

Figure C.7: Data packets delivered to a sink Using different percentages of CHs and multi hops

Figure C.7 shows that the number of data packets delivered to a sink is increased when the percentage of cluster head in the network is high. However, the number of delivered data packets is reduced when the number of multi hop in the network is high. This is due to that fact that when the number of cluster head is high then different routes are available for delivering data, thereby increasing the number of delivered data. On the hand, when multi hop is high then data is more likely to be lost before it is delivered to a sink.

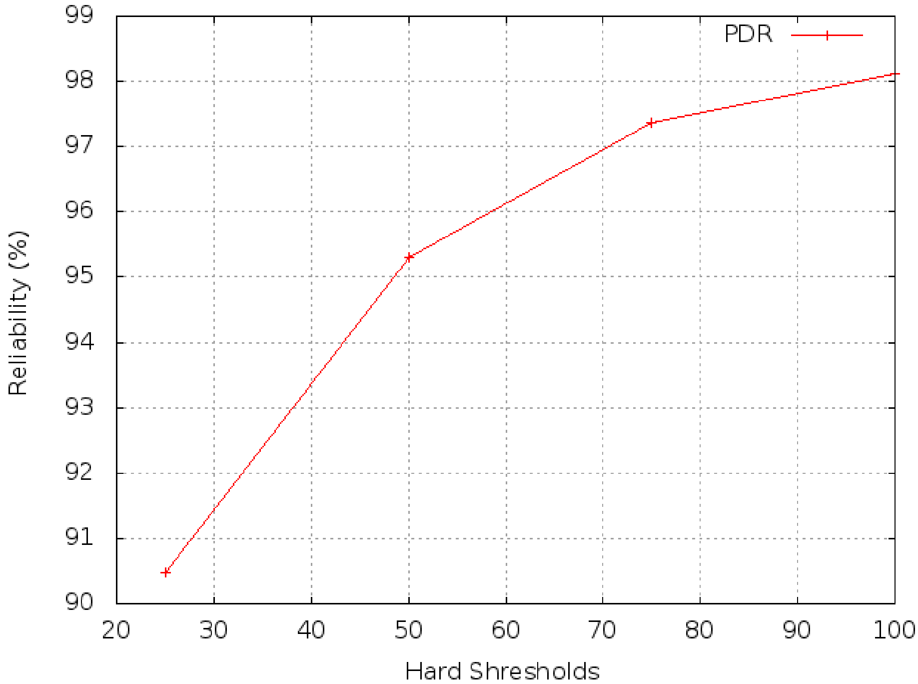

Figure C.8: Reliability of the data delivered to a sink using various data thresholds

Figure C.8 shows that the number of data packets delivered to a sink is increased when data thresholds is high, thereby improving the reliability of the data delivered to a sink. This is to be expected as when data thresholds are high then the number of required transmissions is reduced and then collision with data from other nodes is minimized. This increases the number of successfully data packets delivered to a sink and which results in increasing the reliability of the delivered data.

C.2.2 An Energy Consumption Using Different hops

The following are simulation results regarding the energy consumption by nodes taking different percentages of CH and multi hop into consideration using APTEEN.

