An Energy-Efficient Routing Protocol for Hybrid-RFID Sensor Network

Dulce – Maira Boneke Nokonoko

This thesis is submitted in fulfilment of the academic requirements

for the degree of

Master of Science in Electrical Engineering

in the Faculty of Engineering and The Built Environment

University of Cape Town

August 2011

As the candidate's supervisor, I have approved this dissertation for submission.

Name: Prof. M.E. Dlodlo

Signed: ______________________

Date: ________________________

Name: Dr. A. Bagula

Signed: ______________________

Date: ________________________

Declaration

I declare that this thesis is my own work. Where collaboration with other people has taken place, or material generated by other researchers is included, the parties and/or materials are indicated in the acknowledgements or are explicitly stated with references as appropriate.

This work is being submitted for the Master of Science in Electrical Engineering at the University of Cape Town. It has not been submitted to any other university for any other degree or examination

Name ____________________________________ Date ________________________

This thesis is dedicated to my parents (*Jovita Nokonoko* and *Rafael Boneke*) for their unconditional love. And my mentor *Guy-Alain Lusilao* who guided me every step on the way

Abstract

Radio Frequency Identification (RFID) systems facilitate detection and identification of objects that are not easily detectable or distinguishable. However, they do not provide information about the condition of the objects they detect. Wireless sensor networks (WSNs), on the other hand provide information about the condition of the objects as well as the environment. The integration of these two technologies results in a new type of smart network where RFID-based components are combined with sensors. This research proposes an integration technique that combines conventional wireless sensor nodes, sensor-tags, hybrid RFID-sensor nodes and a base station into a smart network named Hybrid RFID-Sensor Network (HRSN). The HRSN presents some challenges such as energy imbalance among nodes because the sensing process of the hybrid sensor nodes consumes a large amount of the network's residual energy. Existing routing algorithms are designed for WSNs where all components in the network are sensor nodes with equal sensing properties, so routing is designed without considering the sensing energy. Therefore, to achieve efficiency of the HRSN network, this research further proposes a routing algorithm that distributes the energy dissipation evenly among all nodes. The proposed routing algorithm is a centralized cluster-based protocol that assigns nodes different roles in the network based on their sensing energies. The algorithm achieves further energy reduction by letting the base station handle the key tasks. These tasks involve cluster formation, assignment of time slots and a non-randomized cluster head selection.

Simulation results demonstrate that the proposed routing algorithm achieves higher energy efficiency than Low Energy Adaptive Clustering Hierarchy (LEACH) and LEACH-Centralized (LEACH-C). Moreover, the proposed algorithm significantly prolongs the life span of the nodes with high-energy consumption.

Acknowledgements

I would like to express my very special gratitude to The One who always supports me through hardship, the source of my strength, The Almighty God.

I want to thank both of my supervisors, Prof. Dlodlo and Dr. Bagula for closely monitoring my performance with their guidance and intellectual assistance. More particularly, I thank Dr. Bagula for introducing me to such an exciting topic that granted me the opportunity to develop knowledge in the field of sensors and RFID technology.

A special gratitude to Guy - Alain Lusilao-Zodi, without him I would not have completed this research project satisfactorily within the targeted period.

Lastly but not least, I want to thank Mthulisi Velempini, Josephine Nakato and the UCT writing centre team for their assistance.

Table of Contents

List of Figures

List of Tables

List of abbreviations

BCDCP	Base-Station Controlled Dynamic Clustering Protocol
CSMA	Carrier Sense Multiple Access
DD	Directed Diffusion
DSRC	Dedicated short-range communication
DSSS	Direct-Sequence Spread Spectrum
EAS	Electronic Article Surveillance
E-LEACH	Energy-Low Energy Adaptive Clustering Hierarchy
HF	High frequency
HRSN	Hybrid RFID-Sensor Network
HSN	Hybrid Sensor Node
IFF	Identification Friend or Foe system
LEACH	Low Energy Adaptive Clustering Hierarchy
LEACH-C	Low Energy Adaptive Clustering Hierarchy Centralize
LF	Low Frequency
M - LEACH	Multihop Low Energy Adaptive Clustering Hierarchy

RAM	Read-Access Memory
RFID	Radio Frequency Identification
ROM	Read-Only Memory
SPIN	Sensor Protocols for Information via Negotiation
TDMA	Time Division Multiple Access
UHF	Ultra-High Frequency
WSN	Wireless Sensor Network

Chapter 1

Introduction

1.1 Background

The ever-growing need for smarter ubiquitous computer devices that can provide more intelligent services to daily life needs has encouraged the emergence of a new generation of smart networks that integrates the technologies of Radio Frequency Identification (RFID) systems with Wireless Sensor Networks (WSNs) [1] [2] [3]. The following section provides a brief overview of these two technologies.

1.1.1 Brief Overview of RFID Systems and Wireless Sensor Networks

The RFID technology provides a means for automatic identification of objects or persons, which facilitates tracking of their location [1]. The applications can be categorized in five main groups [3]:

- manufacturing and processing (inventory management)
- security (passports, access control, or theft control in retails)
- transportation and logistics (toll collections, automating parking)
- agriculture (animal monitoring)
- healthcare (drug and patient identification and tracking)

An RFID system consists of an RFID reader, RFID tags, and a host. The reader uses radio waves to retrieve information such as identification (ID) number or product type stored on the tags. Tags may be active, if powered by an external battery or passive, if powered by electromagnetic waves from the reader. Figure 1.1 shows the architecture of a typical RFID system.

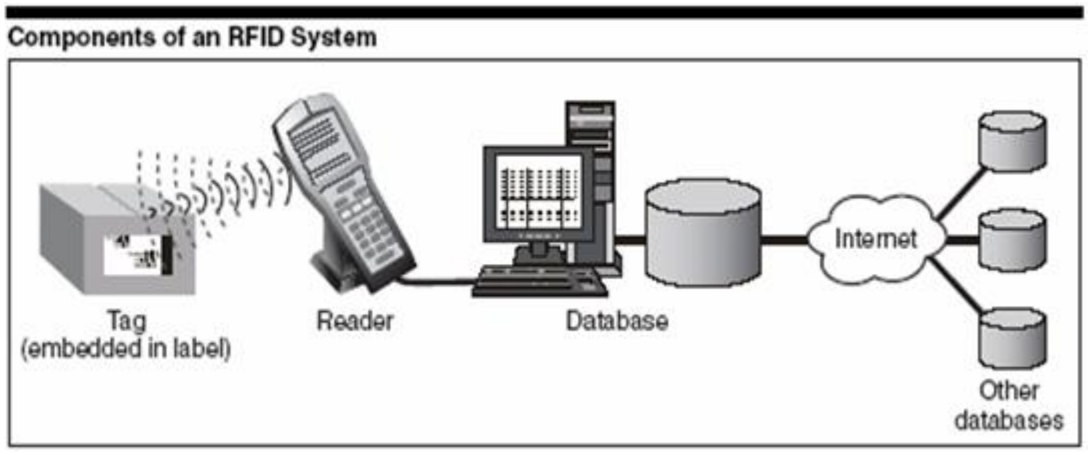

Figure 1.1 Block diagram of RFID system architecture [6]

A WSN, on the other hand, consists of sensor nodes that organize themselves in an ad-hoc fashion co-operatively providing information about a physical condition of an object or the environment. The information is obtained by sensing environmental conditions such as temperature, pressure, humidity, light, vibration, or sound. Figure 1.2 shows an example of a possible WSN topology. The arrows indicate a path that the data may follow to reach the destination.

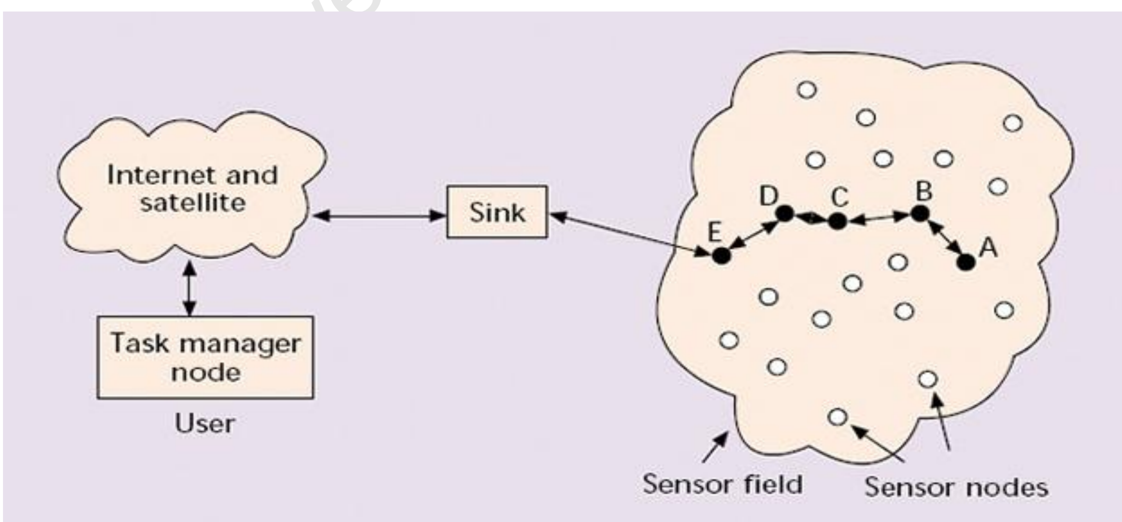

Figure 1.2 Wireless sensor network [7]

Over the years, applications of WSNs have increased involving several fields such as:

- military (battlefield surveillance)
- environmental (geophysical monitoring)
- habitat monitoring (tracking of animal herds)
- health (drug administration in hospitals)
- smart home(automatic lights turn on)
- precision agriculture (soil management)
- transportation (traffic monitoring)
- business processes (supply chain management)

In both systems, RFIDs and WSNs, sensor nodes or RFID readers detect certain events and forward the corresponding information to a central server. This common characteristic makes their integration feasible. These two networks are emerging as the most ubiquitous computing technologies in history due to their important advantages and their broad applicability [2] [4] [5]. RFID technology has received great attention for deployment in industrial applications like shipment tracking, access control, retail stock management, and healthcare. However, WSNs have been the focus of a lot of research activity. However, WSN has been pursued largely as a 'proof of concept' approach, with the main exception being the adoption in the military [1] [5]. Therefore, combining the properties of RFID (identifying and positioning) and WSNs (sensing) not only results in new potential applications but also bridges the gap between industry and academia.

WSNs offer a number of advantages over traditional RFID implementations like sensing capabilities, multi-hop communication, and programmable sensor nodes. RFID systems also offer a number of advantages over WSNs, like ease of tracking of objects that otherwise are difficult to sense, as well as a cost reduction due to tags being much cheaper than sensor nodes. Both technologies complement each other, adding value to the services they already provide [1].

Table 1 summarizes the main differences and similarities between RFID and WSN technologies.

Table 1: Comparison summary of WSNs and RFIDs

	Wireless Sensor Networks	**RFID Systems**
Purpose	Sense parameters of interest (such as temperature, humidity or pressure) in environmental and attached objects	Detect presence and location of tagged objects
Components	Sensor nodes, host	Tags, readers, host
Standards	Zigbee, IEEE 802.11 or WLAN	RFID standard
Communication	Multi-hop	Single-hop
Programmability	Programmable	Usually closed systems
Deployment	Random or fixed	Fixed
Price	Sensor node - medium	Reader-expensive Tag-cheap

Despite the many advantages that the integration of RFID systems with WSNs presents, the resulting network involves challenges that vary depending on the method of integration. This project focuses on the energy challenges experienced by these integrated networks. In this regard, the following section provides some background on the energy challenges existing in WSNs and RFID systems, as well as the energy imbalances introduced when integrating both networks.

1.1.2 Energy Limitations of WSN

One of the key challenges of WSNs is that the efficient functionality of the network is determined by the overall life span of the batteries that power the sensor nodes. Sensor nodes spend energy mainly on transmitting data through the network, as well as on processing data and on sensing [7]. Due to the massive number of deployment and remote unattended positions of these sensor nodes, replacement of batteries can be assumed impossible [7] [8]. Therefore, while traditional networks aim to achieve high quality of service (QoS) provisions, sensor network protocols must focus primarily on power conservation [7]. Harvesting energy from the environment is currently a promising but under developed research area [8] [9]. Therefore, the importance of extending the network lifetime stems from the fact that the energy available to the node is not only limited but also easily diminished if not managed properly. This energy limitation has encouraged a significant amount of research on different techniques for increasing the energy efficiency usage in WSNs [10] [11] [12] [13] [14] [15] [16] [17]. The researchers have focused their investigations on designing energy optimization techniques that cater for the reduction of the energy consumed when communicating through the network. Most of the techniques include reduction of the communication range and/or the amount of traffic among nodes.

1.1.3 Energy Related Issues in RFID Systems

Unlike WSN, RFID systems are designed often under the assumption of unlimited power available for RFID readers [4]. However, as new applications emerge [2] [5], this assumption becomes less accurate. An RFID reader, which is powered by a battery, will quickly drain its battery power because of continually powering passive-tags within its reading range. The greater the transmissions range the more energy that would get dissipated. Communication within an RFID system is only one-hop. Since readers cannot relay data among themselves, it is a disadvantage when readers have to collect data from tags located at a far distance. This is because the long transmission of signal results in a high consumption of energy.

Active RFID-tags are self-powered, unlike the passive RFID tags that need to be powered by an REFID reader. The advantage of having active tags is that they can achieve higher transmission range and they can initiate communication with readers [4]. However, the limited power introduces a disadvantage when deploy in masses because the replacement of battery may become difficult to track. Energy savings then becomes an important asset of the network.

In many applications, readers need to operate physically close to each other. Due to such proximity, the signals from one reader might interfere with the signals from other readers causing a collision. Collisions increase the energy dissipation among readers and tags because of data retransmission. There are many anti-collision proposed to reduce the occurrence of these collisions [18] [19] [20] [21] [22].

Given the energy limitations of WSNs and some RFID systems, their integration may worsen some of these limitations, but depending on the integration technique, both networks can complement each other allowing an improvement in their energy weaknesses. The following section examines possible energy concerns introduced by this integration.

1.1.4 Energy Imbalanced Issues in Hybrid WSN/RFID Networks

For the past decade, researchers have proposed energy efficient routing algorithms that increase the lifetime of WSNs. In such networks, nodes dissipate the same amount of energy in sensing. Therefore, routing protocols were designed considering only the energy used for communication while neglecting the energy consumed for sensing. However, this assumption of equal energy needs is no longer applicable for a network that combines sensor-tags, sensor nodes and hybrid RFID-sensor nodes. Such a hybrid network demonstrates problems related to energy imbalances among nodes. These nodes dissipate energy differently regardless of their role in the network. For example, a sensor node and a hybrid RFID-sensor node may both act as cluster members but the hybrid node would dissipate more energy. This is because the hybrid RFID-sensor nodes spend additional energy for powering RFID tags in the system. Therefore, if nodes with naturally higher energy dissipation perform high-energy consuming roles, the battery power of such nodes would deplete much faster. In addition, each node has a fixed transmission range, so the amount of traffic that nodes are required to forward increases dramatically as the distance to the base station decreases. Consequently, nodes closest to the base station die early, leaving areas of the network completely unmonitored and causing network partitions.

In addition, these routing algorithms also assume that all nodes in the network have the same initial energy. This assumption is no longer accurate for this particular type of hybrid network, where the diverse designs of the different nodes incorporate different battery capacities. This variation in initial energy contributes to the energy imbalances experienced in this type of hybrid network.

Furthermore, many conventional routing protocols also assume that nodes collectively gather the same type of data like temperature [16]. This assumption is also no longer accurate for this type of integrated network. This is because the RFID readers retrieve one type of data from RFID tags and sensor nodes collect a different type of data from the other sensor nodes. Therefore, integrating these two different networks that naturally collect different types of data, leads to high data transmission to the base station, which results in higher communication energy.

1.2 Problem Definition

A hybrid network resulting from the integration of different types of sensing and identification devices may experience problems related to energy imbalance among nodes as a result of:

- *Diversity of nodes that make up the network*. These nodes dissipate energy differently regardless of their role in the network. Therefore, if the nodes with naturally higher energy dissipation perform high-energy consuming roles, it would lead to a much faster depletion of the battery of some nodes.

- *Variation of initial energies among the nodes*. This variation of energy is due to the different design properties of the various types of nodes that make up the network.

This research considers a framework with the characteristics described above. Therefore, to address the issues raised, it is necessary to develop an energy-efficient routing protocol that takes into consideration these challenges to balance energy consumption of the network.

1.3 Objectives of this Research

In an effort to exploit the possibility of new applications for WSNs and RFID systems, this research aims to propose a technique for integrating RFID systems with WSNs in a different manner from similar existing networks. The characteristics of the resulting network are different from conventional WSNs, making existing routing protocols inefficient for the network. Therefore, the main objective of this research was to propose an improved energy efficient routing protocol that takes into account the challenges introduced by this type of network. This objective was accomplished by investigating the following:

- The energy consumption of the different types of nodes that make up the network
- The different factors that cause the different energy consumptions
- A load balancing technique that minimizes the energy effect factors in Hybrid RFID Sensor network
- The effect that the coverage area has on the network
- An efficient mechanism for increasing the network coverage without significantly degrading the energy efficiency of the network

Taking into account these studies, a routing algorithm that distributes the energy dissipation evenly among all nodes was developed. The objective of the routing algorithm is to prolong the lifetime of the network in general but most importantly, the lifetime of the nodes with high energy dissipation.

1.4 Contributions of this Research

Therefore, based on the objectives described above, this thesis makes the following contributions in the field of research for the integration of RFIDs and WSNs.

- *A novel architecture for hybrid networks*. This research presents a combination of sensing/identification devices that widens the potential applications in the field of RFIDs and WSNs. These nodes are arranged in a different manner than similar existing integrated RFIDs/WSNs networks, in a way that allows conventional wireless sensor nodes, RFID readers and RFID tags interact and exchange data among themselves.

- *An improved cluster formation process for hybrid networks*. This research introduces a method for denominating cluster heads based on the sensing properties of each node. This feature combined with spreading of cluster heads all around the network based on a cost factor, are the riding wheel for improving energy efficiency in any network with characteristics similar to HRSN.

- *Unique combination of energy efficient features suitable for hybrid networks*. This research introduces a unique combination of features involving network's load balancing through multi-hoping, spreading of cluster heads around the network based on a cost factor, and assignment of cluster heads based on the sensing energy. Furthermore, the protocol scales well, which makes it suitable for relatively large networks because in HRSN algorithm, global network knowledge is not required by each node since the base station arranges the network and assigns the roles.

- *Improved life span of high-energy consuming nodes in hybrid networks.* Through the improved cluster head election process, simulation results demonstrate that the high-energy consuming nodes experience an elongation of their life span. The importance of this achievement stems from the fact that these nodes play a crucial role in the effective implementation of the potential applications like the pre-mature baby monitoring system described in Chapter 3.

These contributions have been accepted and published in Proceedings of the *IEEE Conference AFRICON2011*. The title of the paper is "An Energy-Efficient Routing Algorithm for Hybrid RFID-Sensor Network."

1.5 Scope and Limitations

This research focuses on the development of a routing algorithm that meets the necessary requirements to achieve energy efficiency and broad coverage for a proposed Hybrid RFID Sensor Network (HRSN). In order to assess the effectiveness of the proposed routing algorithm, the performance is compared to other existing routing algorithms. Although various routing techniques exist, this research focuses on a comparison with Low Energy Adaptive Clustering Hierarchy (LEACH) and LEACH-Centralized (LEACH-C) protocols only, because they share similar characteristics with the proposed algorithm.

Various parameters can be used to compare these three routing algorithms (such as throughput, packets lost, or/and delay). However, for the purpose of this research the only parameters considered are total energy dissipation, nodes lifetime and HSN nodes life span. This is because of their relevancy in assessing the energy efficiency of the proposed network. Other parameters such as throughput or packets lost would be more relevant in a collision avoidance protocol.

The design of the proposed network and the nodes that make up the network are limited to simulation. This research does not include the physical development of any of the nodes described that make up the proposed network.

1.6 Thesis Outline

The rest of this report is organized as follows.

Chapter 2 discusses the related literature background of this research. The discussion encompasses the features and limitations of WSNs, RFID systems and hybrid networks. The chapter also discusses the routing protocols used as basis for developing the proposed routing algorithm; as well as previous work done on integrating WSNs and RFIDs into a single network.

Chapter 3 presents the architecture and characteristics of the proposed methodology for integrating an RFID system and a WSN in one hybrid network. This chapter also provides a thorough analysis of energy usage in such hybrid network, concluding with the proposed energy efficient routing algorithm equipped to meet the requirements of the hybrid network.

Chapter 4 describes the experimental methodology followed in this project to simulate the proposed network with its proposed routing algorithm.

Chapter 5 presents and analyzes the results obtained from the different experiments conducted when simulating.

Chapter 6 discusses the conclusions drawn from the illustrated results, such that emphasis is given to the contributions of such conclusions as well as shortcomings of the overall project and possible recommendations for future research.

Chapter 2

Literature Survey

2.1 Introduction

The scope of this literature background consists of two main investigations: The first is a study of previous work done on integration of RFIDs and WSNs into an ad-hoc type network; the second is a study of previous work done on energy efficient routing protocols in WSNs and in hybrid networks.

This paragraph presents the remaining chapter outline as a clear but brief treatment of the issues under study. Section 2.2 examines existing integrated RFID-WSNs architectures, while also analysing the previous work done on energy efficient routing in such networks. Section 2.3 provides a brief overview on energy efficient routing schemes in WSN, with emphasis on the advantages of hierarchical routing over the other existing scheme. This serves as an introduction for the following section 2.4, which discusses the principle of LEACH and the characteristics of previous enhancements of this protocol. These LEACH extensions are the routing protocols on which the principles of the routing methodology proposed in this research improve. Section 2.6 summarizes this chapter.

2.2 Brief Overview of WSN/RFID Network Integration Techniques

Recent years have experienced the emergence of a new type of smart networks, which combine RFID systems and WSNs [1] [2] [3] [4] [5]. This section discusses the previous work done in this field, focusing on the integration of RFIDs and WSNs into an ad hoc type network. In this regard, the following sections examine the characteristics of different integration techniques.

The integration of RFIDs and WSNs into an ad-hoc type network can be classified into three main categories:

- Integration of RFID tags with sensor nodes,
- integration of RFID readers with sensor nodes,
- and mixing RFID tags and sensor nodes into one network without integrating them into a single node.

2.2.1 Integrating RFID Tags with Sensor Nodes and Wireless Devices

One of the techniques for integrating RFIDs and WSNs into an ad-hoc hybrid network consists of incorporating RFID tags with sensor nodes. This introduces sensing and communication capabilities to the tags. The integrated tags, in addition to communicating with RFID readers, are able to communicate with each other in an ad-hoc fashion [3]. Figure 2.1 shows an example of the architecture of this type of ad-hoc integrated network. The characteristics of this type of hybrid networks are similar to WSNs, because the integrated tags can communicate with each other and they all have the same energy consumption properties and capabilities. The following section discusses previously proposed architectures of this type of hybrid networks.

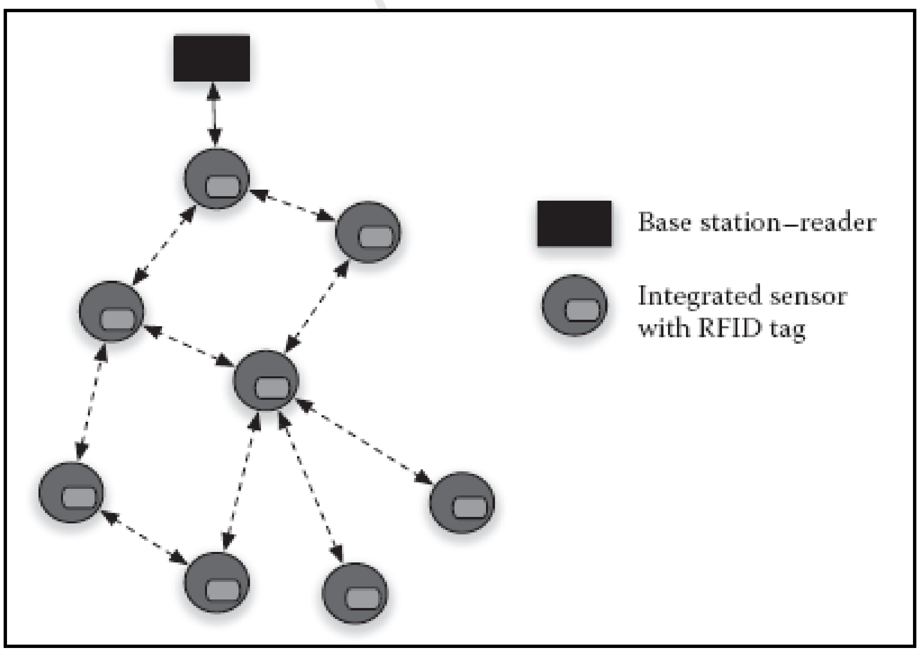

Figure 2.1 Integrated RFID Tags that form an ad-hoc network [3]

2.2.1.1 Proposed architectures

T. Lopez et al. in [23] proposed the integration of RFID tags with sensor nodes for monitoring personal assets. Lopez proposed a three-tiered hierarchy to organize his proposed hybrid network. The upper-layer constitutes a set of fixed integrated tags that take turns to be cluster heads. The chosen cluster head forwards the data from the lower-layer to the base station. At the lower layer, the remaining integrated tags organize themselves into fixed clusters. A tag from a cluster elects itself to become cluster head based on its residual energy. This is as follows. A tag just completing its role as cluster head advertises its remaining energy. If any of the cluster members have higher residual energy than the advertised energy, the tag elects itself to become cluster head for the next round and advertises its new role to its corresponding cluster members.

In [24] [25] and [26] there are further discussions on different architectures for putting together sensor nodes and RFID tags. The objective in the integration is to achieve an ad-hoc network similar to WSNs. In [26], Z. Li et al. proposed a two-tiered non-cluster based hierarchy to improve the energy usage of the network. The integrated tags at the lower-layer collaborate to send their data to the RFID readers, which are at the upper-layer. The routing protocol does not involve any cluster formation or cluster head election. Ruzzelli et al. in [24] decreased the energy consumption of the network by proposing an on-demand wakeup capability that eliminates idle listening.

2.2.1.2 Drawbacks

Although this type of integration technique introduces new potential applications like monitoring of personal assets, this type of hybrid network experiences limitations due to the limited energy of the integrated tags. RFID tags are designed to provide identity to individual items, which therefore become of no used once the battery is exhausted. A more efficient alternative would imply replacing the battery powered sensor-tags, with passive (battery-free) sensor-tags, and RFID readers that have added communication capabilities. This way, even if a reader drains out its battery power, any other reader within reading range of sensor-tags could still retrieves the data and forwards it to the base station. This approach is described in more detail in the following chapter when presenting our proposed network.

The routing protocols presented by Lopez [25] and Li [26] have very similar characteristics as conventional routing protocols. This is because the type of hybrid network that they have been designed for has similar characteristics as WSNs in terms of balanced energy. For example, the sensor-tags, which are the nodes that make up the ad-hoc network, have the same initial energy and similar energy consumption properties. Therefore, these protocols inherit the shortcomings experienced by WSN protocols in meeting the requirements of a hybrid network with imbalanced energy.

2.2.2 Integrating RFID Readers with Sensor Nodes and Wireless Devices

Although the integration techniques discussed in the previous section overcome the communication limitations of RFID tags, the RFID readers still cannot communicate with each other. This section presents another method of integration that consists of adding sensing capabilities to RFID readers and/or RF devices to extend their communication functionalities. Therefore, the integrated readers are able to sense environmental conditions, communicate with each other in wireless fashion, read identification numbers from RFID tags, and effectively transmit this information to the host [1]. This type of hybrid network presents similar characteristics to WSNs because all participating components in the network have the same energy properties and can implement a multi-hop type of communication. The following section discusses previously proposed architectures of this type of hybrid networks.

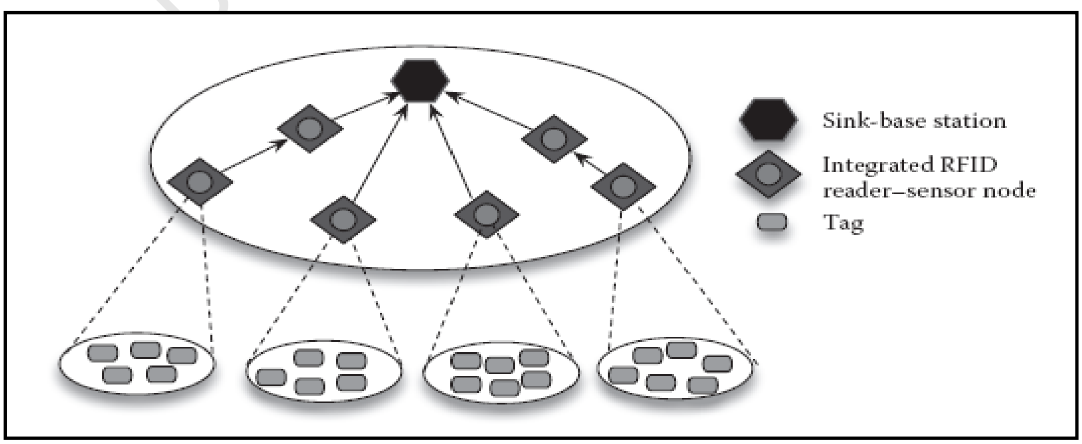

Figure 2.2 Integrating RFID readers with Wireless Sensor Nodes [3]

2.2.2.1 Proposed architectures

Yang et al. in [27] proposed a hybrid network made up of RFID readers with added communication capabilities. The readers form an ad hoc network organized in a two-tiered cluster hierarchy, where readers close to the base station relay the data of readers far from the base station, as illustrated in figure 2.2. This type of network arrangement is characterized by many-to-one traffic patterns, which often demonstrates problems related to energy imbalance among nodes. This is because the network as organized, experiences an increase of data traffic as the distance to the sink decreases. As a result, readers close to the sink die quicker [3]. To solve this problem, Yang in [27] proposed to balance the network's load by adding more readers in areas near the base station. Furthermore, Yang worked out the number of readers that should be added in the neighbourhood of the base station and the distribution strategy. Simulation results showed that the network lifetime increases as the number of readers close to the base station increases.

2.2.2.2 Drawbacks

This type of hybrid network overcomes the disadvantages of limited power for RFID tags as highlighted in the previous section. However, there is still a need for improvement. For instance, the routing protocol proposed in [27] offers a very expensive solution considering the current cost of RFID readers. A more cost efficient alternative may involve the replacement of the additional RFID integrated readers with conventional wireless sensor nodes. The main role of the sensor nodes would then be to relay data of the RFID integrated readers. An additional alternative to adding more RFID readers could consist of allowing the readers close to the base station to take rounds for relaying the network data. This would eliminate the need of having all the readers close to the base station relaying data continuously. Chapter 3 proposes a routing protocol that discusses in more detail these two methodologies.

2.2.3 Integrating RFID Components and Sensor Nodes at the Software Layer

The third method of integration consists of allowing the RFID system and the WSN to coexist in one hybrid network but work independently. Therefore, this integration technique eliminates the need for designing new integrated devices. Instead, the integration takes place at the software layer, when data from both RFID tags and sensor nodes arrive to a common centre control device. Successful operation of either RFID system or WSN may require assistance from one another [1]. For example, the RFID system provides identification for the WSN to find specific objects, and the WSN provides additional information, such as locations and environmental conditions for the RFID system [3]. The following section discusses previously proposed architectures of this type of hybrid networks.

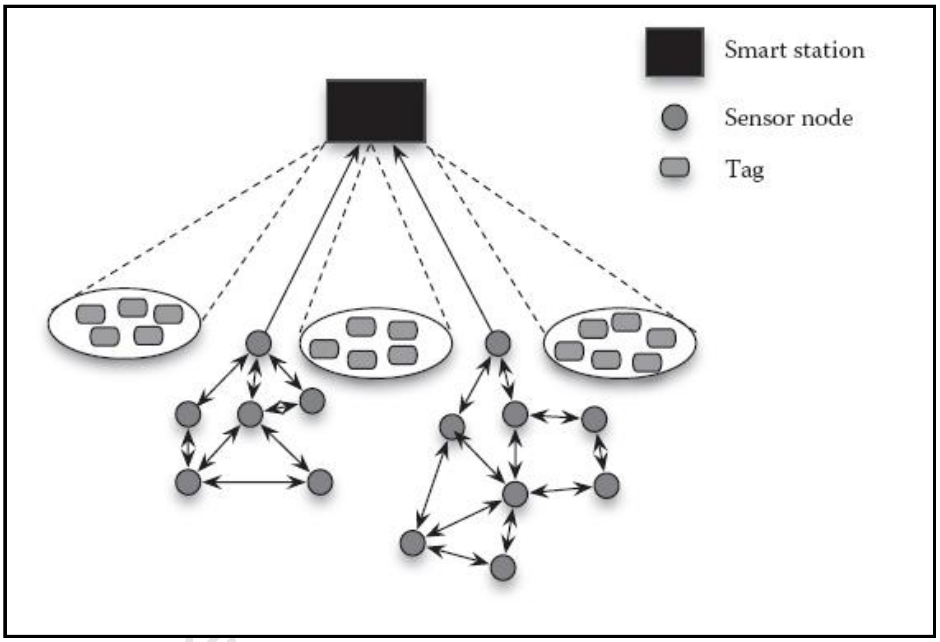

Figure 2.3 Mixed architecture of RFIF tags and sensor nodes [3]

2.2.3.1 Proposed architectures

G. Virone et al. in [28] proposed a hybrid network that combines environmental sensors and wearable interactive devices (like RFID tags) for monitoring health. The architecture is multi-tiered. The lowest level consists of sensor nodes and RFID tags. The sensor nodes collaborate to transmit their data to a backbone, whereas the RFID tags communicate directly. The backbone is at the higher level and acts as a link between the base station and the lower level. In [1] L. Zhang and Z. Wang proposed a hybrid architecture where sensor nodes route their data to the smart station, while the tags transmit their data directly to the smart station. This network arrangement is illustrated in Figure 2.3.

2.2.3.2 Drawbacks

A disadvantage of this type of hybrid network is the possibility of communication interferences between the RFID tags/readers and sensor nodes. This is because they are all physically different devices. Furthermore, the network presents communication limitations because the conventional sensor nodes in the network cannot communicate with the RFID readers. Although the main characteristic of this type of hybrid network is to eliminate the need for designing new integrated devices, an efficient way to overcome the communication limitations is by replacing the conventional RFID readers with integrated readers. This technique for overcoming the communication limitations is developed further in the next chapter when introducing the proposed network.

Another weakness is that the routing protocols designed for this type of hybrid network, like those described above, have similar characteristics as conventional routing protocols because in the network the sensor nodes are the only nodes capable of routing data. Therefore, the protocols do not introduce any methods for balancing different energy dissipations in a network like the one proposed in the following chapter.

2.2.4 Concluding Remarks

Based on the integration techniques discussed in the three categories presented above, there is still a need to design a hybrid network that allows communication among all participating devices in a way that conventional sensor nodes and RFID readers could interact with each other, thus broaden the potential applications of hybrid networks. Chapter 3 introduces a framework with these characteristics. However, the resulting network suffers from energy imbalances among nodes. This creates the need for an energy efficient routing protocol that can balance the energy load among nodes. Therefore, the following section analyses the characteristics of existing energy efficient routing protocols to determine if they can improve the energy imbalances experienced in this network.

2.3 Review of Energy Efficient Routing Protocols in WSN

Depending on the architecture of the network, energy efficient routing protocols can be classified broadly as flat-based routing and hierarchical routing [14]. This classification facilitates a comparative analysis of previous work done for improving energy efficiency in WSNs. This section examines these routing schemes with the objective of determining their efficiency in balancing energy load across the network.

2.3.1 Review of Flat-based Routing Protocols

In flat routing schemes, all nodes typically play the same role and sensor nodes collaborate to perform the sensing task. The base station makes queries to certain regions and waits for data from the sensors located in the selected regions [16]. Early works on this type of routing are *Sensor Protocols for Information via Negotiation (SPIN)* [10] [30] and *Direct Diffusion* [11]. The following paragraphs examine the characteristics of these two routing protocols.

Heinzelman et al. in [10] and [30] proposed a family of adaptive protocols named *Sensor Protocols for Information via Negotiation (SPIN)*. These routing protocols broadcast information at each node to every node in the network assuming that all nodes in the network are potential base stations. The process is as follows. A source node producing data disseminates an advertisement throughout the network. The advertisement package contains a short description of the sensed data. Other nodes interested in the advertised data send back a request packet. Upon receiving a request, the source node sends the full data packet [16] [11]. Therefore, SPIN adopts three types of messages: ADV, REQ, and DATA, as shown in figure 2.4 below.

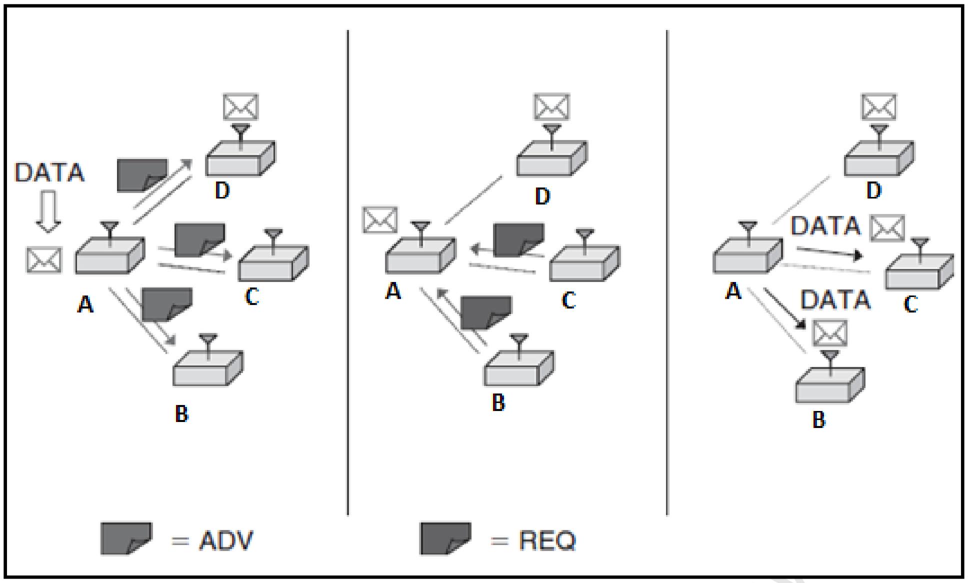

Figure 2.4 The negotiation procedure of SPIN protocol [31]

In the figure, Node A advertises the availability of a new data using the ADV message. Then, Node B and Node C reply with REQ messages to request the advertised data. At the last step, Node A forwards the actual new data with a DATA message to Node B and Node C. This process is repeated each time a node receives new data. The neighbour sensor nodes also repeat this process with their neighbours. As a result, the entire sensor area will receive a copy of the data [31].

Although SPIN improves energy usage and balances network load by disseminating short advertisement packets when detecting an event, this is disadvantageous for periodic network applications because sensor nodes would need to stay active for long periods in order to listen to advertisements coming from all over the network. As a result, nodes would deplete their battery power quickly. Furthermore, advertising data may not be efficient in a network where RFID readers and sensor nodes collect different types of data, because sensor nodes might not be able to interpret messages from RFID readers. Therefore, rather than advertising to any neighbour, a node should check the ID of the nodes to which to direct the ADV data. This would allow nodes to stay on a sleep mode for longer periods. This method is discussed further in Section 2.3.1.2 when discussing hierarchical routing.

One more disadvantage of the advertisement mechanism is that data delivery is not guaranteed because the data must travel through so many nodes that eventually it may be dropped [16]. The overall negotiation process of SPIN introduces high delays [31].

Some SPIN extensions have been proposed in [32], which improve the SPIN protocol. The extensions also consider a network made of nodes with similar energy properties, which is a common characteristic of WSNs [16]. Therefore, they do not introduce a method for balancing energy load among nodes of different energy properties: like assigning different roles based on the functions of each node; or reducing the participation of high-energy consuming nodes in the negotiation process. Chapter 3 provides further discussion on this type of routing technique when introducing the proposed routing protocol.

The other pioneer of flat-based routing in WSNs was introduced by C. Intanagonwiwat et al. in [11], who proposed a data aggregation paradigm named *Direct Diffusion*. In Directed Diffusion, the base station requests data by broadcasting interests. Interest describes a task required to be done by the network. Interest diffuses through the network hop-by-hop, and is broadcast by each node to its neighbours. As the interest is propagated throughout the network, gradients are setup to draw data satisfying the query towards the requesting node. Each sensor node that receives the interest sets up a gradient towards the sensor nodes from which it received the interest [16]. Each gradient contains a data rate field that specifies the data rate requested by the neighbour [11]. This process continues until gradients are setup from the sources back to the base station. Data is aggregated along the way to reduce communication costs. Figure 2.5 below summarizes the process described above.

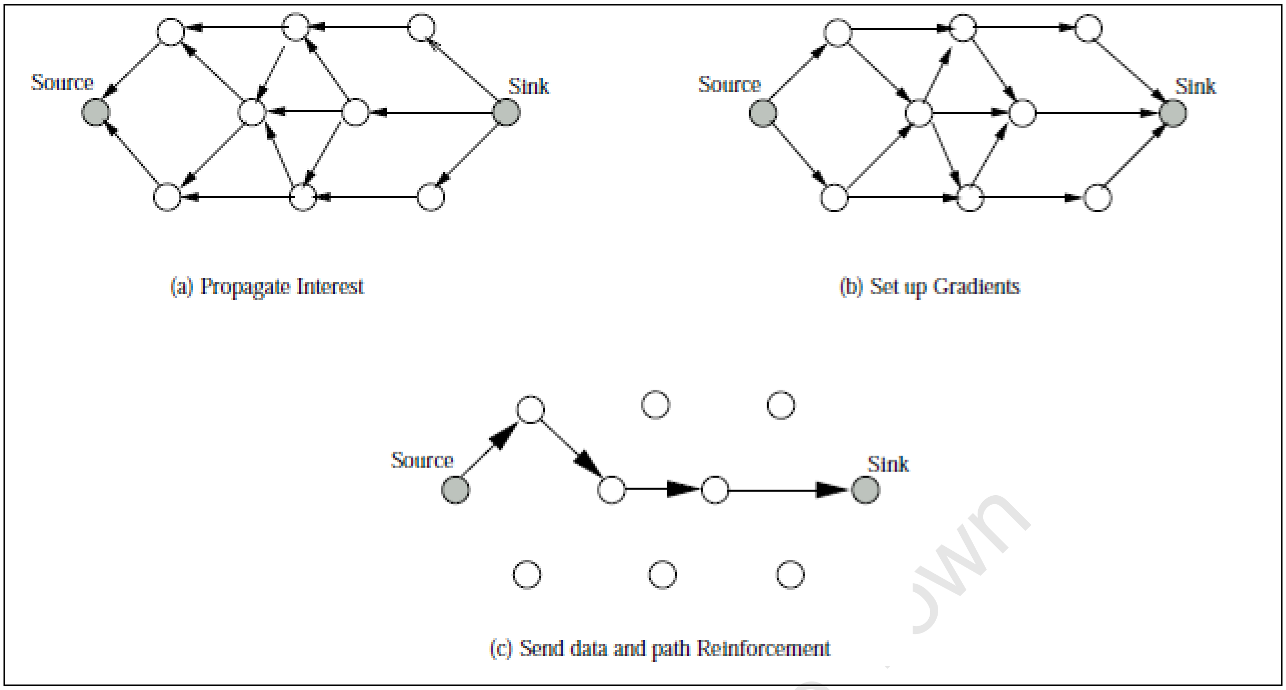

Figure 2.5 An example of the Directed Diffusion data routing process [31]

For example, in part (a) of the figure, a sink sends an interest message and each node broadcast it to its neighbours. Part (b) of the figure shows the gradients being setup in a multi-path fashion back to the destination. Through the process of reinforcement, the best paths are chosen based on the speed of the link. In part (c) of the figure, the data is disseminated along the reinforced path, which corresponds to the path with the highest data rate [31].