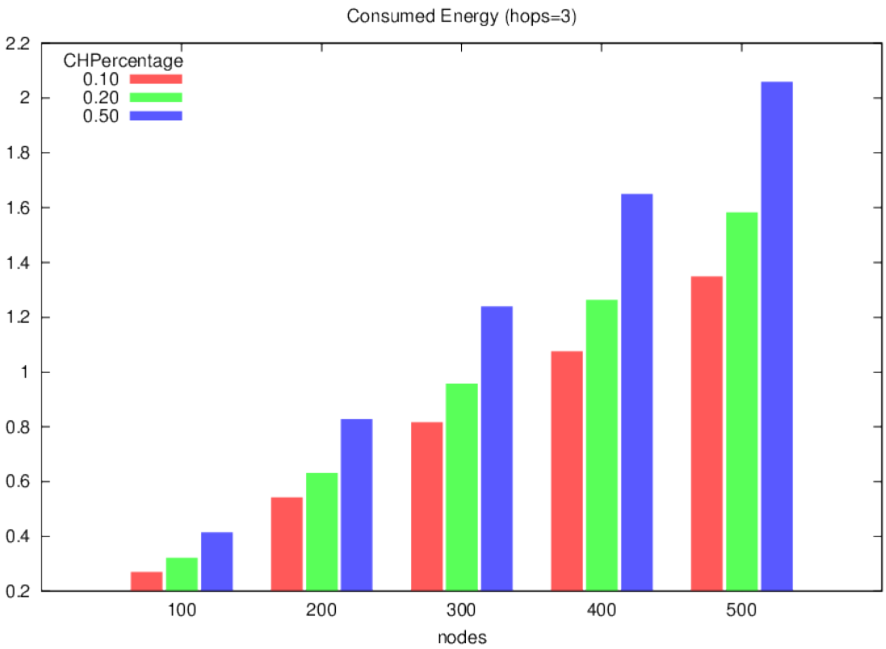

Figure C.9: Energy consumption when maximum hop = 3

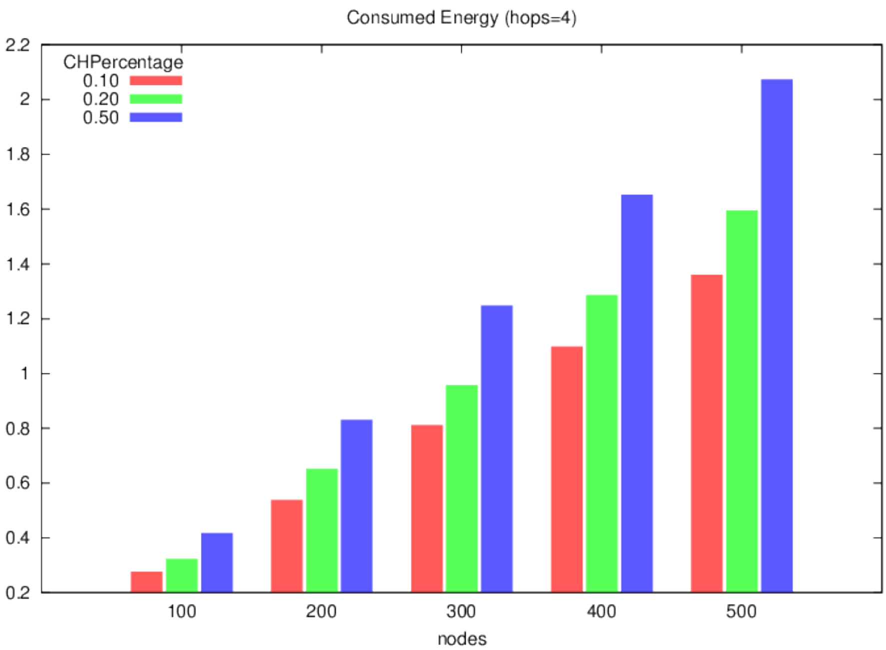

Figure C.10: Energy consumption when maximum hop = 4

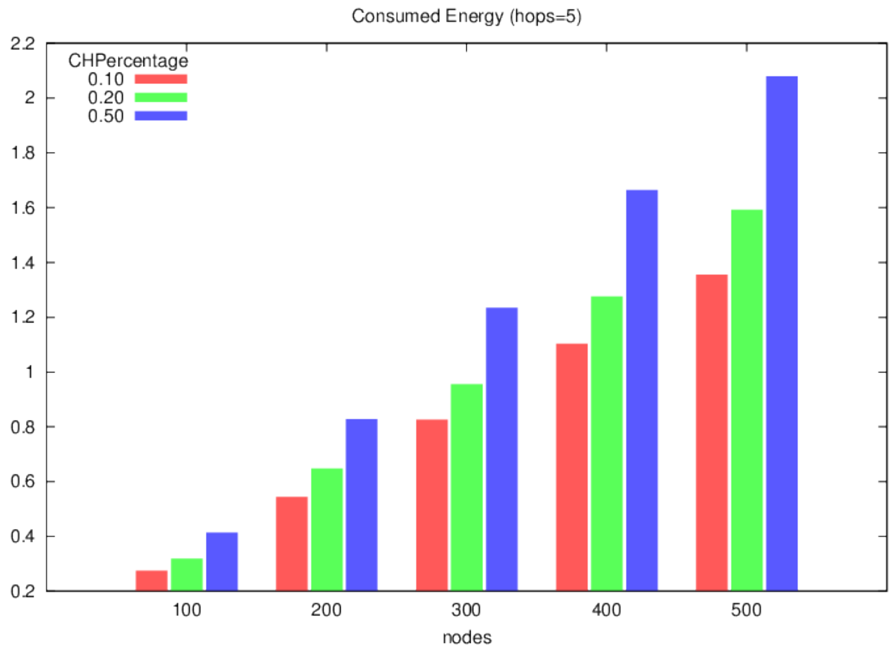

Figure C.11: Energy consumption when maximum hop = 5

Figures C.9, C.10 and C.11 show that energy consumption by nodes using APTEEN is increased by increasing the percentage of CH. This is due to the fact that cluster head consumes more energy to aggregate data and find routes before data is transmitted to a sink. However, energy consumption is not increased a lot when multi hop is increased as APTEEN uses the same amount of energy for both single hop and multi hop communications when data is delivered a sink.