Although Directed Diffusion achieves energy savings by diffusing interests through the network, this type of routing protocol is not efficient to applications that require continuous data delivery to the base station [16], such as the network considered in this research. This is because the query-driven on demand data model cannot help in this regard. Moreover, matching data to queries might require some extra overhead at the nodes [16] [31]. Several routing protocols have been proposed in [33] [34] [35] [36] [37] [38] that improve the Directed Diffusion protocol. However, these protocols assume a homogenous type of network. Therefore, the routing methods proposed in these protocols are not designed to efficiently meet the energy requirements of a hybrid network that combines nodes with different energy properties.

Directed Diffusion differs from SPIN in terms of the on demand data querying mechanism it has. In Directed Diffusion, the base station queries the sensor nodes if a specific data is available by flooding some tasks. In SPIN, however, sensors advertise the availability of data allowing interested nodes to query that data [16]. The following section examines some SPIN and Directed Diffusion extensions with characteristics that improve load balancing in WSNs.

2.3.1.1 Additional flat-based routing protocols

This section only discusses routing protocols with characteristics that improve network load balancing in WSNs. The only protocols examined are Rumor routing, Gradient-Based Routing, and Energy Aware because they are commonly studied flat-based routing protocols [16] [31].

D. Braginsky et al. in [33] proposed a routing protocol named *Rumor routing*, which offers an alternate approach consisting of routing the queries to the nodes that have observed a particular event rather than flooding the entire network to retrieve information about the occurring events [16]. When a node detects an event, it adds such event to its local table, called events table, and generates an agent. Agents are long-lived packets that travel the network in order to propagate information about local events to distant nodes. When a node generates a query for an event, the nodes that know the route, may respond to the query by inspecting its event table. Hence, there is no need to flood the whole network, which reduces the communication cost [31] [33] and balances the energy consumption at the expense of more data processing. Rumor routing maintains only one path between source and destination as opposed to Directed Diffusion where data can be routed through multiple paths at low rates.

A weakness of Rumor routing is that it performs well only when the number of events is small. For a large number of events, like a hybrid network made of thousands of nodes that are monitoring tag's ID and different environmental data, the cost of maintaining agents and event-tables in each node becomes infeasible [16] [31] as each node must transmit data periodically to the base station, rather than only when there is a query. In general, the concept of using event tables is more suitable for on-demand type of network applications, which is not the case with the network considered in this research.

Furthermore, using agents to propagate events hop-by-hop to inform distant nodes about an event introduces high delays. Due to these weaknesses, Rumor routing is not efficient for large hybrid networks that suffer from energy imbalances among nodes.

Schurgers et al. [34] proposed a slightly more improved version of Directed Diffusion, called *Gradient-based routing (GBR)*. The main principle of GBR is to keep a record on the number of hops when the interest is diffused through the network. Hence, each node can discover the minimum number of hops to the sink, which is called height of the node. The difference between a node's height and that of its neighbour is considered the gradient on that link. Data is forwarded on a path with the largest gradient. [34] [16]. These paths are maintained and chosen by means of a certain probability. The value of this probability depends on how low the energy consumption of each path can be achieved [34]. By having paths chosen at different times, the energy of any single path does not deplete quickly. When a node's energy drops below a certain threshold, it increases its height so that other sensors are discouraged from sending data to that node. This achieves longer network lifetime as energy is dissipated more equally among all nodes. The data spreading schemes strives to achieve an even distribution of the traffic throughout the whole network, which helps in balancing the load and increases the network lifetime. The employed techniques for traffic load balancing and data fusion are also applicable to other routing protocols for enhanced performance [16].

Although this routing protocol incorporates a way of checking the energy level of each node, the protocol lacks two important features: A means of differentiating the high-energy consuming nodes, and a method to reduce the participation of these nodes in forwarding network's data. These features that balance the network are developed further by the routing protocol proposed in Chapter 3.

Another weakness of GBR is that it requires gathering the location information and setting up the addressing mechanism for the nodes, which complicate route setup compared to the Directed Diffusion [16] [31]. Furthermore, for periodic network applications, as it is the case in the network considered in this research, paths would need to be set periodically as opposed to only when there is an event. This would cause high delays if using only one path to transmit the data of the entire network. The following paragraph presents a routing protocol that explores the technique of allowing simultaneous transmissions.

Shah and Rabaey in [35] proposed to use a set of sub-optimal paths occasionally to increase the lifetime of the network in a routing protocol named *Energy Aware Routing*. Therefore, Energy Aware Routing improves on Directed Diffusion by maintaining a set of paths rather than just one optimal path. These paths are maintained and chosen by means of a certain probability. The value of this probability depends on how low the energy consumption of each path can be achieved. Every time data is to be sent from the source to destination, one of the paths is randomly chosen depending on the probabilities. By having paths chosen at different times, the energy of any single path will not deplete quickly. Through this technique, Energy Aware Routing achieves longer network lifetime compared to Directed Diffusion, because energy is dissipated more equally among all nodes [16] [35]. The protocol assumes that each node is addressable through a class-based addressing, which includes the location and types of the nodes.

Although the technique of using more than one path to forward the network's data to the base station balances the network's load, there is a need to improve it in order to meet the requirements of an imbalanced hybrid network like the framework considered in this research. For instance, when setting up the cost of the paths, those with high-energy consuming nodes should be considered of high cost even if there is more residual energy available. In the *Energy Aware Routing* protocol, the multiple paths transmit by turns rather than simultaneously. This will increase the network delay. Section 2.3.2 examines some routing protocols that explore simultaneous transmissions of different paths.

2.3.1.2 Concluding Remarks

Although the flat-based routing scheme efficiently improves energy usage of small on demand type of networks, the characteristics are not suitable for an imbalanced network that have nodes with different energy requirements, which is the case with the framework considered in this research. For example, all nodes performing the same role in the network may imply the faster depletion of the power of the high-energy consuming nodes. In addition, each node broadcasting information to all nodes requires every node to be awake for longer periods, which results in a faster exhaustion of the network energy. Moreover, nodes closer to the base station would deplete their battery power sooner because data from any part of the network gets to the base station through them, which contributes further to the imbalance among nodes. Furthermore, considering the amount of data that needs to be collected, the total traffic to be processed would be excessive as the network increases, thus increasing the network delay.

In conclusion, a flat protocol operation implemented in an imbalanced large network can cause further network imbalances, high network delays, uneven distribution of load, and a very short network lifetime. Many of these shortcomings can be overcome by assigning different roles in the network. The following section discusses routing protocols that follow this technique for routing data in WSNs.

2.3.2 Review of Hierarchical Routing Protocols

Hierarchical routing schemes often group nodes together, by functions, into a hierarchy or cluster. This type of routing scheme can be viewed as a set of flat routing protocols, each operating at different levels of granularity. For example, in a two-layer cluster routing scheme, higher energy nodes act as a flat routing protocol that processes, aggregates and routes the intra-cluster data. While low energy nodes act as a flat network that performs the sensing. The two leading pioneers of this type of routing technique are *Low-Energy Adaptive Clustering Hierarchy (LEACH)* [12] and *Power-Efficient Gathering in Sensor Information Systems (PEGASIS)* [13]. The following paragraphs describe the characteristics of these two protocols but emphasizing on PEGASIS since LEACH is discussed in Section 2.4.

In [12] W.R. Heinzelman et al. proposed a hierarchical routing protocol named *Low-Energy Adaptive Clustering Hierarchy (LEACH)*. LEACH organizes the network into clusters, where cluster heads are elected randomly for each cluster. Each cluster head transmits its intra-cluster data to the base station. Section 2.4 offers further discussion about LEACH.

S. Lindsey et al. proposed one of the earliest hierarchical routing protocols of WSNs in [13], named *Power-Efficient Gathering in Sensor Information Systems (PEGASIS)*. PEGASIS organizes the nodes into a single chain using the greedy algorithm [36] from the node farther to the base station [16] [13]. As in the greedy algorithm, in PEGASIS the neighbour distances increase gradually since nodes already on the chain cannot be revisited. Therefore, the chain grows from one end only and the next node to be added is the as-yet unselected node closest to the current end node [13] [37]. This type of network arrangement is illustrated in Figure 2.6.

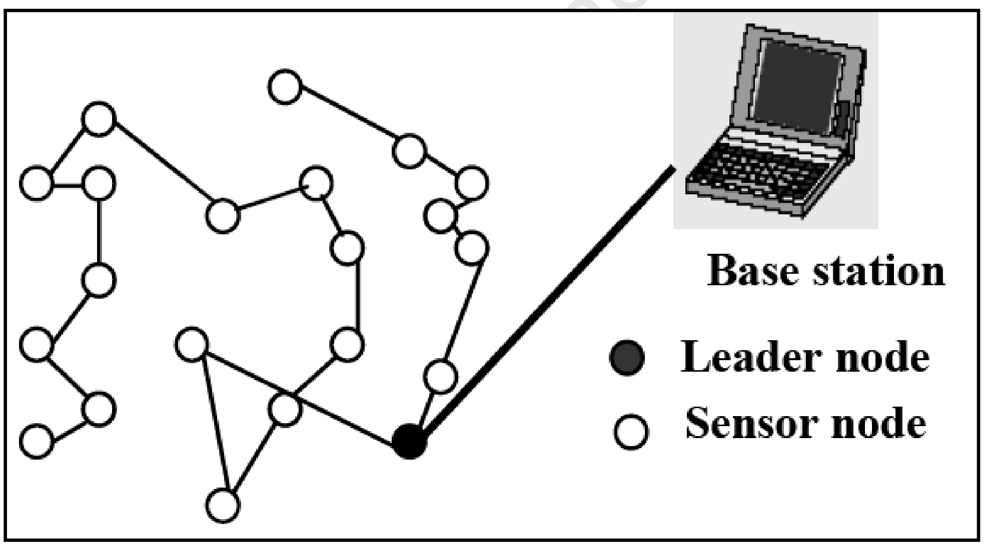

Figure 2.6 PEGASIS [29]

The base station randomly selects a node to be the leader of the chain. The selected leader node transmits the network’s data to the base station. The leader node can be arbitrarily far away from the base station and potentially has to use high transmission power to deliver data to the base station [16] [37].

The actual data collection takes place along the chain. If the leader node is not at the end of either side of the chain, then it sends a token out into the chain's two ends, as shown in Figure 2.6. The token propagates until the end, and return the data, aggregating it along the way. Once the leader receives the data, it sends the token to the other part of the chain and the process repeats. Once data from both halves has arrived, it is forwarded to the base station [14] [37].

Although the chain technique of PEGASIS improves the usage of the energy resources of WSNs, the protocol suffers some weaknesses like the random selection of the leader node, which may result in some nodes becoming leaders more than once consecutively. In addition, PEGASIS does not take into consideration the energy resources of each node when selecting the leader node; consequently, nodes with already low energy may be selected to transmit the data of the entire network. These disadvantages further contribute to the imbalanced experienced by a hybrid network made of nodes with different energy properties. To ensure balanced energy dissipation in the network, an additional parameter that would compensate for nodes that must do more work every round can be considered. For example, if the sensor nodes have different initial energy levels, then we could consider checking the residual energy level of each node in addition to the energy cost of the transmissions already implemented in PEGASIS.

Another disadvantage of PEGASIS is the high delay experienced due to its data collection process. One way to improve this is by exploiting possible parallelism of transmissions in the network [38].

Many subsequent hierarchical routing protocols designed for WSNs incorporate characteristics of LEACH, PEGASIS or both [38] [39] [40] [41] [42]. Since section 2.4 examines extensions of LEACH developed for periodic network applications, which correspond with the characteristics of the hybrid network considered in this research, then the following section only examines some extensions of PEGASIS with the objective of highlighting their inefficiency for imbalanced hybrid networks.

2.3.2.1 Additional Hierarchical Routing Protocols

In order to improve the high delay experienced in PEGASIS, A. Savvides et al. proposed in [38] a 3-Level *Hierarchical PEGASIS* [16]. Savvides reduced the network's data transmission delay by incorporating simultaneous transmissions with the use of signal coding and spatial transmissions. To avoid collisions and possible signal interference among the sensors, two approaches have been investigated. The first approach incorporates signal coding like CDMA. In the second approach, only spatially separated nodes are allowed to transmit at the same time. The chain-based protocol with CDMA capable nodes, constructs a chain of nodes, that forms a tree like hierarchy, and each selected node in a particular level transmits data to the node in the upper level of the hierarchy. At the lowest level, the nodes construct a linear chain similar to PEGASIS [16] [43].

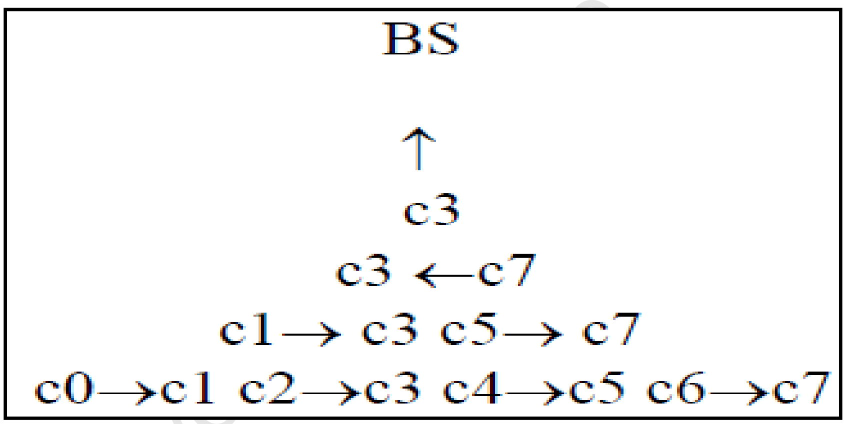

Figure 2.7 Data gathering in a chain-based binary scheme [43]

For example, in Figure 2.7, node c3 is the designated leader for round 3. Since node c3 is in position 3 (counting from 0) on the chain, all nodes in an even position will send to their right neighbour [38]. Nodes that are receiving at each level rise to next level in the hierarchy. Now at the next level, node c3 is still in an odd position (1). Again all nodes in an even position will aggregate its data with its received data and send to their right. At the third level, node c3 is not in an odd position, so node c7 will aggregate its data and transmit to c3. Finally, node c3 will combine its current data with that received from c7 and transmit the message to the base station [16] [43].

Although the Hierarchical-PEGASIS balances the network's load by allowing nodes to only transmit to their closest neighbour, the principle of having nodes to transmit or receive data based on their position in the chain as either odd or even, rather than based on their energy properties, is random and inefficient for an imbalanced hybrid network. Besides, as the number of nodes increases nodes will be required to transmit and receive more. For example, in Figure 2.5, if there were 200 nodes in the lowest level chain, that would imply that 100 nodes would be transmitting in the next level and 50 nodes in the next and so on until it comes down to the last node. This would require eight levels of hierarchy to get to the single node level. Consequently, some nodes would have to transmit and receive at least four times just for a single network transmission to the base station. An alternative for the multiple transmissions of some nodes is discussed in the following paragraph, which consists of having multiple chains and more than a single leader node.

S. Jung et al. in [39] proposed a routing protocol named *Concentric Clustering Scheme (CCS)* that improves the energy consumption of PEGASIS. CCS organizes the whole network into co-centric circular tracks and each one of these tracks represents a cluster. Each track is assigned a level as shown in Figure 2.8.

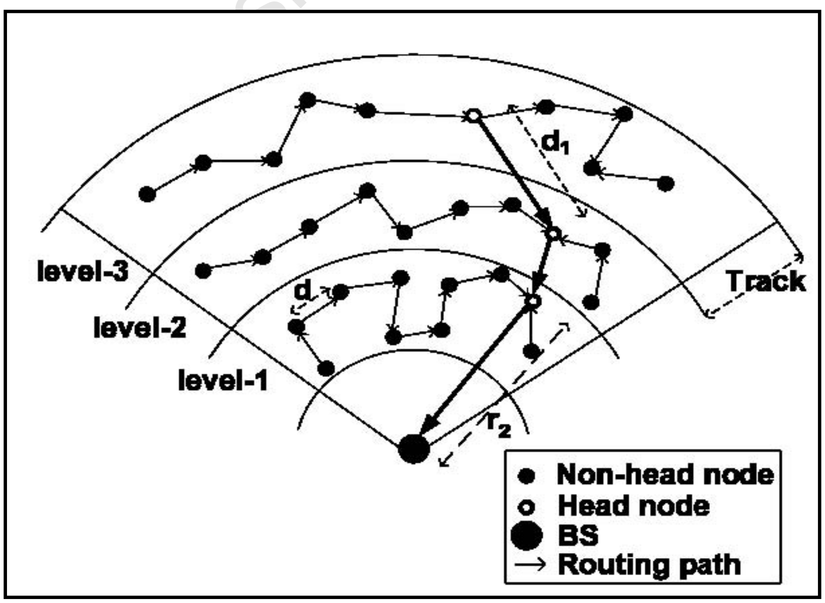

Figure 2.8 Data gathering at head nodes in CCS [43]

For example, as shown in the figure, the nearest track to the base station is assigned as level-1, and as it moves further from the base station the level number increases to level-2, level-3 and so on [39] [43]. On each level, nodes form a chain just like PEGASIS. One of the nodes in the chain is selected as the head node and these head nodes are assigned with node numbers. Each non-head node in a chain receives data from its one-hop neighbour, fuses it with its own data, and then transmits it to its one-hop neighbour. After transmitting data in a track and receiving it at the head node, the head node in level-n transmits data to the head node in level-(n-1) and this procedure continues until delivering data to the BS is accomplished [39].

The principle of having multiple chains with their different leader nodes in the network is an efficient technique of balancing the network load while experiencing less delay than PEGASIS. However, this technique needs improvement in order to be efficient for a large imbalanced hybrid network. For instance, the multiple chains can be constructed based on the ID of the nodes, such that integrated RFID nodes would form chains among themselves and conventional sensor nodes would do the same. This would ensure that data of the same nature are forwarded along the chain, instead of aggregating data of different information like sensed temperature and tag ID. In addition, only cluster heads should make up the multiple chains. In a large network, this would decrease the network delay. The following chapter proposes a routing protocol that introduces this improvements for balancing energy load among nodes of a hybrid network.

2.3.2.2 Concluding Remarks

The hierarchical concept of assigning different roles is quite suitable for an imbalanced hybrid network that combines nodes of different properties such as sensing, communication, and processing capabilities, similar to the framework considered in this research. This way of routing data allows high-energy consuming nodes to perform low-energy demand roles. However, as designed currently, the routing protocols do not eliminate efficiently the type of energy imbalanced problems experienced by this type of network. Therefore, there is a need for improvement of these protocols in order to meet efficiently the different energy requirements. For instance, the assignment of roles needs to take into consideration the sensing energy properties of the different nodes that constitute the network. In this regard, the following section discusses in more detail the principles of the LEACH protocol and analyses in a more specific manner the areas in need of improvement. These improvements set the basis of the protocol proposed in the following chapter.

2.4 Low-Energy Adaptive Clustering Hierarchy Protocol

2.4.1 The Principles of LEACH Protocol

The architecture of the LEACH protocol consists of two phases: Setup phase and steady phase. These phases take place in rounds. Each round begins at the start of the setup phase.

2.4.1.1 Setup phase

The setup phase is characterized by the cluster formation. The process starts with a distributed algorithm where all nodes make autonomous decisions to determine the cluster heads. The election of the cluster head process is as follows. Every node in the network determines the threshold value in the current round. The value of the threshold varies according to the number of rounds and the desired number of cluster heads. When the number of rounds becomes equal to the ratio of desired cluster heads over total nodes, the system resets the count of rounds back to zero. Each node randomly selects a number between zero and one. If the chosen number is equal or less than the threshold value, the node becomes a cluster head for the current round [16] [12]. Figure 2.9 below illustrates a flowchart that summarizes the above described cluster head election process.