C.2.3 Lifetime of the Network

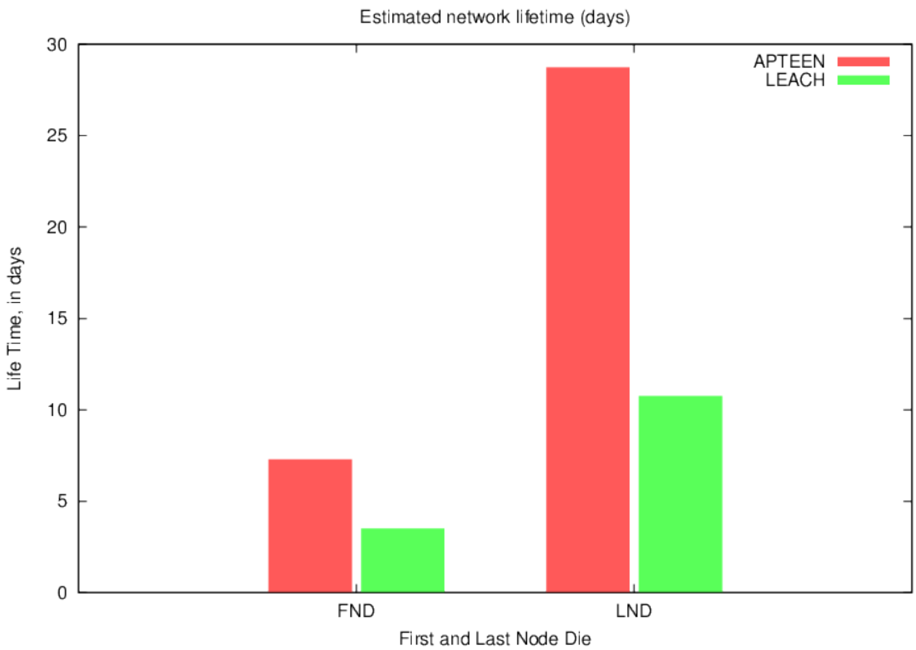

Figure C.12: Network lifetime when a First (FND) and a Last Node (LD) are Dead

Figure C.12 shows that nodes in APTEEN consume less energy than in LEACH, thereby extending the lifetime of the nodes in the network. This is due to the fact that nodes in the LEACH protocol does not consider any data threshold values when data is transmitted from source nodes to a sink. This makes LEACH an unsuitable routing protocol for applications when data does not need to be sent in all cases as this decreases both the lifetime of the network and reliability of the delivered data.