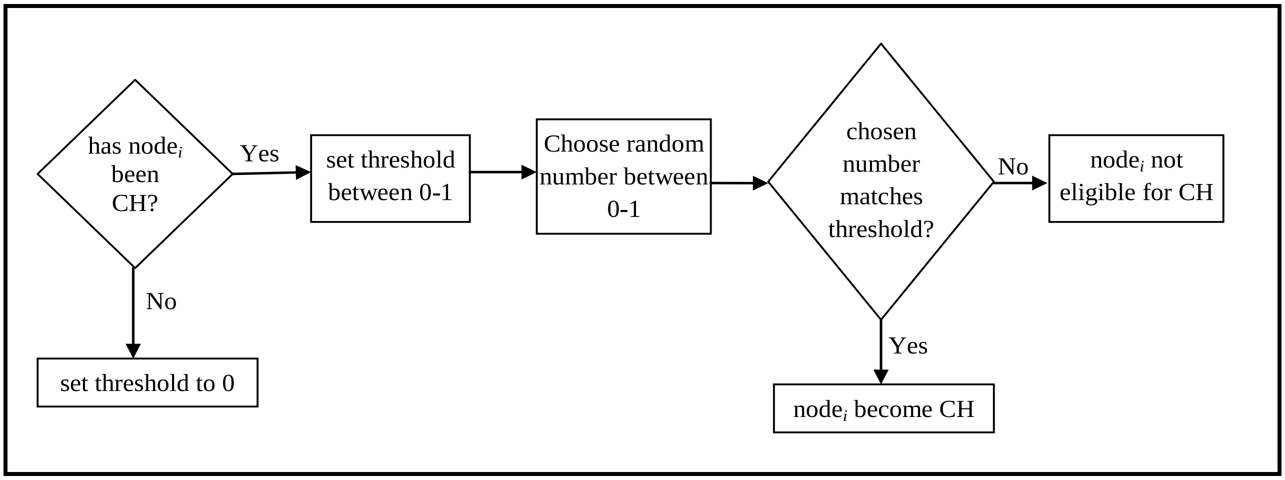

Figure 2.9 Flowchart of cluster heads election process in LEACH

Once a node becomes a cluster head, it broadcasts an advertisement message (ADV) with its ID number. Non-cluster heads in the network listen to the different messages and choose the cluster head with the strongest signal. The signal strength of a message determines the distance from the transmitter to the receiver, so by choosing the message with the strongest signal it would imply belonging to the cluster with minimum communication energy required [12]. After each node chooses a cluster head, they inform their respective cluster heads with a (JOIN-req) message. Cluster heads set up a TDMA schedule for all nodes belonging to their cluster. When all clusters are ready, the set-up phase is complete and the next phase begins.

2.4.1.2 Steady phase

At the steady phase, cluster members start sensing the environment and transmit data to their corresponding cluster head for the duration of the respectively allocated transmission slots. LEACH achieves further energy savings by allowing non-cluster heads to switch to a SLEEP mode until their transmission schedule slot. Cluster heads on the other hand, stay AWAKE for the duration of their role. Once they receive all the information from their corresponding cluster members, they perform data aggregation to reduce uncorrelated noise among signals. Each cluster head transmits the aggregated data to the base station. In order to avoid inter-cluster interference, each cluster uses a unique spreading code determined by direct-sequence spread spectrum (DSSS) [44]. Figure 2.10 illustrates a typical configuration of the LEACH protocol once the two phases described above are complete.

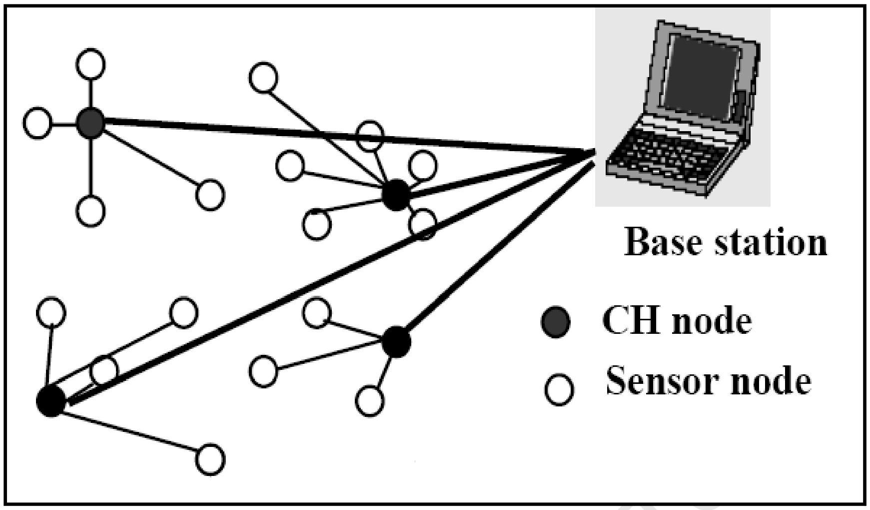

Figure 2.10 Architecture of a WSN when implementing the LEACH protocol [29]

2.4.2 Disadvantages of LEACH Protocol

Although LEACH significantly improves the energy consumption in WSNs, it still has room for improvement. For example, nodes elect themselves to become cluster heads based on randomly matching a threshold value. The autonomous and random election of cluster heads lead to an unpredictable behaviour because in some rounds the number of nodes that match the threshold value, and thus become cluster heads, turns out to be either more or less than the expected. In addition, due to the randomness, some nodes may match the threshold value in consecutive rounds, leading to a faster depletion of their battery power and contributing further to the energy imbalances of a network that integrates devices with different sensing properties. Furthermore, the cluster head election does not take into consideration the residual energy of each node when assigning roles in the network. As a result, some nodes deplete energy faster, when becoming cluster heads despite of having low energy left.

Another weakness during the set-up phase is that the algorithm does not ensure that nodes becoming cluster heads are not all located next to each other, but rather spread out in the network to allow a more even distribution of the intra-cluster communication among nodes. These drawbacks become even more significant in a network where the different nodes need to be organized such that, the nodes with already high-energy consuming properties perform low energy demand tasks. Choosing cluster heads with this random probability of matching a threshold value, does not guarantee an even distribution of power expenditure in such network, which has similar characteristics as the hybrid network considered in this research.

Because of the weaknesses highlighted above, some subsequent routing protocols that improve LEACH replace this random election with an energy-based election. Therefore, the LEACH protocol, as designed, cannot efficiently meet the requirements of the type of energy imbalanced network considered in this research. The following paragraphs present routing protocols that improve some of the LEACH weaknesses highlighted above.

2.4.3 Extensions of the LEACH Protocol

Extensions of LEACH designed for periodic network applications can be categorized broadly as distributed and as centralized. In the distributed category, the sensor nodes organize the network autonomously. Whereas, in the centralized approach, the routing protocols usually leave the responsibility of network arrangement to the base station. The following sections study these two routing schemes.

2.4.3.1 Distributed-based LEACH extensions

Energy-LEACH (E-LEACH) [14] is a derivation of LEACH that improves on the election of cluster heads. E-LEACH shares all the same features of LEACH, with the exception that random election of cluster heads is replaced by an energy-based election. Hence, in E-LEACH, the nodes with highest residual energy elect themselves to become cluster heads. However, when deciding the nodes with highest residual energy, the paper in [14] does not provide any details on how each node would be aware of the remaining energy level of the other nodes in the network.

Energy Efficient Clustering Scheme (EECS) [15] improves E-LEACH by letting candidates broadcast their residual energy to neighbouring candidates. If a given node does not find a node with more residual energy, it becomes a cluster head. In [40], [41] and [42] there are more routing protocols that selects cluster heads based on the residual energy of each node, which is used to probabilistically choose the initial set of cluster heads or the highest residual energies. Electing cluster heads based on the node's residual energy, presents a further disadvantage to a network where not all the nodes have the same initial energy. The nodes with higher energy would become cluster heads regardless of the nature of their energy consumption properties. In addition, since nodes elect themselves to become cluster heads, then the protocol suffers from the same disadvantage of unpredictable behaviour of LEACH.

Multihop-LEACH (M-LEACH) protocol [14] only differs with LEACH on that cluster heads form a chain to transmit the inter-cluster data. The authors in [65] present a protocol similar to M-LEACH where cluster heads and cluster members communicate through multi-hoping, rather than directly to the base station. Both protocols achieve higher network coverage and higher energy efficiency by reducing the transmission ranges of cluster heads and cluster members. However, both protocols also inherit all other weaknesses of LEACH, mainly those related to the process of cluster head election, which does not guarantee low-energy consumption in imbalanced networks, as discussed in section 2.5.2.

2.4.3.2 Centralized-base LEACH extensions

LEACH-Centralized (LEACH-C) [17] protocol is an enhancement of LEACH, that similar to it, is also divided in two phases: set-up and steady phase. The steady phase of the protocol is the same as the one presented in LEACH. The set-up phase, on the other hand, replaces the random and autonomous election of cluster heads by assigning the process of the election to a base station. At the beginning of each round, nodes send their ID number, residual energy, and location to the base station. The base station selects the desired number of cluster heads based on two factors: location in the network and residual energy. Upon receiving the data from all nodes, the base station determines the average energy of the network. Then, it disqualifies any nodes with residual energy value less than the average energy left in the network. The nodes with energy higher than the network average become cluster head in a random manner and depending on their relative spatial positions.

LEACH-C uses the *K*-means clustering algorithm [44], which attempts to find the centre point of a cluster by minimizing the distance between points assigned to be within a cluster and at the centre of that cluster [45]. The optimal position is determined by minimizing the total sum of the distances between the preliminary cluster heads and the non-cluster heads. After forming the most optimal clusters, the base station also goes on creating a Time Division Multiple Access (TDMA) schedule for each cluster. The base station ends this phase by broadcasting messages with the cluster head nodes' ID. If a node's cluster head ID matches its own ID, the node is a cluster head; otherwise, the node determines its TDMA slot for data transmission and goes to sleep until it is time to transmit data.

One problem with this protocol is that it only takes into consideration communication energy and neglects sensing energy. In a hybrid network, such as the one considered in this research, that combines different types of nodes, the nodes with energy higher than the network's average energy may include nodes with high-energy consuming features. These nodes may have an initial energy higher than the conventional sensor nodes, thus they would be in higher probability of becoming cluster heads in consecutive rounds. This will lead to an accelerated depletion of their power. Therefore, LEACH-C protocol requires an algorithm that can differentiate between nodes with high-energy consuming properties from that of lower consumption. In addition, the protocol also needs an algorithm that can allow routing the data of cluster heads that are too far from the base station. In LEACH-C, the election of cluster heads ultimately reduces to the position in the network of the pre-elected nodes. This can be improved by taking into consideration the energy of each pre-elected cluster head when determining the optimal clusters. The routing protocol proposed in Chapter 3 improves on these drawbacks by incorporating the features mentioned above.

Base-Station Controlled Dynamic Clustering Protocol (BCDCP) [46] is another centralized protocol. BCDCP has the same architecture as LEACH-C, with the improvement that the base station does not only form the clusters but it also sets a routing path for cluster heads data. In BCDCP, cluster heads take random turns to transmit the data of all the other cluster heads to the base station. Figure 2.11 illustrates a conceptual example of how the BCDCP protocol arranges the network. In the figure, the furthest cluster head receives data from all the other cluster heads and then forwards the received data to the base station.

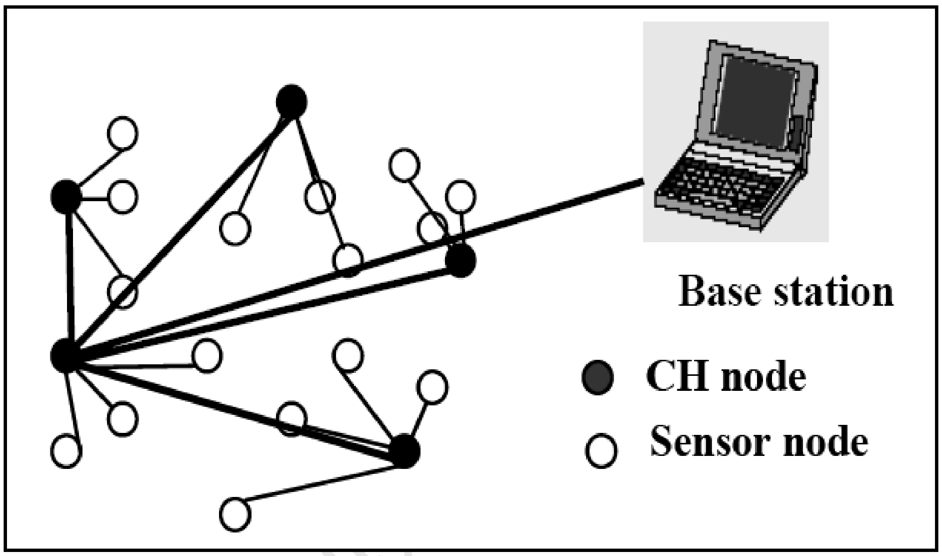

Figure 2.11 Architecture of the BCDCP protocol [29]

The drawbacks of this protocol are similar to the ones highlighted in LEACH-C. Although this protocol incorporates an algorithm that allows routing of cluster heads data, the random assignment of a cluster head to send the data of the entire network introduces yet another disadvantage. This is because the randomness causes a faster depletion of the energy of cluster heads that are far from the base station. Such nodes transmit the data of the entire network, from a long transmission range, thus depleting the battery power faster. A final disadvantage of this protocol is the potential bottleneck point created by the single cluster head transmission. The routing algorithm proposed in the following chapter improves on these drawbacks by creating more than one chain of cluster heads, and eliminating the random assignment of one cluster head to forward the data of the entire network.

2.4.4 Disadvantages of the LEACH Extensions for Hybrid Networks

The LEACH extensions presented in this section are designed for WSNs, with assumptions suitable to the characteristics of WSNs. However, the characteristics of a hybrid network that combines nodes with different sensing properties, different processing and communication capabilities, as well as different initial energies, encourages the study and analysis of an improved routing protocol that takes into consideration these characteristics. A routing scheme that organizes the nodes and assigns roles based on the sensing energy properties of the network, because the energy dissipated by such nodes constitutes a large amount of the network's residual energy.

The energy efficient routing protocols presented in this chapter do not cater for the specific imbalance requirements introduced in the framework considered in this research. This calls for the redesign and development of a new energy efficient routing protocol. In this regard, to materialize efficiently this type of hybrid network, the following chapter also proposes a routing protocol that overcomes these limitations.

2.5 Chapter Summary

This chapter analysed existing hybrid networks as well as the energy efficient protocols implemented in such networks. The discussion highlighted the shortcomings of the related work, which has motivated to the proposal of the hybrid network and the routing algorithm described in the following chapter. This chapter also examined LEACH protocol and its enhancements, which serves as the basis of the developed routing algorithm proposed in Chapter 3.

Chapter 3

Proposed Methodologies

3.1 Introduction

As mentioned earlier in Chapter 2, there is a need to design an integrated RFID-WSN network that overcomes the communication limitations currently experienced by this type of hybrid networks. In this chapter, we propose an integration architecture that overcomes some of these limitations. However, after a rigorous analysis of the energy consumption of the proposed network, the findings demonstrate the presence of energy imbalances among the different components of the network. This creates a need for a routing protocol that would take into consideration these imbalances in order to improve energy usage in the network. However, as discussed in the previous chapter, existing routing protocols as designed, they cannot to eliminate such imbalances. Hence, as a second contribution, this chapter proposes a routing protocol that improves energy usage, by assigning roles in the network based on the sensing energy properties of each node.

The remainder of the chapter is organized as follows. Section 3.2 describes the architecture and characteristics of the proposed network. Section 3.3 presents a detailed analysis of the energy usage in the proposed network. Following from this analysis, Section 3.4 introduces the proposed energy efficient routing protocol for hybrid imbalanced networks. The chapter ends with a summary in section 3.5.

3.2 The Proposed Hybrid-RFID Sensor Network (HRSN)

This section introduces an integration architecture in which conventional wireless sensor nodes, sensor-tags, Hybrid Sensor Node (HSN) and a base station (host) are combined to enhance the advantages of RFID systems and WSNs. We named this framework Hybrid RFID-Sensor Network (HRSN). The conceptual architecture of the HRSN is illustrated in Figure 3.1. As seen in the figure, the network is arranged into clusters where sensor-tags, HSNs and sensor nodes cooperatively forward any physical or environmental data to the base station. The variety of the components that make up the HRSN, together with the architecture of the network, results in a combination that is different from similar existing networks. The following section describes the characteristics of each of these components, and their role in the network.

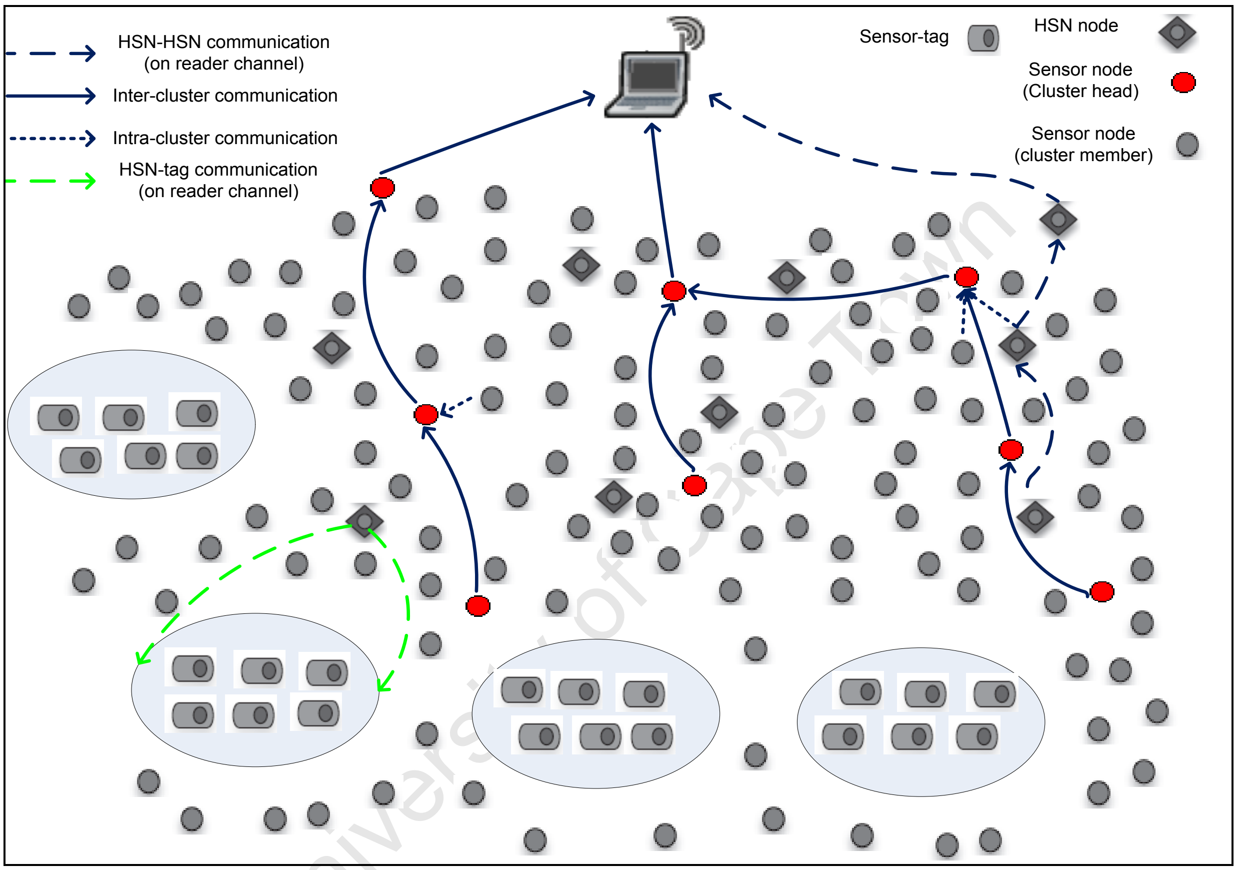

Figure 3.1 Architecture of the proposed hybrid network

3.2.1 Components of the HRSN

As mentioned earlier, the HRSN is made of sensor-tags, HSNs, conventional wireless sensor nodes and a base station.

A *sensor-tag* is an important component of the HRSN because upon interrogation, these tags provide identification and sensing information to the reader. For the purpose of this research, we define a *sensor-tag* to be an Ultra High Frequency (UHF) RFID passive tag that has a sensor attached to it, similar to the device designed in [47]. Passive UHF RFIDs allow tags to be interrogated at a range of up to 10 meters [30]. Due to the passive feature, a *sensor-tag* only has power and sensing capabilities while being interrogated by an RFID reader.

Another key component of the network is the *Hybrid Sensor Node (HSN)*. HSNs are the brain of the HRSN because through them, communication among the different network components is possible. *HSN* combines an RFID reader and a wireless sensor node in a single node. The resultant device can perform the following functions:

- sense environmental conditions,
- communicate with other conventional sensor nodes in a wireless fashion,
- read identification numbers from tagged objects or persons and
- effectively transmit this information to the base station or next HSN.

The integrated sensor node side of the HSN provides both sensing and communication functionalities to the RFID reader side of the node. The sensor side of the HSN uses 2.4GHz and the RFID reader side uses 915MHz. This way transmission on the sensor channel does not affect any on-going communication on the reader channel. This technique of communicating in separate channels is similar to the method presented in [19] and [20], where authors Ruzzeli et al. and Kim et al. proposed similar techniques to minimize the occurrence of collisions. In the HRSN, the reader channel is used for HSN-to-tag communication, whereas the sensor network's channel is used for HSN-to-HSN and HSN-to-cluster head communication. We assume today's advancement in technology allows the implementation of a microcontroller intelligent enough to differentiate the different types of data and take appropriate action based on that. These actions involve decisions like to which node to forward the received data and on which channel. For example, if the received data is a temperature reading, the data will be forwarded to a sensor node or an HSN. However, if the received data is a sensor-tag's ID the information will be forwarded only to an HSN because of its capability to interrogate sensor-tags. A similar commercially available device but with limited functionalities is introduced in [48].

The last component of the network to be discussed is the conventional *wireless sensor node*. The main role of the *wireless sensor node* is to act as relay while providing additional information about the environment. The presence of wireless sensor nodes in the network is higher than the other components because the wireless sensor nodes perform the high-energy consuming roles of the network, such as being a cluster head. Using sensor nodes to perform such roles balances the energy dissipation in the network, because it allows saving of the power of HSNs, whose functions are very energy consuming. An additional advantage of the incorporation of the wireless sensor nodes is the reduced cost of the design of the network, because by increasing their presence in the network, fewer HSNs are required. Similar to HSNs, the wireless sensor nodes communicate among themselves through the 2.4GHz sensor network's channel.

The interaction among all these components and their arrangement in the network introduces features that are unique to the HRSN. To grasp a better appreciation of this innovation, the following section describes the architecture of the HRSN.

3.2.2 Network Scenario and Architecture

As mentioned earlier, the wireless sensor nodes and HSNs are organized into clusters, where a cluster-head is elected. A cluster may or may not contain an HSN. The wireless sensor nodes constitute the largest portion of the network. They are distributed randomly all across the network area. Unlike the wireless sensor nodes, the positions of HSNs within reading range of sensor-tags are predetermined and placed separated enough to avoid reader-tag collisions. The reading range of the sensor-tags is 10 meters as specified earlier, so the separation distance of the HSNs furthest from the base station is based on that information.

Sensor-tags are located in groups that are within reading range of HSNs. The RFID-reader side of the HSNs periodically interrogate all sensor-tags positioned within their reading range. The

HSNs that are out of reading range of sensor-tags and closer to the base station, operate as relays for other HSNs that are further from the base station.

Unlike previously suggested hybrid networks, the different nodes in the HRSN network can communicate among themselves. HSNs forward their data either to a wireless sensor node or to another HSN closer to the base station. This introduces an advantage to HSNs, because increasing the presence of wireless sensor nodes in areas close to the base station where the amount of traffic is high, saves the power of HSNs since they can then use the sensor nodes to relay their data. HSNs are more expensive than wireless sensor nodes due to their combination with RFID readers. However, sensor-tags can only communicate to HSNs because of the capability of these HSNs to powering them. This unique feature enhances the feasibility of new applications. The following section describes one of these potential applications.

3.2.3 An Application Scenario

A practical example application for the proposed network can be implemented in hospitals that contain rooms with pre-mature babies. In the scenario, each of the pre-mature babies is placed inside an incubator. The incubators contain sensor nodes, and each baby placed inside an incubator must wear a sensor-tag. Since the sensor-tags are battery free, it would be harmless to the babies in terms of heat dissipation. In addition, the radio channel used is similar to that of WiFi so it should be safe for the newborn babies.

The sensor-tags worn by the babies are read by HSNs that are within the reading range. In addition, HSNs relay the sensor data received from the sensor nodes placed inside the incubators. In the case where an HSN is too far from a base station, the collected tag information is routed to another HSN closer to a base station. Based on which HSN interrogated a particular sensor-tag, the base station determines the location of a baby as well as any additional data received about that particular baby and the incubator where the baby is placed. Through the information received from the HSNs, health practitioners can monitor each baby’s health and easily track their exact location within the hospital. Determining the exact location of a baby is crucial in emergencies because this reduces any possible delays caused while trying to locate the baby. The system sets an alarm when an HSN located in the hospital exit detects the presence of a sensor-tag.

The wireless sensor nodes that are not place inside incubators, help monitoring the overall temperature of the room.

Table 2 provides examples of queries that can be made about the babies when implementing the HRSN. At the same time, the table also shows how such queries could not be made if only either WSN or RFID system is implemented. Therefore, this table emphasizes the importance of implementing the HRSN in terms of acquiring more detail information about an object or a person, in this case pre-mature babies.

Table 2: Possible questions to ask to understand the importance of the integration

	When the baby has RFID only	**When the baby has Sensor only**	**When the baby has both RFID and Sensor**
Temperature	Where has the baby been in the last 24 hours?	What has been the temperature of the baby in the last 24 hours?	Has the baby been exposed to excessive heat while inside the incubator in the past 24 hours?
Blood pressure	Was the baby taken to the examination room 4 hours ago?	What is the blood pressure of the baby?	Did the baby's blood pressure start raising while being treated in the examination room?

3.2.4 Energy Challenges of the HRSN

Although hybrid networks have been proposed before, so far the networks proposed do not suffer from the type of energy imbalanced experienced in the HRSN. The amount of data that need to go through the traffic in the HRSN is more than that of conventional WSNs. This is because of the additional sensor-tags' identification numbers, which results in a faster depletion of the battery power of the various nodes. For example, the HSNs have higher dissipation energy because of their communication capability with conventional wireless sensor nodes, besides themselves. Moreover, they periodically have to energize the sensor-tags to collect their data. The following section provides a more detailed analysis of how these different energy dissipations influenced the overall energy performance of the HRSN.

3.3 Energy Analysis of the HRSN

The role that each node performs in the network has a significant impact on the total energy dissipation. Therefore, in order to assign roles fairly, a thorough understanding of the energy consumption of the different types of nodes is required. Through this analysis, a more energy efficient method for the usage of resources available in HRSN can be achieved. The following subsections provide analysis of the consumption of the different types of nodes.

3.3.1 Overview of the Energy Dissipation

The total energy dissipated by each node is the sum of the energy dissipated for its functions and its role in the network.

- A sensor node acting as cluster member spends energy on sensing and transmitting data to its cluster head.
- A sensor node acting as cluster head dissipates energy for receiving, processing and transmitting data from its cluster members as well as on relaying data from other cluster heads.

- An HSN acting as cluster member spends energy sensing and transmitting data to its cluster head, in addition to interrogating sensor-tags and relaying data from other HSNs.

- An HSN acting as cluster head spends energy for receiving, processing and transmitting data from its cluster members, as well as on interrogating sensor-tags and relaying data from other HSNs.

This overview on the overall energy dissipation shows that although the different components of the HRSN have different energy consumptions, they all have a common energy dissipation factor, which is communication. The nodes communicate through a radio system. Therefore, the following section describes the energy requirements when operating the radio.

3.3.2 The Radio Model

Every node in the HRSN contains a radio communication subsystem that consists of transmitter/ receiver electronics, antennae and an amplifier. To determine the energy dissipated by these components, this research follows the radio model illustrated in Figure 3.2. In the figure, k-bits of data need to be forwarded. The data is processed through the electronics of the node, and then amplified by the antenna for the signal to be strong enough to travel a distance *d* to a receiving node.

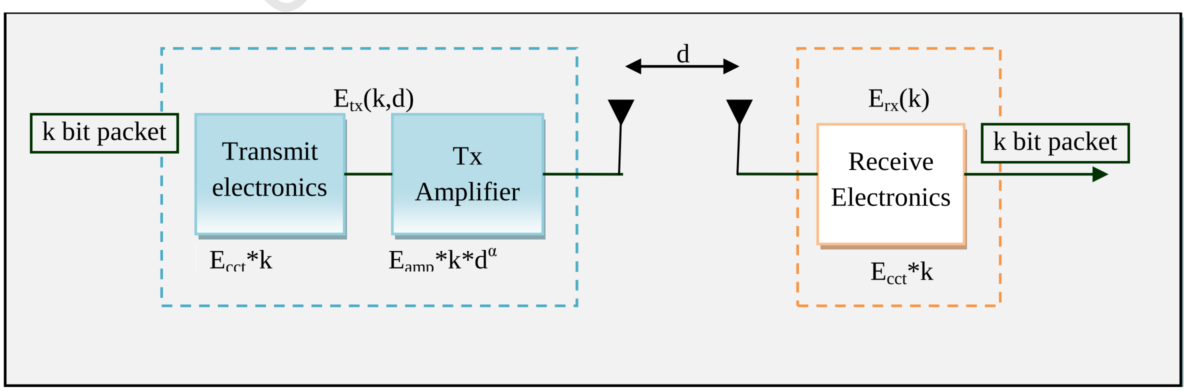

Figure 3.2 Radio energy dissipation model

Therefore, if E_{tx} and E_{rx} denote the energy spent by a node for transmitting and receiving data respectively, then the total energy E dissipated by the radio of a node during the reception and transmission of data is obtained using Equation 3.1:

$$E = E_{tx} + E_{rx} \tag{3.1}$$

where E_{tx}, the transmission energy, consists of the energy E_{cct} dissipated for operating the electronics of the transmitter, and the energy E_{amp} dissipated for amplifying the signal that is about to be transmitted. Thus, the energy required to transfer k bits of data between two nodes separated by a distance d, is obtained using Equation 3.2:

$$E_{tx} = E_{cct} * k + E_{amp} * d^{\alpha} * k \tag{3.2}$$

For reception of data, the energy E_{rx} is only spent while running the electronics of the receiver. Therefore, the energy dissipated to receive k bits of data between two nodes at a distance d from each other is obtained as given by equations 3.3:

$$E_{rx} = E_{cct} \cdot k \tag{3.3}$$

The value of E_{amp} – in Equation 3.2 – varies depending on the transmission distance since longer distances need higher amplification of the signal. Therefore, for a given threshold transmission distance d_0, the free space propagation model ε_{FS} [49] is applied when $d < d_0$, because the equation was derived assuming a short distance transmission range with no reflection or multipath loss of signal. The model is mathematical described as in Equation 3.4:

$$\varepsilon_{FS} = \frac{16\pi^2}{G_T * G_R * \lambda^2} \tag{3.4}$$

On the other hand, the two-ray ground reflection model ε_{TR} [49] of equation 3.5 is used when $d \geq d_0$ because the model considers reflection or multipath signal loss. With these two models, the energy spent to amplify a signal is obtained as illustrated in Equation 3.6:

$$\varepsilon_{TR} = \frac{L}{G_T * G_R * h_t^2 * h_r^2} \tag{3.5}$$

$$E_{amp} = \begin{cases} \varepsilon_{FS} * d^2 & if \ d < d_0 \\ \varepsilon_{TR} * d^4 & if \ d \geq d_0 \end{cases} \tag{3.6}$$

where G_T and G_R are the transmitting and receiving antennae gain respectively, h_t and h_r are the height of the transmitting and receiving antennae respectively, L is the non-propagation systems loss, d is the transmission distance, $\lambda = \frac{c}{f}$ is the wavelength of the carrier.

In this research, we set the value of the threshold distance to be the ratio of the free space model over the two-ray ground model, which mathematically is as shown in equation 3.7:

$$d_0 = \sqrt{\frac{\varepsilon_{FS}}{\varepsilon_{TR}}} = \frac{\sqrt{(16 * \pi^2 * L * h_t^2 * h_r^2)}}{\lambda^2} \tag{3.7}$$

Since a transmitted signal’s attenuation is proportional to the power function of the transmission distance (see equation 3.4), it is generally more energy efficient to send packets over a route with many short hops. However, short hops augment the number of relays and so the energy used for packet reception over a path increases. However, this latest consequence can become negligible when an optimized number of hops are implemented. In addition, the packet delay and the energy required for packet processing on a route is reduced by the optimized number of hops, but remains higher than in the case of a one-hop communication. Therefore, the following section examines the energy spent for data processing, to determine whether data processing has higher cost than a long data transmission.

3.3.3 Energy Consumption for Data Aggregation

One of the advantages of organizing the HRSN into clusters is that the amount of data transmitted to the base station can be compressed and correlated. To determine the energy consumption of a cluster head for aggregating data, we follow the principle presented in [50].

Let E_{DA} denote the total energy dissipated by a cluster head node's digital electronics for aggregating k bits of data from m cluster members, then the energy spent on the electronics is specifically due to current leakage and to switching capacitance. Therefore, energy for data aggregation is the sum of the energy lost to switch capacitance (C_{tot}) and the energy lost in current leakage I_{leak} [51]. Then, E_{DA} can be described mathematically as follows:

$$E_{DA} = (C_{tot} * V_{DD} + I_{leak} * \Delta t)V_{DD} \times \Delta t \qquad (3.8)$$

where V_{DD} is the voltage supply and Δt is the latency for aggregating k bits of data from each m cluster members.

This energy, depending on the role of the nodes, represents an important part of the overall energy consumption of the nodes. The following sections discuss the overall energy of the different components of the network.

3.3.4 Energy Consumption of the Wireless Sensor Nodes

Conventional sensor nodes in the HRSN can be divided into cluster-heads and cluster members based on their role. Section 3.1 described the energy dissipated for each role. Using equation 3.1

and equation 3.8, we calculated the total energy dissipated by a sensor node based on its role in the network. Such that, a sensor node acting as cluster head (CH) of m cluster members, as well as relaying the data of l other cluster heads, would spend communication energy for receiving the data from all l cluster heads and m cluster members. However, when transmitting the received data, the node only spends energy for relaying the data of the l cluster heads and one aggregated data corresponding to the m cluster members. This mathematically translates to:

$$E_w^{SN}(t) = (m + l)E_{rx}^{CH} + (1 + l)E_{tx}^{CH} \tag{3.9}$$

where:

- E_{tx}^{CH} is the energy used by a cluster-head while transmitting data to the next cluster head or base station.
- E_{rx}^{CH} is the energy dissipated for receiving data from the cluster.

Otherwise, if the node is acting as a cluster member (CM), the energy dissipated is only on sensing and transmission of environmental data. Therefore, at a given time t a sensor node w spends in total:

$$E_{tot_w}(t) = \begin{cases} E_w^{SN}(t) + (E_{DA} * k * m)\,; & if\ CH \\ E_{tx}^{CM} + E_{sens}^{CM}; & if\ CM \end{cases} \tag{3.10}$$

where E_{tx}^{CM} is the energy used while transmitting data inside the cluster and E_{sens}^{CM} is the energy spent for sensing the environment.

3.3.5 Energy Consumption of the HSNs

A. Energy for interrogating sensor-tags

Unlike the conventional sensor nodes, HSNs dissipate a significant amount of energy when interrogating sensor-tags. The total energy dissipated is directly dependent on the density of the sensor-tags within the sensing region. The higher the number of sensor-tags to be interrogated the higher the amount of energy dissipation. Given that $S = \{s_1,\ s_2, \ldots, s_n\}$ denotes the set of sensor-tags in the network, and $H = \{h_1, h_2, \ldots, h_i\}$ denote the set of HSNs within reading range of sensor-tags, then by letting S_i denote a subset of S that represents the set of sensor-tags randomly distributed within the reading area of h_i, then in a given region, the set S_i can only have a maximum of n sensor-tags. Each sensor-tag generates k bits of data. Assuming that h_i successfully receives the data from all n sensor-tags, then by following the principle in equation 3.1, the energy consumption of h_i for interrogating n sensor-tags at a time t would be:

$$E_i^{sens}(t) = \sum_{j=1}^{n} \left[\left(E_{cct} * k + E_{amp} * k * d_{i,j}^{\alpha} \right) + E_{cct} * k \right] \tag{3.11}$$

where $0 < d_{i,j} \leq max\{d_1, \ldots, d_t\}$ is the distance between h_i and sensor-tag j within its reading range and α is the propagation loss coefficient with values 2 or 4 depending on the value of d as defined in Equation 3.4.

B. Total Communication Energy of an HSN

HSNs constitute a large portion of the network's energy consumption, and this is mainly because of their capability to communicate with all the components that make up the HRSN. An HSN acting as cluster head has the same communication energy dissipation as that described for sensor nodes, in addition to relaying the data of other HSNs. Then, using equation 3.8 and equation 3.10, we derive the total amount of communication energy dissipated by an HSN acting as cluster head of m cluster members as well as relaying the data of l other cluster heads and h other HSNs, as shown in the following equation:

$$E_i^H(t) = E_i^{SN}(t) + \sum_{\varphi=1}^{h}(E_{tx}^{HSN} + E_{rx}^{HSN}) \qquad h \in [0, H) \tag{3.12}$$

where $E_i^{SN}(t)$ represents equation 3.9; E_{tx}^{HSN} denotes the energy spend to forward collected sensor-tag data to a next HSN hop and E_{rx}^{HSN} denotes for energy spent receiving the sensor-tags data of other HSNs.

Otherwise, if the HSN is acting as a cluster member (*CM*), the energy dissipated is only for transmitting sensed data to a cluster head, in addition to receiving and forwarding sensor-tags data from the other h HSNs. Therefore, at time *t*, HSN h_i would spend:

$$E_{com_i}(t) = \begin{cases} E_i^H(t) + (E_{DA} * k * m); & if\ CH \\ E_{tx}^{CM} + E_{sens}^{CM} + \sum_{\varphi=1}^{h}(E_{tx}^{HSN} + E_{rx}^{HSN}); & if\ CM \end{cases} \tag{3.13}$$

Using equations 3.9, equation 3.11 and equation 3.12, the total energy consumption of the HRSN at a given time t is obtained as derived in Equation 3.14:

$$E_{HRSN}(t) = \sum_{i=0}^{H}\left(E_{com_i}(t) + E_i^{sens}(t)\right) + \sum_{w=0}^{N} E_{tot_w}(t) \tag{3.14}$$

The above analysis shows that HSNs dissipate the most energy in the HRSN. Therefore, the following section introduces a method for routing data in the HRSN that ensures a more even consumption of energy among the nodes.

3.4 The Proposed HRSN Routing Algorithm

The development of the proposed routing algorithm takes place in four phases: discovery of nodes, cluster formation, neighbourhood discovery, and lastly sensing and communication. Each phase is described below.

A. Discovery of nodes

In the first phase, each node (HSNs or sensor nodes) advertises its information to the base station. The broadcasted information contains an identification number, the position of the node in the network (i.e. XY position) and the residual energy of the node. This phase is repeated every T-seconds, which represents the duration of each round.

B. Cluster formation

The second phase of the algorithm is for arranging the network into the most optimized clusters. The process for cluster formation is handled by the base station. This way the nodes spend less energy on processing data and on communicating amongst themselves. Besides, this replaces the LEACH random probability of matching a threshold value. The cluster formation phase takes place in five different stages: Computation of the network's average residual energy; nomination of candidates for the role of cluster head; election of cluster heads and cluster formation; assignment of transmission slots; and finally inform all nodes about the cluster arrangements for this particular round. These steps take place as follows:

1) *Computation of Average Residual Energy:* The base station receives all the broadcasted information from all the nodes and stores it in a list. Then, it computes the average energy available in the network based on the residual energy information received from each node.

2) *Nomination of candidates for the Cluster Head Election:* After computing the energy, the base station proceeds with the pre-election of cluster heads. Table 3 shows the algorithm that each node undergoes in order to participate in the election of cluster heads.

Table 3: Pre-election of cluster head candidates

Algorithm 1. Pre-election of Cluster Head

```
1: for each node n_i do
2:     #check the current energy E_i
3:     if ( (E_i == I_E || (E_i > avgE) && (E_i >= E_{i+1}) then
4:         n_i is eligible
5:     else
6:         n_i is not eligible
7:     #check if n_i is a hybrid node
8:         if ( n_i Є HSN ) then
9:             n_i is not eligible
10:        end if
11:    end for
12:    #check if there are enough participants for election
13:    if ( count_eligible < required_CHs ) then
14:        for each node n_i do
15:            if ((E_i > avgE) then
16:                n_i is eligible
17:            end if
18:        end for
19:    end if
```


In lines 3-6, the base station first checks if the current node has energy larger than the network's average residual energy. If this is the case, then the current node's energy is compared with the following in the list. If the current node has higher energy than the following node, then it becomes eligible to participate in the cluster head election. The combination of both conditions enhances the probability of only qualifying the nodes with the highest energy in the network. If the node meets both conditions, then in lines 8-9, the base station checks if the node's ID belong to an HSN, if so then it disqualifies the node from participating in the election of cluster heads. We assume that the base station knows which nodes are HSNs because when setting up the components of the network, the information is stored in the base station. In lines 13-19, the base station checks if the number of nodes meeting all the previous requirements are fewer than the predetermined number of cluster heads. If there are fewer nodes, then the base station re-examines each node in the network and selects any node whose energy is greater than the average.

3) *Election of Cluster Heads and Cluster Formation:* Once the base station determines the nodes with highest energy and eligible to participate in the election process, it checks for the position of each pre-elected cluster head. In order to spread cluster heads around the network, the base station uses the position of each pre-elected cluster head and their current energy to implement an optimization algorithm that determines the most optimal k clusters, as defined in equation 3.17 [41]. The equation is derived as follows. Given k clusters, let f_1 represent the function for the maximum average distance of non-eligible nodes to their associated cluster heads, mathematically defined as:

$$f_1 = max\left\{ \sum_{\forall n_i \in C_k} \frac{d(n_i,\ CH_k)}{|C_k|} \right\} \tag{3.15}$$

where $|C_k|$ is the number of nodes that belong to cluster C_k for $k \in \{1, 2, \ldots, K\}$. Then, assign node n_i to CH_k such that $d(n_i,\ CH_k) = \min_{\forall k=\{1,2\ldots K\}}\{\ d(n_i,\ CH_k)\}$. However, to balance the available energy in each cluster, let f_2 represent the ratio of total initial energy of each node n_i in the network over the total residual energy of the pre-elected cluster heads in the current round of iterations. Then, f_2 is described mathematically as:

$$f_2 = \sum_{i=1}^{N} E(n_i) \Big/ \sum_{k=1}^{K} E(CH_k) \tag{3.16}$$

Using the functions described in equation 3.15 and equation 3.16, the base station evaluates the fitness of each individual n_i , such that the pre-elected CH_k becomes a cluster head if after the maximum number of iterations is reached, CH_k is among the k most optimum cluster head cost. Below is the mathematical model of the cost.

$$cost = \beta f_1 \times (1 - \beta) f_2 \tag{3.17}$$

The constant β is used for weighing the contribution of each of the functions.