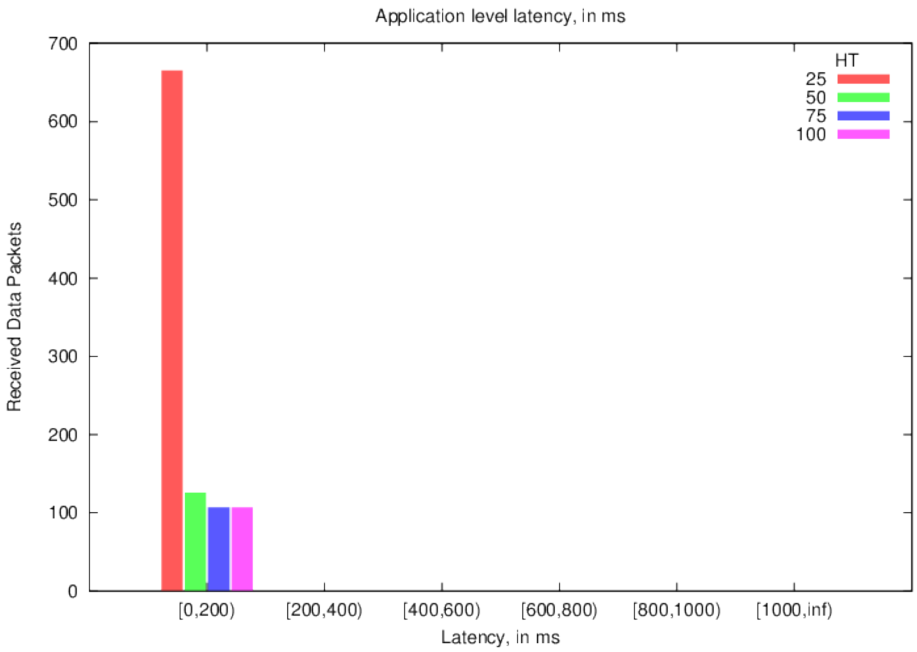

Figure C.13: Delay of the data delivered to a sink using different data threshold values

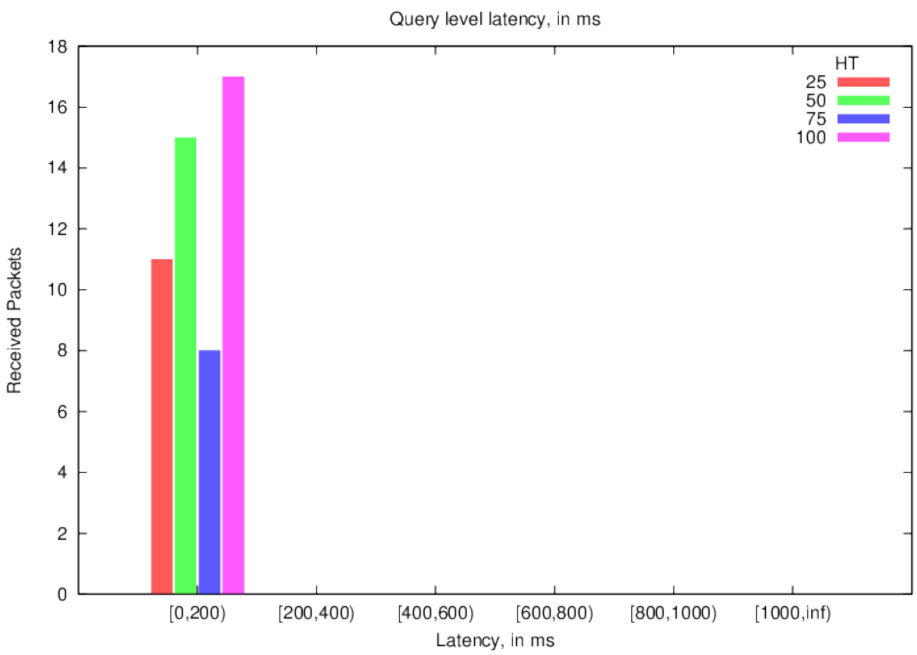

Figure C.14: Delay of the query delivered to a sink using different data threshold values

Figures C.13 and C.14 show that APTEEN delivers packets holding different information such as normal data packets and query packets from source nodes to a sink with a short delay. This is because of the aggregating data at the intermediate nodes before forwarding it to a sink.

C.3 Healthcare Application

Different scenarios using the healthcare application were simulated in Section 5.4. More simulation results about the same application are given in this section. Figure C.15 shows the number of data packets holding information from patients themselves as well from the environment using the proposed healthcare application to a sink. Future decision in the healthcare application is based on this information. Figure C.16 shows different types of delivered data to a sink such as queries, normal data and counter time (CT).