This process aims to minimize simultaneously the intra-cluster distances between cluster members and cluster heads, as quantified by f_1, while optimizing the energy efficiency of the network, as quantified by f_2.

4) *Assignment of Transmission Slots:* Once the most optimized clusters have been formed, the base station creates Time Division Multiple Access (TDMA) schedules to assign transmission slots to each node within a cluster as well as Code Division Multiple Access (CDMA). The CDMA is for avoiding interference between cluster heads.

5) *Inform Nodes About Cluster Arrangement:* In the last step, the base station broadcasts a message containing the cluster head's ID and the respective TDMA slots. If a node's ID matches a cluster head ID, the node becomes aware of its role of cluster head.

The cluster formation phase is repeated every *T*-seconds, when the base station receives broadcasted information from the nodes.

C. Neighbourhood discovery

This phase is for setting the routing path for CH-to-CH multi-hopping as well as HSN-to-HSN multi-hopping. The cluster-heads create chains with the following steps.

1) *Step 1:* Each cluster head selects the minimal value from the distances between itself and other cluster heads including the base station. To locate the closest cluster head, all of them broadcast their signal. Then, each cluster head estimates the closest neighbour based on the strongest received signal. Therefore, letting d_{BS} denote the distance of CH_i to the base station and d_{CH} represent the distance of CH_k-to-$CH_{(k+1)}$, then if $d_{BS_k} < d_{BS_{(k-1)}}$ and if $d_{CH_k} < d_{CH_{(k-1)}}$ or $d_{CH_k} < d_{CH_K}$ $CH_{(k-1)}$ next hop is CH_k. For $k \in \{1, 2, \dots, K\}$

2) *Step 2:* Each cluster-head records the IDs of its pre-hop node and next-hop node.

The HSNs follow the same process for setting their routing path.

D. Sensing & Communication

For simplicity, this paper assumes that all sensors are sensing the environment at a fixed rate and have data to send periodically. Each cluster-member transmits its sensing data to its corresponding cluster head only during its own allocated time slot. After a cluster member transmits the data, the node moves to a sleep state until its next transmission slot.

Once a cluster-head has received the data from all its cluster members, it aggregates all the data and forwards it to its next hop. The aggregated data from a given cluster head undergoes further processing as it hops along the CH-to-CH path.

The HSNs periodically interrogate sensor-tags within their reading range using the 915MHz channel, while using the 2.4GHz channel for intra-cluster communication. Once the RFID reader part of the node collects the information data from its sensor-tags, it routes the data to the next hop along the HSN-to-HSN path.

Figure 3.4 summarizes the HRSN algorithm described above. The aim of the flowchart is to illustrate the interconnection among all four phases during the development of the HRSN algorithm. However, for simplicity, some steps are omitted. The four different phases are represented in four different colours as follows:

- Green represents the nodes discovery phase.
- Pink represents the cluster formation process.
- Yellow represents the third phase, which is the neighbourhood discovery process.
- Blue represents sensing and communication.

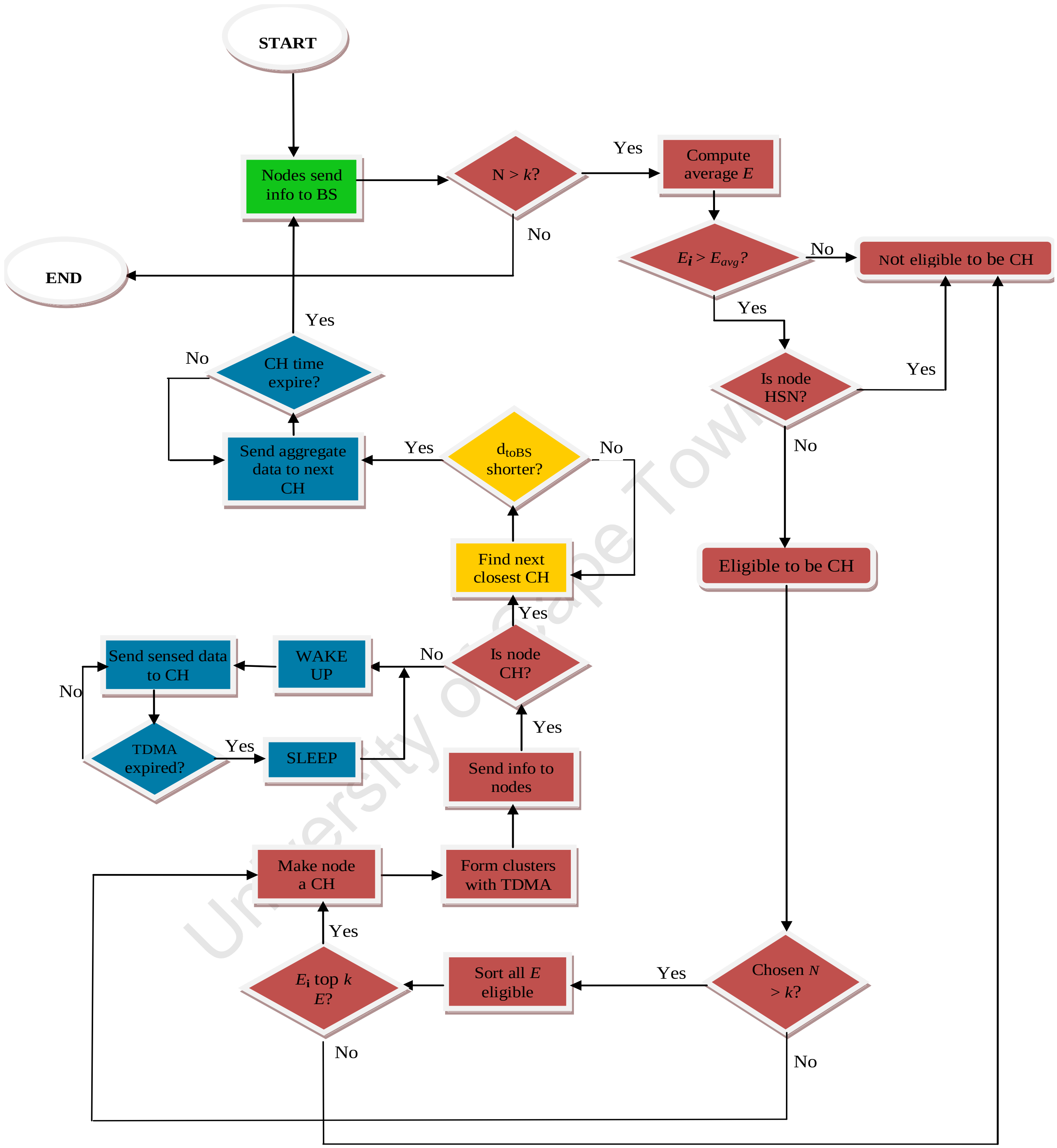

Figure 3.3 Flowchart of the HRSN algorithm

3.5 Chapter Summary

This chapter described the architecture of the hybrid network proposed in this research, named HRSN. The chapter also provided a thorough analysis of the main energy characteristics of the HRSN. The findings of the analysis served as a guideline when developing the HRSN algorithm for assigning roles to the different components of the network. The key features of the proposed algorithm are:

- A centralized cluster based routing protocol that takes into consideration the energy imbalances of the network,
- an improved spreading of cluster heads based on the analytical model presented
- and multi-hop communication among cluster heads and HSNs.

The HRSN and the proposed routing algorithm described in this chapter, have been implemented using the simulator tool described in the following chapter.

Chapter 4

Experimental Methodology

4.1 Introduction

This chapter describes the platform on which simulations conducted for the routing protocol proposed in the previous chapter were made. The different simulation scenarios and the parameters used to assess the performance of this algorithm are also described.

The remainder of this chapter is organized as follows. Section 4.2 describes the network simulator tool used in this project. The advantages and limitations of this network simulator are highlighted. Section 4.3 summarizes the assumptions made, followed by definitions of all performance metrics and parameters in section 4.4. Section 4.5 describes the different simulation scenarios considered in this project. Section 4.6 summarises the chapter.

4.2 Simulator Tool

To model the HRSN and to investigate the efficiency of the HRSN routing algorithm, we made use of the Network Simulator 2 (NS-2) as our simulator platform. NS-2 is an open-source simulator tool that runs on Linux. It is an object-oriented, discrete event driven network simulator. The programming languages it uses are C++ and OTcl. OTcl is a Tcl script language with Object-oriented extensions developed at MIT. C++ is used to implement the detailed protocol and OTcl is used for users to control the simulation scenario and schedule the events [52] [53].

Appendix A describes the set up procedure required to run NS-2.27 successfully on Ubuntu 9.10. NS-2 like any other software has strong and weak features. The following sections discuss the strong features of NS-2 that makes it suitable for this research, as well as the limitations encounter when using it.

4.2.1 Reasons for Choosing NS-2

There are many other network simulators available apart from NS-2. Some of the more popular ones are *OPNET* [54], OMNET [55], *Glomosim* [56], *JiST* [57] and *SWANS* [58]. The primary reason for choosing NS-2 as our simulator platform is due to the availability of source codes. This facilitates a comparison of the HRSN algorithm with similar existing protocols. In addition, NS-2 was chosen because it is designed to be a "network" simulator only. Although this might pose a disadvantage to other projects, to this project it is quite advantageous due to the amount of detailed design incorporated in it. Furthermore, NS-2 has a rich set of communication protocol models designed to provide real network simulation results [59]. Many of these protocols had been implemented before, thus NS-2 provided us with a ready platform for our simulations in one package. One last reason for choosing NS-2 is its widespread use in the academic research community, as well as the comprehensive manuals and tutorials that are freely available for users. This eases the process of developing a programming code and increases the probability of finding help when needed.

After choosing NS-2, we decided to concentrate on the hierarchical cluster based network protocols that have been implemented for WSN namely, LEACH and LEACH-C.

NS-2 includes the most common network technologies and applications, for easy and fast network specification and simulations [59], but despite all these advantages, the software suffers some limitations that influence the full assessment of routing protocols implemented using it as the simulator tool. The following section provides a discussion of some of these limitations.

4.2.2 Scalability Limitations of NS-2

NS-2 poses many advantages that are important to the implementation of this project, as highlighted above. However, the simulator also experiences some drawbacks that limit a full assessment of the performance of the HRSN algorithm. Some of these disadvantages are discussed below.

One of the most common problems faced while running large simulations in NS-2, is running out of memory [60]. NS-2 offers real network environment for its simulations. Although this poses an advantage to having a more accurate knowledge of what to expect at the materialization stage, the memory required often exceeds that available on existing computers.

NS-2 has scalability problems on simulating large network topologies. This disadvantage causes the main limitation faced at the implementation stage of this project, whereby the total number of nodes that could be simulated was limited depending on the size of headers and packets required for the simulated routing protocol. The following paragraph provides some more details on this scalability limitation.

Different types of packet headers are defined for different protocols. A packet in NS-2 keeps all packet headers for any protocols implemented in NS-2. For example, a DSR routing packet may keep DSDV, AODV, or even a PING application header. Consequently, a packet used in NS-2 simulation usually contains a header size of approximately 40KB to 64KB. Therefore, for a typical simulation with 100 nodes connected by a link of 1GPS bandwidth and 100ms delay, approximately 100,000 packets are exchanged. This may use a memory of at least 6.4GB [61], which would definitely crash your computer.

A proposed solution presented in [61] and [62] suggests removing all packet-headers that are not required for the experiment. Similar to the result in [62], removing unnecessary headers reduced memory usage to only 500 bytes per packet. This allows a maximum of 300 nodes to be simulated on the computer used for this project.

4.3 Assumptions

For the development of the proposed algorithm described in chapter 5, some assumptions were made about the sensor nodes and the underlying network model. This section discusses these assumptions.

- Each node has a built-in GPS, with the exception of sensor-tags. In broadcast positioning systems, signals flow only in one direction, towards the receivers that determine either their own position or that of the transmitter [17] (GPS being a prominent example).
- All nodes can transmit with enough power to reach the base station.
- Nodes can use power control to vary the amount of transmit power, and each node has the computational power to support different MAC protocols and perform signal processing functions.
- For the network under study, we use a model where nodes always have data to send to the end user and nodes located close to each other have correlated data.
- For the evaluation, perfect correlation is assumed such that all individual signals can be combined into a single representative signal. In addition to that, we assume that the fused data undergoes further processing as it hops along the routing path.

These assumptions are reasonable due to technological advances in radio hardware and low-power computing. Besides the above assumptions, the simulated network assumed 20 bits of data to be transmitted periodically as sensor-tags' data by HSN nodes far from the base station. 2 bytes per sensor-tag, 1 byte representing tag ID and the other byte is for the sensed data of the tag. Each HSN node assumed to be reading 10 sensor-tags. The simulated network did not include sensor-tags because they have no power and their energy depend on the power of HSN nodes. However, using equations 3.10 and 3.11 in the previous chapter, the energy dissipated for powering sensor-tags was modelled and at each periodic transmission of sensor-tags' data the model is implemented.

The following section defines the parameters and performance metrics chosen in this research given these assumptions.

4.4 Performance Evaluation Metrics and Parameters

In order to test the performance of the proposed routing algorithm, this thesis defines a set of performance evaluation metrics, which are analyzed under various parameters.

4.4.1 Performance Metrics

There are different possible evaluation metrics, but in this project, we focus on performance metrics that assess the energy efficiency of the proposed routing algorithm, which are: the energy dissipated per round, the network residual energy, the network lifetime, and the HSNs life span. These metrics are defined as follows.

Energy dissipated per round: The HRSN combines nodes with different sensing properties. Therefore, depending on the role that each of them performs in the network, the energy dissipated at a particular time in the network will be affected. For this reason, the energy spent in every round is recorded and analyzed. The interval between rounds varies in accordance with the experiment being conducted. The analytical model used to simulate this derives from Equation 3.16, which is as follows:

$$Energy\ per\ round = \frac{E_{HRSN}(t)}{\Delta t} \tag{4.1}$$

where Δt denotes the latency between rounds.

Network residual energy: Although it is useful for load balancing purposes to investigate the "instantaneous" energy consumption of the HRSN, the accumulative energy consumption is also important. This is because the energy consumption of a network usually determines its lifetime. However, due to the variation in initial energy of the nodes and their different energy dissipation rates, the energy left in the network is not a clear indication of the total nodes alive. Therefore, to assess the performance of the HRSN algorithm in terms of managing the network's energy resources, the following equation was used:

$$Residual\ energy = E_{start} - \sum_{t=0}^{T} E_{HRSN}(t) \tag{4.2}$$

where E_{start} denotes the total initial energy in the HRSN and T denotes the duration of the simulation at the time of measuring this metric.

Network lifetime: In this context, network lifetime is the total time that it takes until the total nodes alive in the network is equal or less than the number of cluster heads in the network.

HSNs life span: One of the key features that make the HRSN different from conventional WSNs is the incorporation of the HSNs. Therefore, one of the objectives of this research is to keep the HSNs alive as long as possible because of their role in the network. To assess the efficiency of this objective the HSNs life span monitors the time it takes all HSNs to exhaust their power.

These performance metrics were measured under various parameters, which allow the study of the performance of the HRSN algorithm under different conditions of the network. The following section discusses the different parameters.

4.4.2 Parameters

The chosen parameters are variables that affect the overall energy performance of the HRSN.

The parameters taken into consideration in this project are the number of nodes, the number of HSNs, the network area, and the number of cluster heads. These parameters are defined in the following paragraphs.

Number of nodes: The HRSN is made up of three different types of sensing/identification devices: sensor-tags, wireless sensor nodes and HSNs. The HRSN model simulated only considers the last two, because of the sensor-tags not having a self-powered unit. The increased of the number of these devices in the HRSN introduces some challenges to routing protocols; such as higher energy demands. This parameter evaluates the scalability of the proposed routing algorithm.

Number of HSNs: The different features of HSNs influence significantly the overall energy performance of the network because they are high in energy consumption. Therefore, the higher the presence of such nodes the higher the energy demands of the network, which influences the behaviour of the network as well as the efficiency of the HRSN algorithm. This parameter examines the performance of the HRSN algorithm as the number of these nodes increases.

Number of Cluster Heads: Nodes acting as cluster heads dissipate more energy than the non-cluster head nodes because the cluster heads are responsible for processing and forwarding the network's data. The long transmission of the data to a base station results in high energy consumption. Therefore, the higher the number of nodes performing these roles the higher the overall network energy demand that is expected. In addition, if this role is performed by HSNs the energy demand of the network is expected to be even higher. This parameter investigates the behaviour of the network as the number of cluster heads increases, as well as how it affects the performance of the HRSN algorithm.

Network Area: As the overall area of the network gets larger, the transmission distances among nodes also get longer, which results in higher energy consumption. Different methods for alleviating the effects of the overall network coverage have been incorporated in the HRSN algorithm. Therefore, this parameter investigates the behaviour of the HRSN and the performance of the HRSN algorithm for large environments.

Table 5 summarises the values of the parameters discussed above, as well as other parameters already described in Chapter 3. Like the energy consumed for data aggregation E_{DA}. This value was determined using the experimental results of [49] and parameters in [17].

Table 4: Simulation parameters

Description	Value
Network dimensions	*100m×100m to 1000m×1000m*
Total number of nodes in the network	*100 to 250*
Total number of HSN nodes in the network	*10 to 40*
Initial energy of HSN nodes	*3.5J*
Initial energy of the conventional sensor nodes	*2J*
Energy consumed by the amplifier to transmit at a long distance	ε_{TR}=0.0013pJ/bit/m^4
Energy consumed by the amplifier to transmit at short distances	ε_{friss}=10pJ/bit/m^3
Energy consumed in the electronics circuit to transmit or receive signal	$E_{Tx} = E_{Rx}$ = 50nJ/bit
Energy consumed by the RFID reader of an HSN to interrogate sensor-tags	0.8nJ/bit
Data aggregation energy	*5nJ/bit/cycle*

4.5 Overview of the Simulation Scenarios

The implementation stage of the project took place in three different experiments. Each experiment was made on a similar network scenario. The details of the topologies of these scenarios are described in the following chapter. This section only provides a more general description of the different scenarios.

Figure 3.1, in Chapter 3, illustrates the HRSN conceptual scenario used for simulating the HRSN algorithm. The network is made of N sensor nodes and H HSNs randomly distributed in an $M \times M$ area. The variables of $N, H\ and\ M$ vary according to the experiment conducted with the values presented in Table 5. All sensor nodes have an initial energy of 2J and HSNs an initial energy of 3.5J. The simulated network assumed 20 bytes of data to be forwarded periodically as sensor-tags data by HSNs far from the base station. This implies 2 bytes per sensor-tag, 1 byte representing tag ID and 1 byte for the sensed data of the tag. We assume 50% of all HSNs are within reading range of 10 sensor-tags each. The 50% HSNs correspond to those that are furthest from the base station. The simulation scenario varies according to the simulation test conducted. Each of these scenarios will be described further in Chapter 5, when discussing the results obtained in those tests.

4.6 Chapter Summary

This chapter described the simulator tool used for the implementation of the HRSN and the proposed routing algorithm. The chapter discussed the limitations of the simulator tool. These limitations introduced some constraints in some of the parameters described in this chapter. Chapter 5 presents some results obtained in the various simulation tests conducted. These tests are based mainly on the parameters described in this chapter.

Chapter 5

Simulation Results and Analysis

5.1 Introduction

This chapter presents the results of experiments carried out for evaluating the performance of the proposed energy efficient routing protocol described in chapter 3. For a better assessment of the performance, the proposed HRSN algorithm is compared to two other routing protocols, namely, LEACH and LEACH-C. The choice of these two routing protocols for performance comparison is guided by two important reasons. Firstly, similarly to HRSN algorithm, both LEACH and LEACH-C organize the network into hierarchies where nodes are assigned roles based on their energy attributes. Secondly, for the evaluation to be meaningful, the performance of the proposed protocol should be compared to the performances of certain well-known existing energy aware protocols, as it is the case with LEACH and LEACH-C. The performance metrics discussed in chapter 4 are examined under five main experiments, which are characterized by various configurations of the different parameters discussed in that chapter. On each experiment, we simulated 28 different HRSN topologies. The plotted results are the averages of the different performance metrics from all 28 topologies.

The remainder of this chapter is organized as follows. Section 5.2 presents results obtained when investigating the performance of the HRSN as compared to WSN. Section 5.3 presents the set of simulation tests run for analysing the effect that the number of cluster heads has on the performance of the HRSN algorithm, the LEACH and the LEACH-C protocols. Section 5.4 shows the results obtained when testing the scalability of the three routing protocols under study. Section 5.5 presents results obtained when assessing the performances of the LEACH, the LEACH-C and the HRSN protocols as the network area increases. The last section investigates the effect that increasing the presence of HSNs in the network has on the performances of the three routing protocols under study. Each section ends with conclusions drawn from the discussions made in the section.

5.2 First experiment: Comparison of WSN and HRSN

The first experiment compares the dissipation of energy in WSN to that of HRSN with and without the HRSN algorithm. The objective of this experiment is to compare the HRSN as an energy imbalanced network to WSN, a balanced network. A comparison of their different performances provides a general idea of how much the HRSN algorithm improves the efficient use of energy resources in the HRSN.