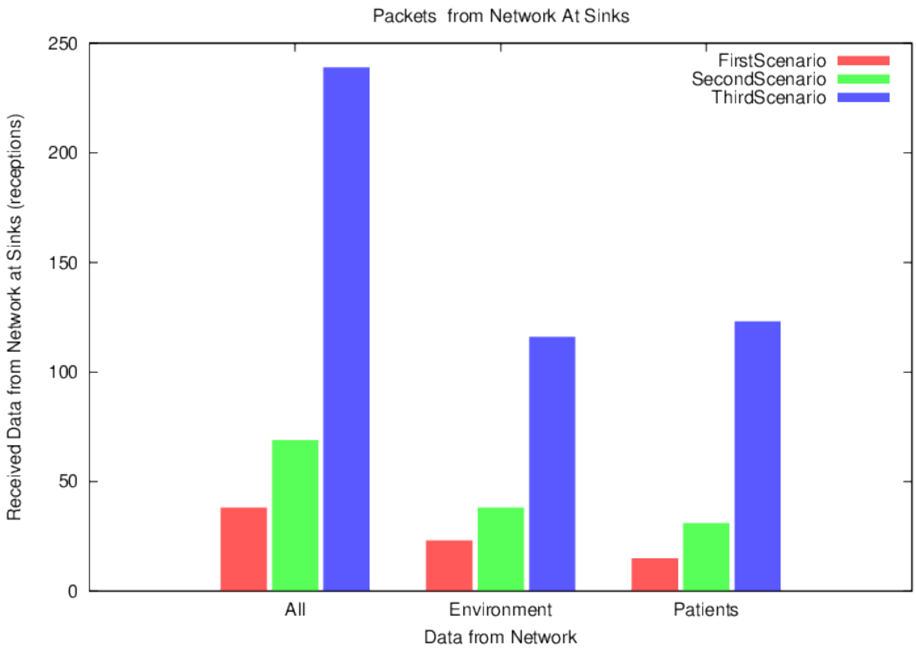

Figure C.15: Data delivered to a sink in the healthcare application

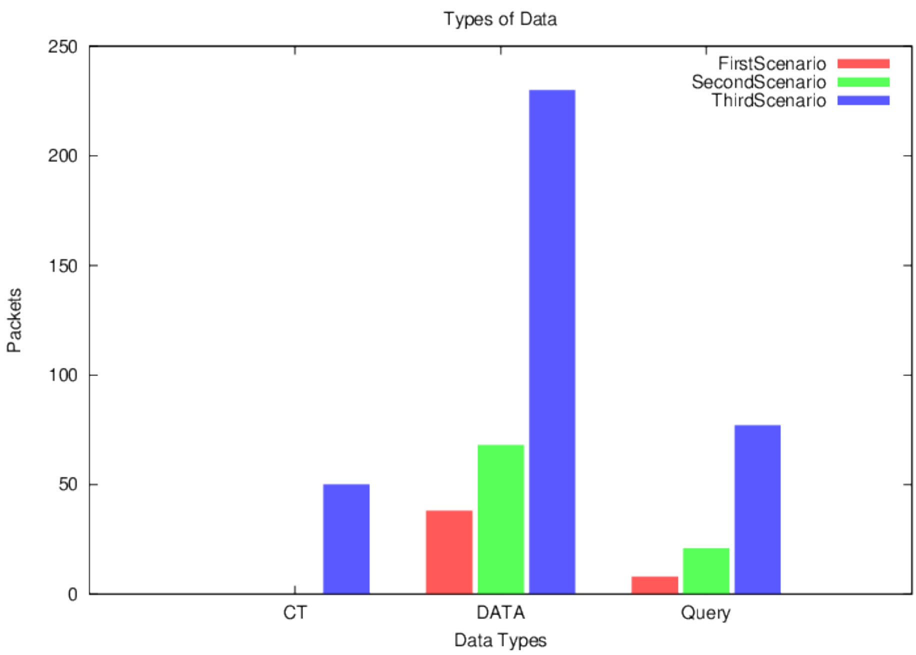

Figure C.16: Different types of delivered packets using a healthcare application

C.4 Multimedia Applications Using the Cross Layer Protocol

Multimedia based application taking various scenarios into account were simulated and results were given in Section 5.5.3. In this section, more simulation results regarding the same application and scenarios are given.

Figures C.17, C.18 and C.19 show that the cross layer protocol extends the lifetime of the network, compared to the LEACH protocol, when a large number of nodes was involved. This is due to the fact that cross layer based protocol distributes energy between nodes while LEACH does not have this feature.

Figure C.20 shows the lifetime of the network when 10% of nodes were dead using different scenarios. This shows that the cross layer protocol extends number of rounds where nodes can be still alive. This prolongs the lifetime of the entire network. Figure C.22 shows number of detected intruders in the environments using different scenarios.

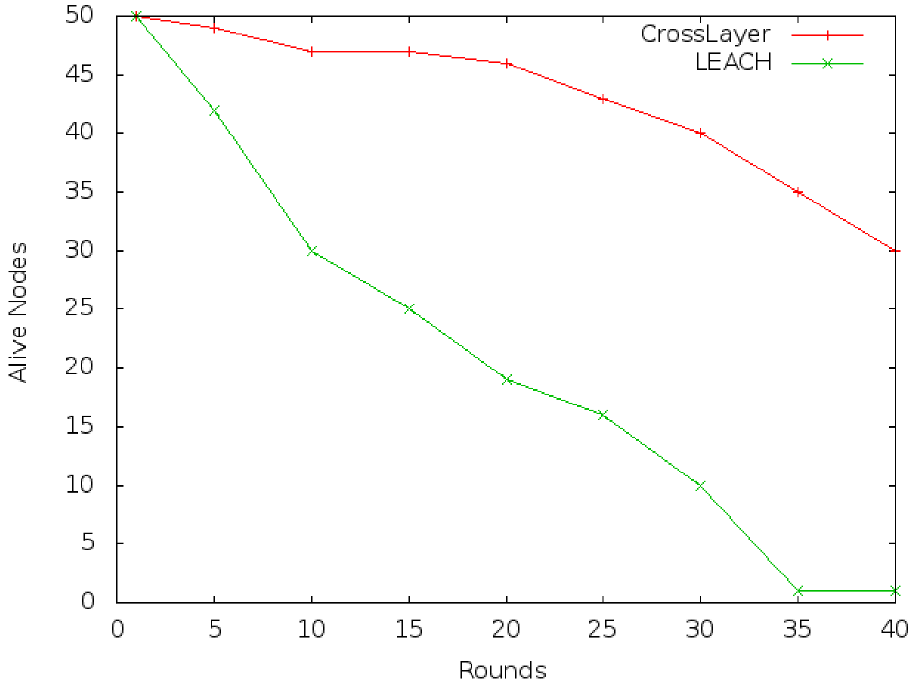

Figure C.17: Network lifetime based on rounds when First Node Dies (FND) and Number of nodes = 50

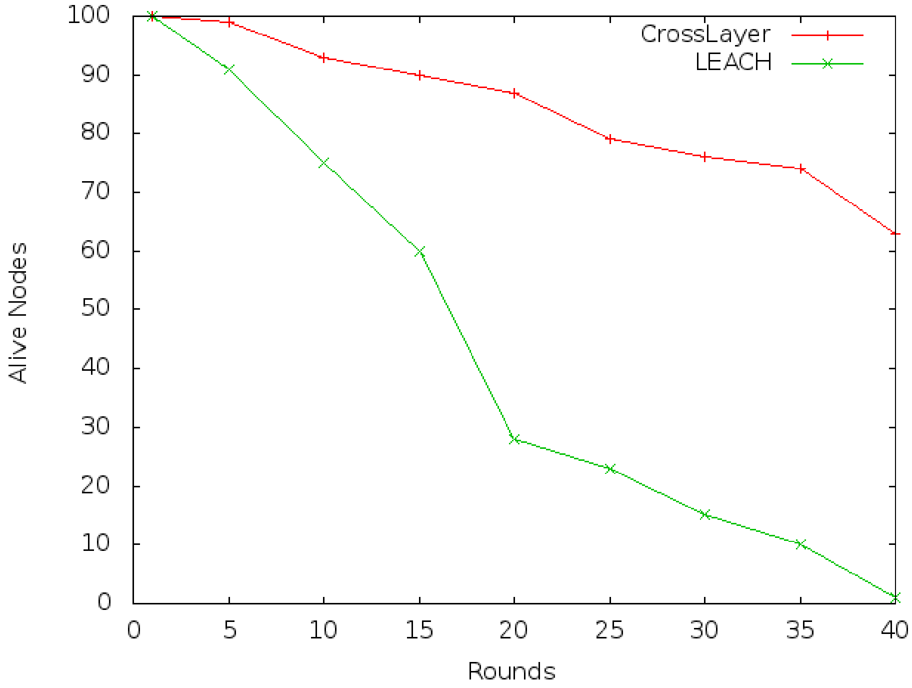

Figure C.18: Network lifetime based on round when First Node Dies (FND) and number of Nodes = 100