In this experiment, both networks are made of 100 nodes. In the WSN, all nodes are wireless sensor nodes randomly spread throughout an area of $100m \times 100m$. In the HRSN, 70 nodes are wireless sensor nodes and 30 are HSNs equally spread throughout the same network size. Figure 5.1 illustrates the results obtained when simulating the amount of energy usage in each of the networks. The routing protocol implemented in WSN and in the imbalanced version of HRSN is LEACH-C.

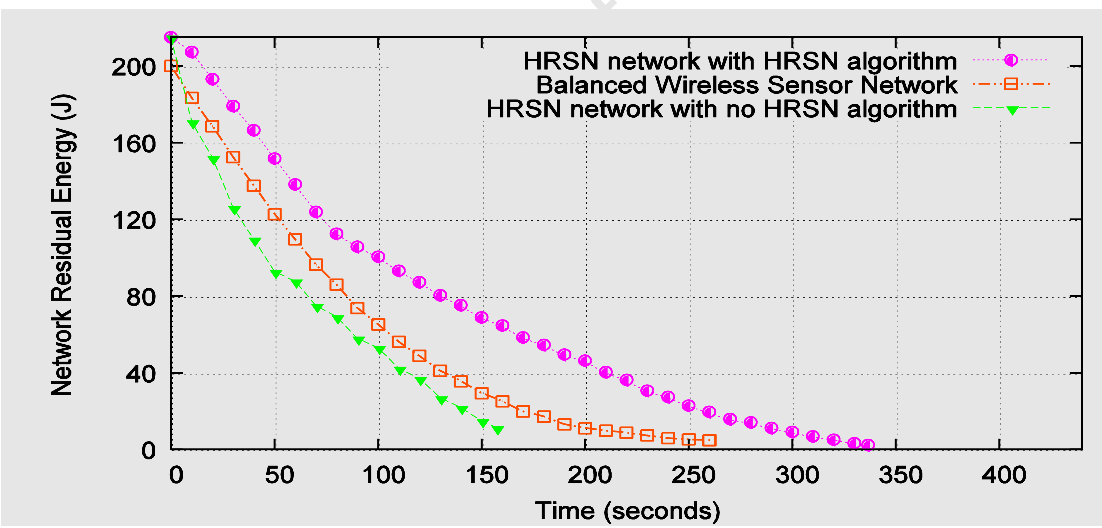

Figure 5.1 Energy dissipation performance comparison of WSN, imbalanced HRSN and balanced HRSN.

The plotted graphs show that the performance of HRSN is worse than WSN when the HRSN algorithm is not implemented in the network. This behaviour can be attributed to the imbalanced experienced among nodes in HRSN and higher energy requirements of some nodes. Nevertheless, the energy dissipation significantly improves when implementing HRSN algorithm. The much higher network residual energy is due to two main reasons. First, this is because of a higher network initial energy, which in the WSN is 200 J and in the HRSN is 215 J, this when manage correctly it offers an advantage. Second, in addition to the higher initial energy, implementation of the HRSN algorithm allows for a more even distribution of the energy load. The improved distribution of energy load is as a result of a better allocation of roles in the network, which takes into consideration the different sensing energy properties of the nodes in the HRSN.

5.3 Second Experiment: Effects of Total Cluster Heads in HRSN

The amount of data traffic in the network influences the network performance because the communication energy increases as the amount of traffic increases. As the number of cluster heads increases, more traffic is routed to the base station. Therefore, the number of nodes acting as cluster heads to transmit data is varied for assessing the performance of the HRSN. In this experiment, the simulation environment consists of 200 nodes, 190 wireless sensor nodes and 10 HSNs dispersed randomly on an $100m \times 100m$ area. The base station is located at 215 meters away from the nearest node in the network area, which in NS-2 corresponds to (50, 215) XY-coordinates. The graphs presented in this section are an illustrative summary of the results obtained in the simulations. The results are the averages of all the 28 different topologies simulated from each of the different cluster configurations.

5.3.1 Energy Dissipation as a Function of Cluster Heads

Figure 5.2 illustrates the performance of the HRSN algorithm in terms of the total residual energy in the network. The plots represent the performances of the HRSN when there are 5-CHs, 10-CHs, 15-CHs, 20-CHs and 30-CHs in the network. As mentioned above the number of cluster heads is increased to investigate the performance of the network as traffic to the base station increases.

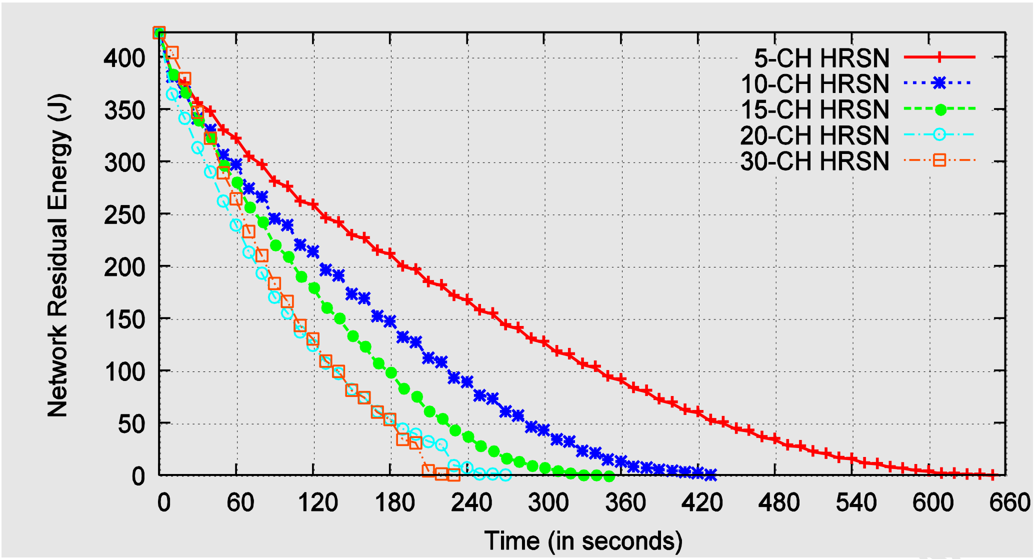

Figure 5.2 A comparison of the energy consumption of HRSN as the number of cluster heads increases from 5-CHs to 30-CHs

The results demonstrate that the amount of energy consumption significantly increases as the number of cluster heads in the network increases. For example, 120 seconds after running the simulation, the total network residual energy in an HRSN organized into 5 clusters is approximately 40% more than when there are 15 clusters and more than 100% higher in the case of 30 clusters.

From the five different simulations run, the plotted results show that more energy is dissipated in the network as the number of clusters increases. This is because more nodes are appointed high-energy consuming roles that involve direct communication with the base station.

5.3.2 Life Span of all Nodes in the HRSN

The number of nodes alive in the network at any given time is illustrated in Figure 5.3, which represents the results obtained for the different configurations of clusters in the HRSN.

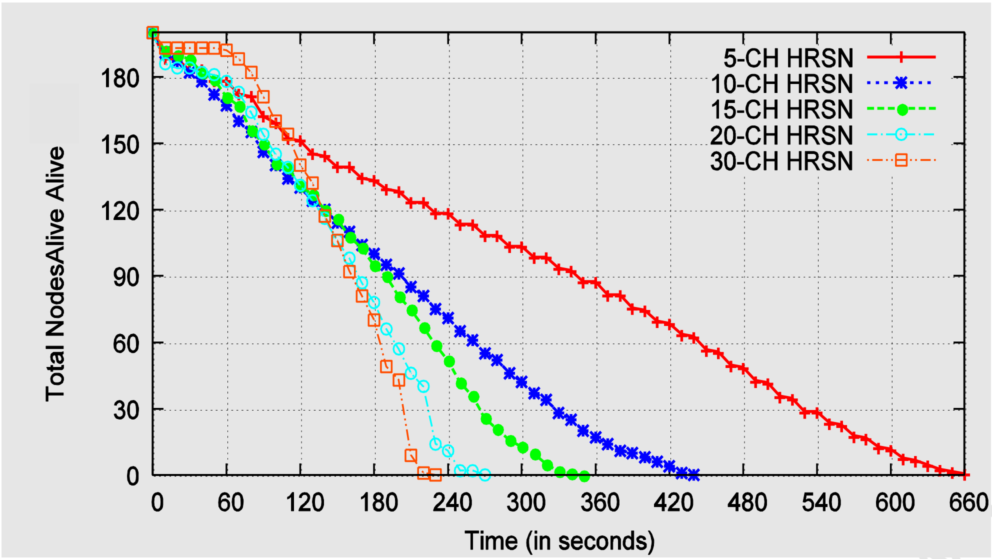

Figure 5.3 A comparison of the lifetime of nodes in the HRSN as the number of cluster heads increases from 5-CHs to 30-CHs

The plotted graphs demonstrate that as the number of nodes appointed with high consuming roles increases, such as is the case with cluster heads, more nodes deplete their power quicker. Consequently, the overall lifetime of the HRSN shortens. For example, 180 seconds through the simulation, the HRSN with 5 cluster heads still has approximately 63% of nodes alive, while the 30 clusters HRSN only has 30% of nodes alive, which is less than half of those alive in the case of 5 clusters HRSN.

5.3.3 HSNs Lifetime

The most important analysis in this experiment is to investigate the effect that increasing the number of clusters in HRSN has on the energy conservation of the HSNs. Figure 5.4 provides an illustrative summary of the findings. From the plotted graphs, it can be observed that the higher the number of cluster head nodes the longer the life span of HSNs.

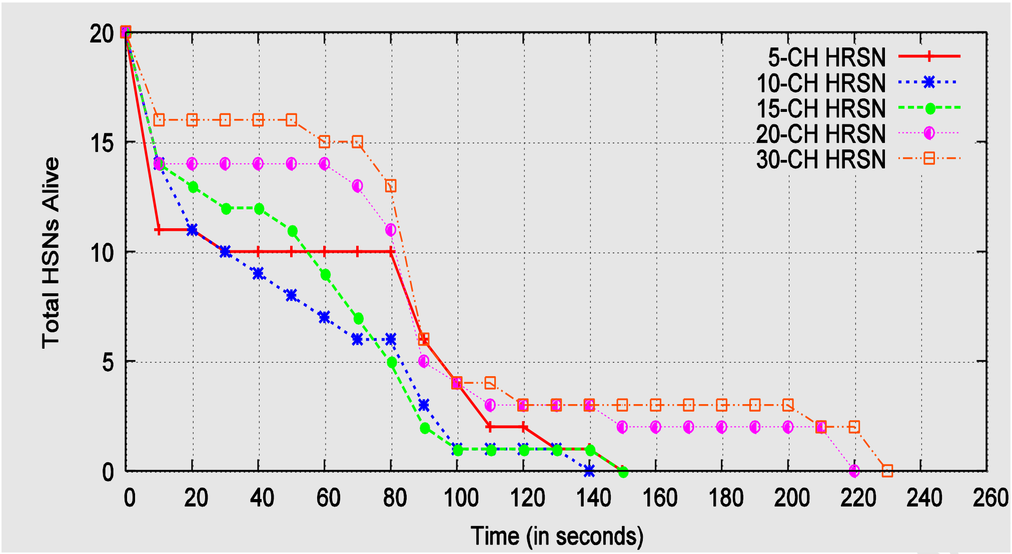

Figure 5.4 A comparison of the performance of the life span of HSNs as the number of cluster heads increases from 5-CHs to 30-CHs

For example, it takes approximately 230 seconds of network activity to exhaust the power of all HSNs in an HRSN with 30 cluster heads, while it only takes 140 seconds in the HRSN with 5 cluster heads. The following section discusses the reasons for the improved life span.

5.3.4 Discussion of Results

The results illustrated in figure 5.2, figure 5.3 and figure 5.4 demonstrate that the higher the number of cluster heads in the network the higher the overall network's energy consumption. However, despite this increase in energy consumption, to HSNs a higher number of cluster heads offers great advantages in terms of the durability of their power. This is because the transmission distance between each HSN and its corresponding cluster head reduces, implying less communication energy. Consequently, the life span of HSNs significantly increases, whereas the overall lifetime of the network drastically decreases.

The graphs presented in figure 5.3 show that the total network's residual energy is not a clear indication of the nodes alive in HRSN. In the example discussed above, at 120 seconds the 30-

CHs HRSN topology has exhausted more than 75% of its total energy whereas only 30% of its total nodes are dead, instead of 75% of those. This is due to the different initial energies of the different type of nodes, as well as the different energy dissipation characteristics.

5.3.5 Conclusion

Therefore, from the above discussion it can be concluded that the least number of cluster heads the better for the overall consumption of energy. However, since having more cluster heads in the network poses an advantage to HSNs then, it is necessary to implement an optimized number of cluster heads.

5.4 Third Experiment: Assessment of HRSN Scalability

This experiment investigates the scalability properties of the HRSN as related to the three different routing protocols. The number of nodes is increased from 50 to 250, throughout an area of size $1000m \times 1000m$. The base station is positioned within the network at (550, 850). The initial number of HSNs is 10 in the HRSNs with 50 – 100 nodes, and 15 HSNs for the HRSNs with 150 – 250 nodes. The network is organized into 15 clusters. The following figures show the averages of the performances of the HRSN algorithm as compared to LEACH and LEACH-C. The average results presented in this section correspond to the 28 different topologies simulated for each network size, which in total represents 112 different topologies that simulated for this experiment. This section only includes some of the plotted figures. Please refer to appendix A for additional results.

5.4.1 Energy Dissipated per Round

The following set of measurements examines the performance of the HRSN in terms of energy dissipation balance. To examine the effect that the number of initial nodes has on the network at particular times, the simulation recorded the amount of energy spent in the HRSN at every round. For the purpose of this section only, a round refers to energy readings taken at intervals of 10 seconds during the simulation.

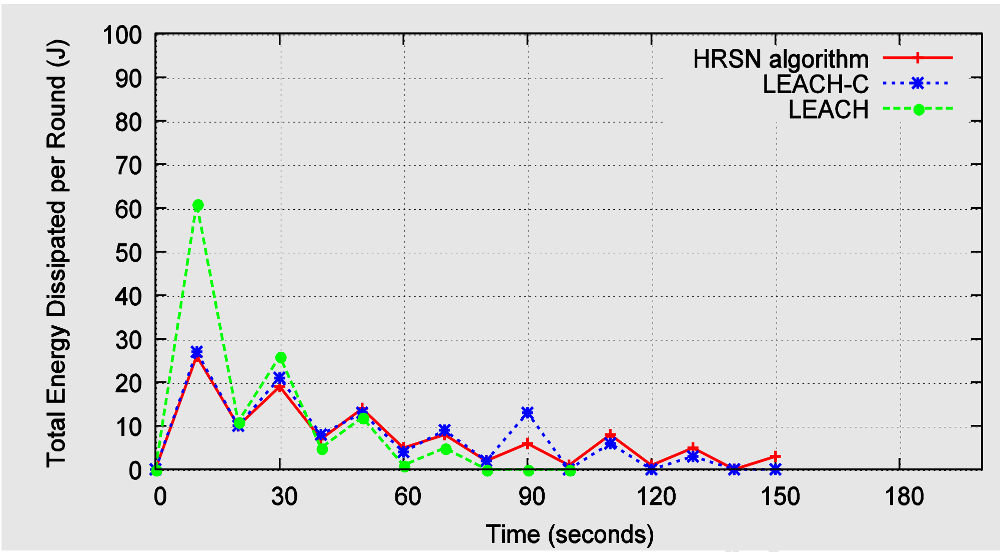

Figure 5.5 A comparison of the energy consumption every 10 seconds in a 50-nodes HRSN when employing the HRSN algorithm, LEACH and LEACH-C

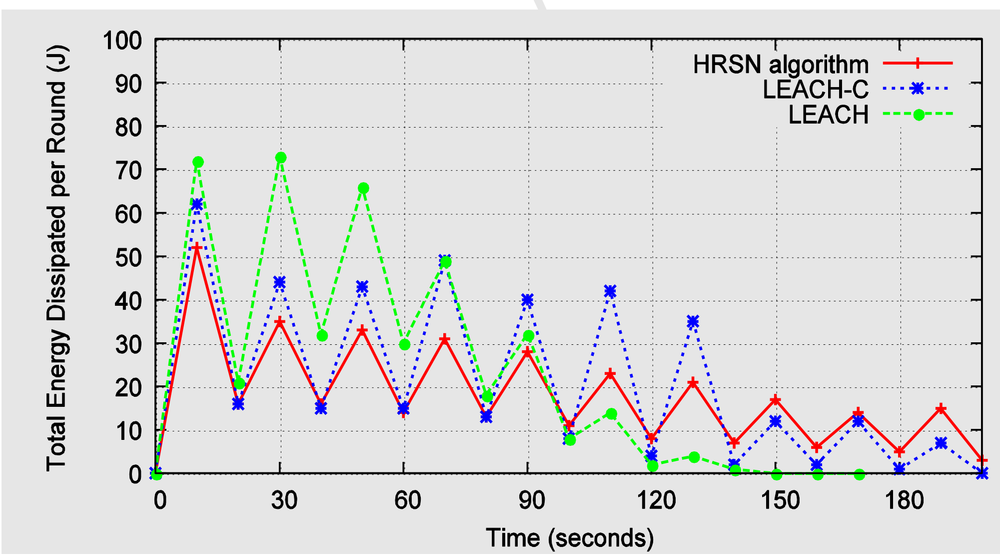

Figure 5.6 A comparison of the energy consumption recorded every 10 seconds in a 250-nodes HRSN, when employing the HRSN algorithm, LEACH and LEACH-C protocols

Figure 5.5 illustrates the performances of the three routing algorithms in terms of balancing the total energy dissipated in the network in relation to rounds. The plotted results are the averages of all the 28 different topologies corresponding to an HRSN made of 50 nodes. Figure 5.6 also shows the graphical performances in terms of total energy dissipated per round, but in this case, the initial number of nodes is 250. The following section discusses these results.

5.4.1.1 Discussion of Results

Figure 5.5 shows that all three algorithms experience their highest energy demand at the beginning of the simulation. This is because all nodes are still alive, so there is more traffic and more data processing. Consequently, more energy is dissipated in the first round. The higher energy dissipation and lower energy dissipation corresponds to the communication and sensing phase, and the cluster formation phase respectively. Both LEACH-C and HRSN algorithm let the base station perform the cluster formation process, which is the reason for the similar performance during that phase. However, as the number of nodes required to forward their data to the base station becomes significantly less than that of HRSN algorithm, the energy demand of LEACH-C for such rounds becomes significantly lower than HRSN algorithm. The energy dissipated at each round when using the HRSN algorithm, decreases gradually in a balanced way in each phase, unlike LEACH-C that in round nine, despite having less nodes, the network experiences a significant raised of energy dissipation.

Figure 5.6 shows a significant higher performance difference among the three routing protocols under study, of which, HRSN algorithm achieves the most desirable energy balance. The amount of energy dissipated in each round for both LEACH and LEACH-C appears not to be influenced significantly by the number of nodes during the communication phase. For example, at the 5th round of network activity, LEACH experiences a total energy consumption of approximately 68J and LEACH-C dissipates approximately a total of 40J. However, on the 7th round the total energy consumed increases to 50J in the case of LEACH-C instead of decreasing as less nodes are still alive. Such network behaviour can be attributed to the arrangement of cluster heads implemented in LEACH-C. Such that, if an HSN far from the base station becomes a cluster head, an even more significant energy will be dissipated. This is due to the larger transmission range combined with an increased amount of data as compared to a 50 nodes HRSN. However, as nodes exhaust their power, the amount of communication energy should decrease rather than increase, as it is the case in LEACH-C. Furthermore, in the rounds where more HSNs act as cluster heads, the energy drop is drastic, which shows non-balanced dissipation of energy among rounds.

The results illustrated in figure 5.5 and figure 5.6 demonstrate that the routing algorithm proposed in this thesis is the most suitable in terms of balancing the energy consumption in large scales HRSN. Throughout the different simulation scenarios, the HRSN algorithm achieves the lowest peak of energy dissipation. This is because the energy load is distributed evenly among all nodes throughout the lifetime of the network.

5.4.2 Energy Consumption as a Function of Total Nodes

The next set of measurements examines the performances of each of the three routing protocols under study in terms of the network's average energy consumption.

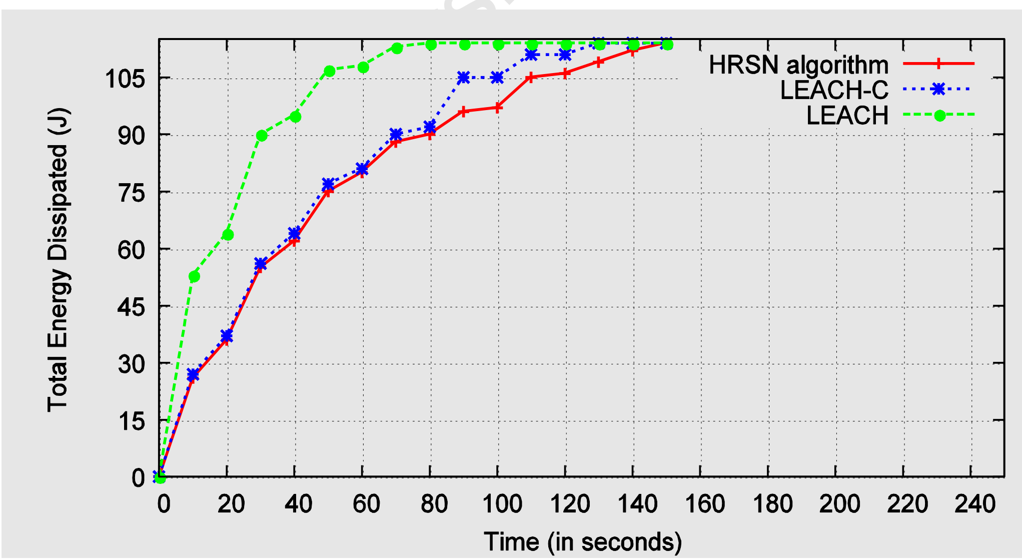

Figure 5.7 A comparison of the average energy consumption in a 50-nodes HRSN employing the HRSN algorithm, LEACH protocol and LEACH-C protocol

The effect that the number of nodes has on the amount of overall energy dissipation of the HRSN is analyzed as illustrated in the following figures and the above figure. Figure 5.7 shows a graphical comparison performance in terms of the total energy dissipated for each of the routing protocols (LEACH, LEACH-C and the HRSN algorithm) for a 50-node HRSN.