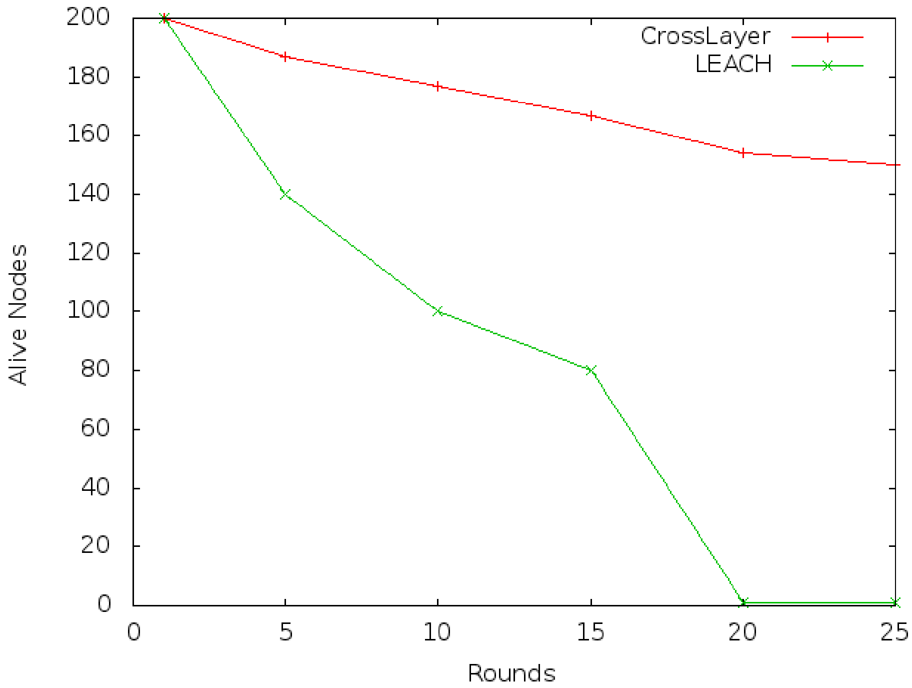

Figure C.19: Network lifetime based on round when First Node Dies (FND) and number of nodes = 200

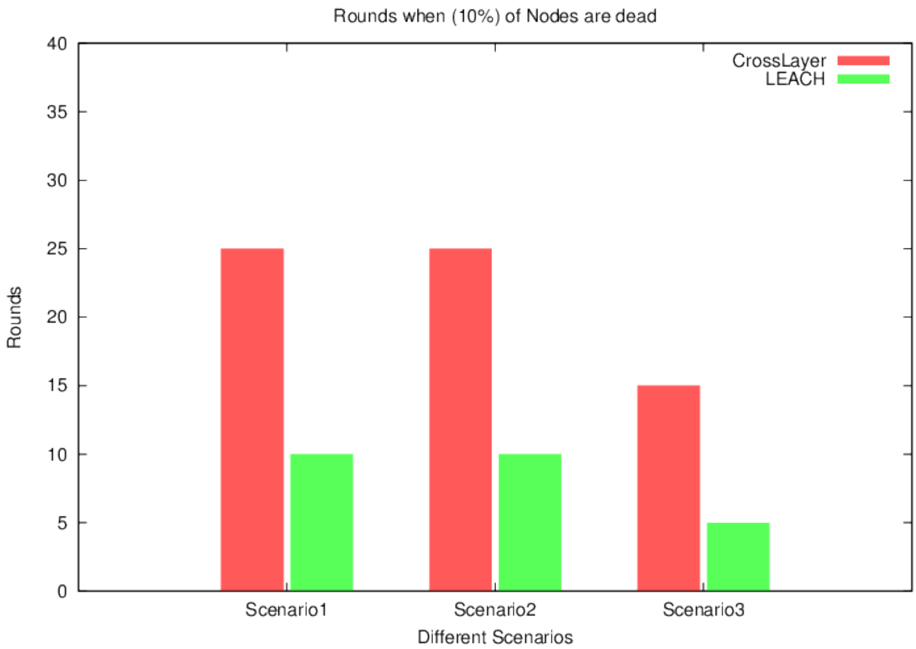

Figure C.20: Network lifetime based on rounds when 10% of nodes are out of energy using multimedia application

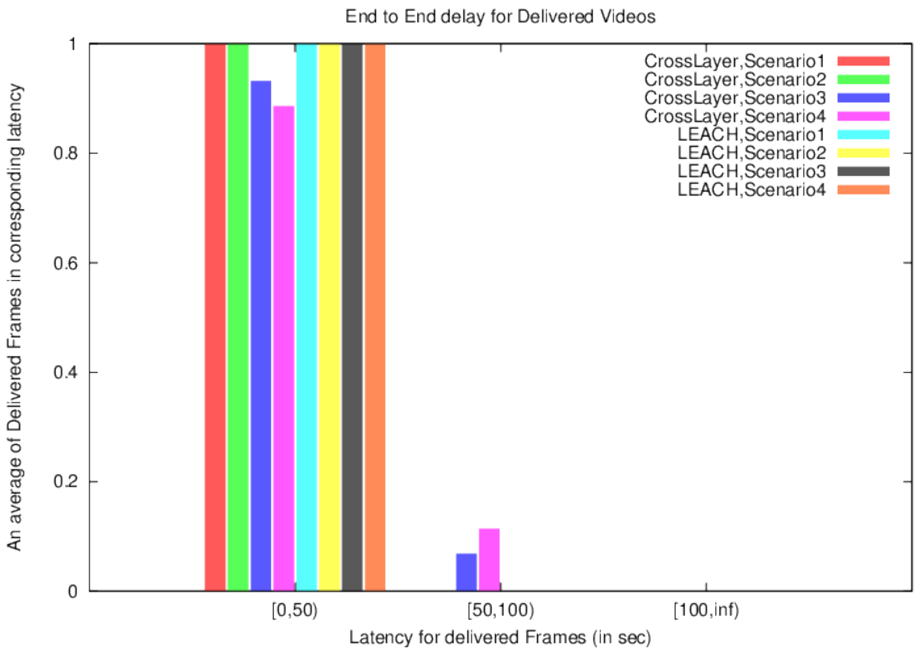

Figure C.21: End to end delay of the frames delivered to a sink using a multimedia application

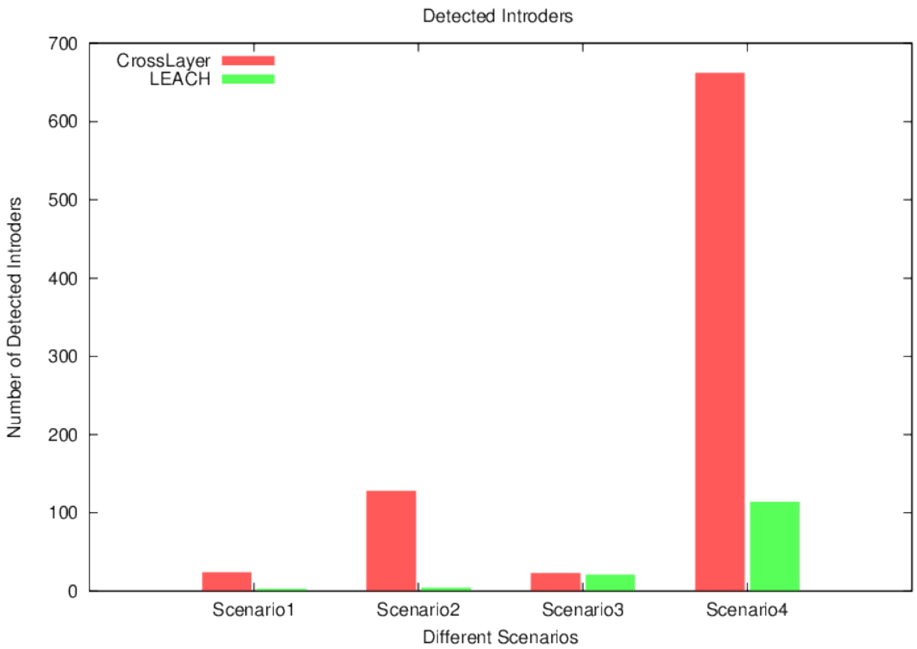

Figure C.22: Number of Detected Intruders in a Multimedia Application