Figure 5.8 also illustrates the performances in terms of the total dissipated energy, but in a 250-node HRSN. The following paragraphs discuss these results.

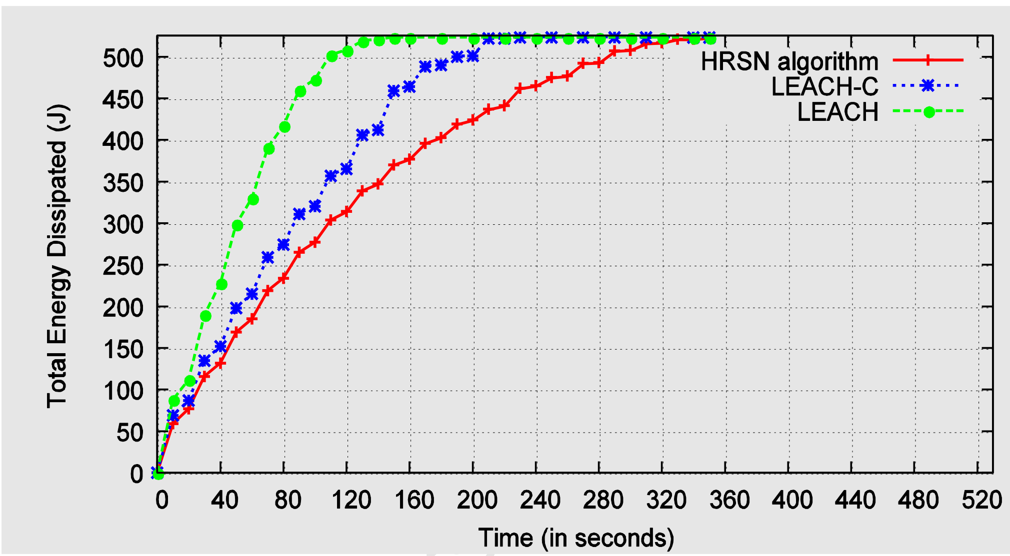

Figure 5.8 A comparison of the average energy consumption in a 250-nodes HRSN employing the HRSN algorithm, LEACH and LEACH-C protocols

5.4.2.1 Discussion of Results

The graphs in figure 5.7 show that initially LEACH-C performs as well as the HRSN algorithm for approximately the first 80 seconds of the simulation, and both of them outperforming LEACH. HRSN algorithm spreads the cluster heads all around the network area. This is one of the strongest features of HRSN algorithm. However, in a network of area size $1000m \times 1000m$ with only 50 nodes, this feature becomes disadvantageous because the transmission distance among cluster heads becomes longer. Therefore, the transmission energy does not compensate for the amount of data needed to be forwarded, which on average it corresponds to data from only 5 cluster members. However, as the number of nodes increases, the amount of data to be forwarded also increases, allowing a more appreciable advantage of the spreading of cluster heads, as illustrated in figure 5.8.

Figure 5.8 demonstrates that on average, HRSN algorithm exhibits a reduction in energy consumption of 20 and 30 percent over LEACH-C and LEACH respectively. Consequently, the total consumed energy in the network takes the HRSN algorithm almost double the time spent when implementing LEACH-C; and approximately three times the duration of that of LEACH.

The results illustrated in figure 5.7 and figure 5.8 show that more energy is dissipated in the network as the number of nodes increases. For example in figure 5.8, after 80 seconds of simulation time, in the case of HRSN protocol, 250 J of the network's energy is already dissipated. However, in figure 5.7, at 80 seconds the total dissipated energy is 90 J. This is because of the increased amount of data to be collected from all cluster members and thus, also total data requiring processing by the cluster heads.

The performance difference between the HRSN algorithm and that of LEACH and LEACH-C becomes much more noticeable in a network with larger number of nodes. This is because HRSN alleviates the increased traffic to be transmitted to the base station through multi-hopping and the implementation of further aggregation. While on the other hand, cluster heads in both LEACH and LEACH-C transmit data directly to the distant base station, which in turn causes a further disadvantage to the already high data traffic.

5.4.3 Network Lifetime

The set of measurements presented in this section examines the average lifetime of all participating nodes that make up the network. Figure 5.9 illustrates a comparison of the performances of the three algorithms in terms of network lifetime when there is an initial number of 50 nodes in the network. Figure 5.10 shows how the different routing algorithms perform in terms of total nodes alive for an HRSN made up of 250 nodes.

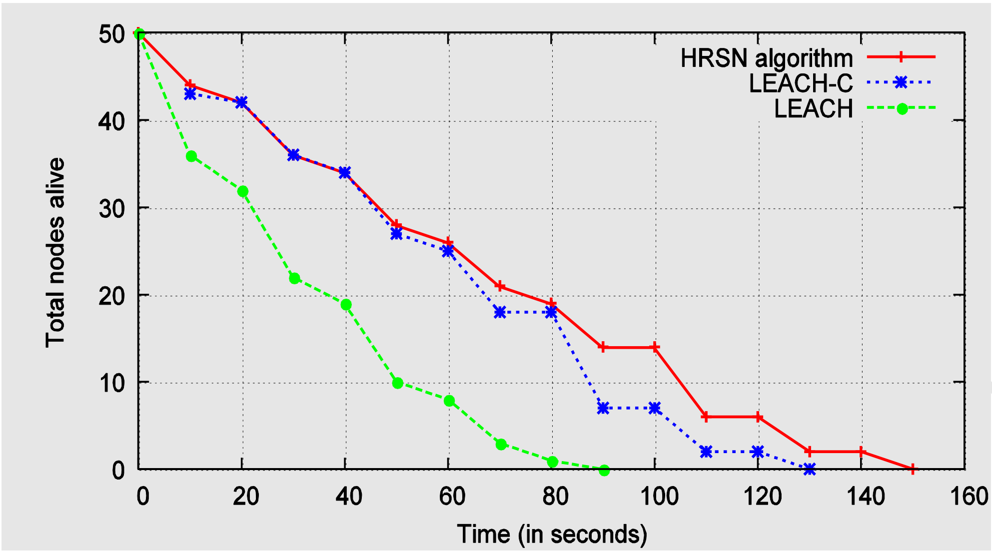

Figure 5.9 A comparison of the average lifetime of HRSN algorithm in a 50-nodes HRSN employing the HRSN algorithm, LEACH protocol and LEACH-C protocol

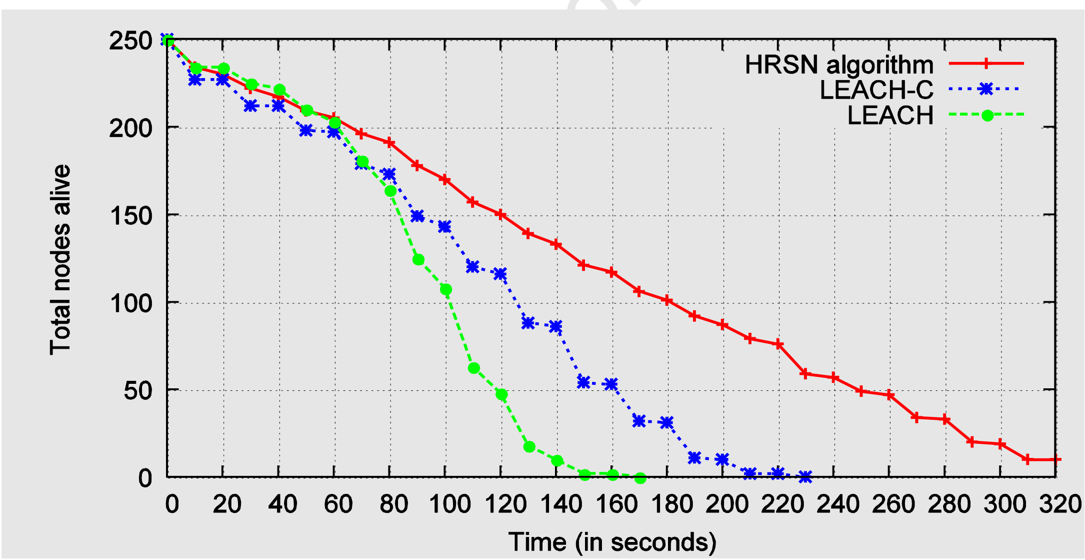

Figure 5.10 A performance comparison of the nodes lifetime in a 250-nodes HRSN employing the HRSN algorithm, LEACH protocol and LEACH-C protocol

5.4.3.1 Discussion of Results

The plotted results in figure 5.9 illustrate that for the first 40 seconds network activity, the performance of LEACH-C and HRSN algorithm is the same. This is due to the long intra-cluster communication ranges. Although, HRSN algorithm eventually outperforms LEACH-C, the improvement gained through the HRSN algorithm is better exemplified in figure 5.10, which represents the results of HRSNs made of 250 nodes. Through the implementation of HRSN protocol, the lifetime of HRSN is improved by double when compared to LEACH and by 90% as compared to LEACH-C. LEACH in both scenarios achieves the worst performance but the poorest performance being for the 50 nodes HRSNs. This is due to all nodes exhausting their power on exchanging information among themselves during the cluster formation process. This exchange of information takes place at longer transmission ranges due to the dispersion of nodes all over the network.

Figure 5.9 and figure 5.10 further exemplify the improvement gained of HRSN algorithm, which in this case is in terms of system lifetime. The simulated results demonstrate that the HRSN algorithm scales well because the larger the number of nodes in the network, the more appreciable the advantages of HRSN protocol.

5.4.4 HSNs Lifetime

One of the main objectives of this research is to expand the lifetime of the high consuming energy nodes, HSNs. The next set of measurements study the efficiency of this objective.

Figure 5.11 compares the performances of the three routing protocols under study in terms of average life span of all HSNs as the initial presence of HSNs increases. Figure 5.12 evaluates the performance of all three algorithms in terms of average life span of the HSNs when there are 10 HSNs in a network with a total of 50 nodes. Figure 5.13 examines the performances of HRSN algorithm, LEACH and LEACH-C in terms of keeping HSNs alive in a network made of 15 HSNs and 235 wireless sensor nodes.

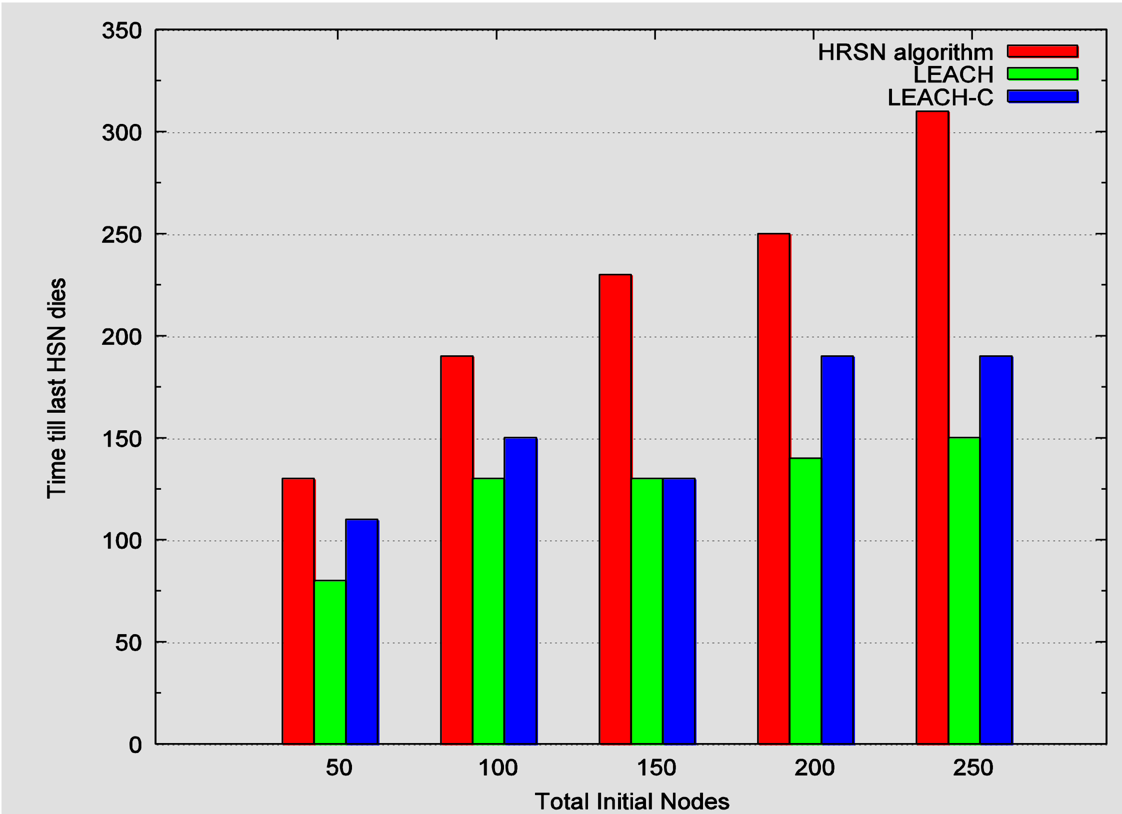

Figure 5.11 A Performance comparison of HSNs' life span as the number of nodes increases from 50 to 250 in an HRSN employing the HRSN algorithm, LEACH and LEACH-C

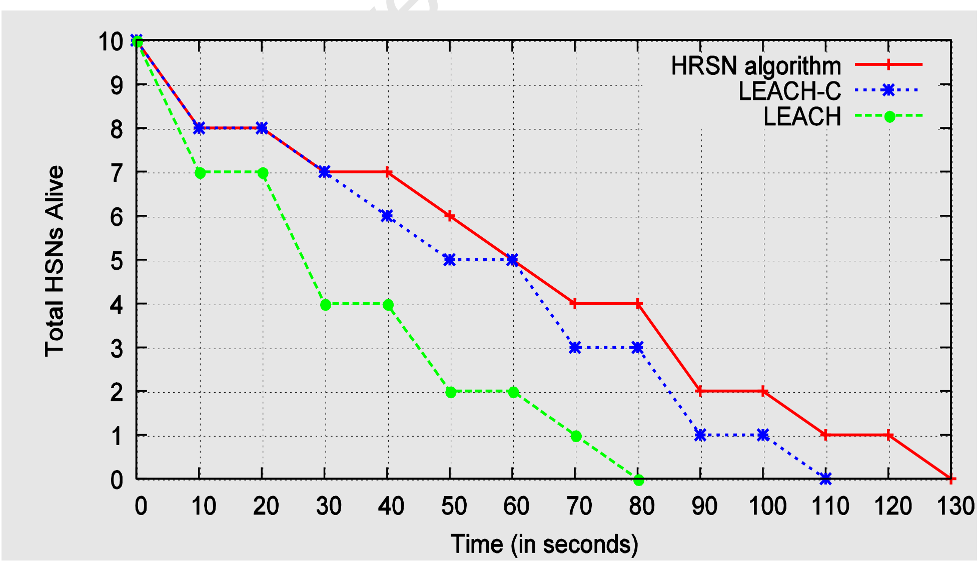

Figure 5.12 A performance comparison of the HSNs' life span in a 50-node HRSN

employing the HRSN algorithm, LEACH and LEACH-C

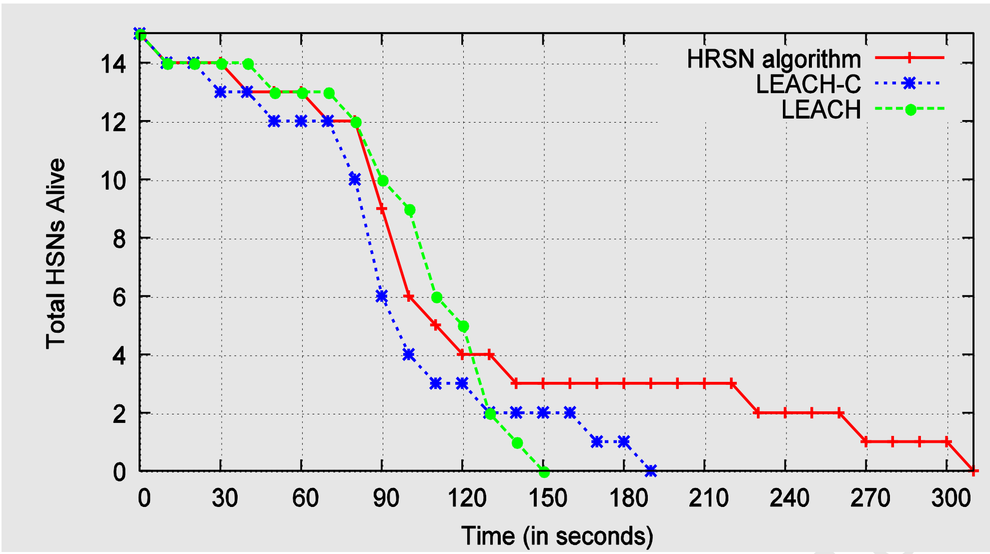

Figure 5.13 A performance comparison of the HSNs' life span in a 250-node HRSN employing the HRSN algorithm, LEACH and LEACH-C

5.4.4.1 Discussion of Results

The plotted results from figure 5.12 show that HRSN algorithm improves the overall life span of the HSNs by 20% longer than LEACH-C and 90% longer than LEACH. The results plotted in figure 5.13 and figure 5.11 show that HRSN algorithm expands the lifetime of HSNs by more than double that of LEACH-C and three times longer than LEACH. This is as a result of preventing HSNs from performing high energy consuming roles such as cluster head in addition to the multi-hop communication among HSNs. These advantages are less appreciable in figure 5.12 because of the long transmission ranges within cluster and among HSNs.

5.4.5 Conclusion

The results obtained throughout this experiment have once again confirmed the energy efficiency improvement gained with the implementation of HRSN algorithm. From the above results presented and discussions made, it can be concluded that the advantages provided by HRSN algorithm are essential for large-scale networks. As the initial number of nodes increases, the improvement gained of HRSN protocol becomes more appreciable. This is because the energy spent by cluster heads for data processing increases, which proves the need for not using HSNs for such roles.

The energy efficiency improvement offered by HRSN algorithm is mainly due to the decrease in the number of transmissions through the implementation of further data aggregation. In addition to an improved cluster organization and multi-hopping.

5.5 Fourth Experiment: Analysis of the HRSN Coverage

The fourth experiment investigates the behaviour of the HRSN as the size of the network area increases. The network's size is increased from $100m \times 100m$ to $1000m \times 1000m$. For each network size the base station remains at least 100 meters away from the network area. The plotted graphs are the averages of all 28 topologies from each network area, which in total represents 280 network topologies. The total number of nodes is 100, of which 10% are HSNs. The network is organized into 11 clusters. The performances of all three routing algorithms are compared and examined under the following metrics: energy consumption per network coverage, energy dissipation during the network lifetime, number of nodes alive and HSNs life span.

5.5.1 Energy Consumption as a Function of Network Area and Time

In this section the behaviour of the network's energy consumption is examined in terms of network size and as a function of network lifetime.

5.5.1.1 Energy Spent as a Function of Network Area

Figure 5.14 compares the performance of the three protocols in terms of energy dissipation as a function of network size.

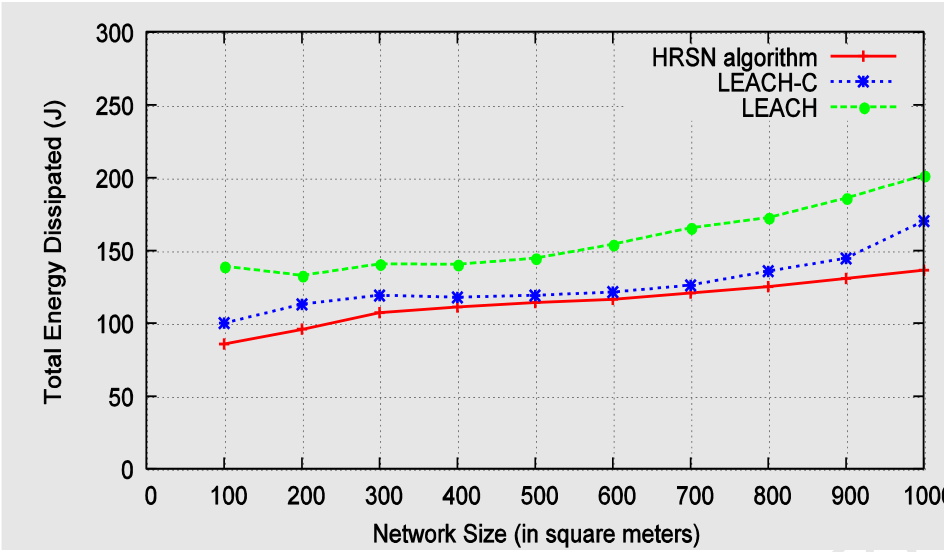

Figure 5.14 A performance comparison of the average energy consumption as the area of HRSN varies while employing the HRSN algorithm, LEACH and LEACH-C

To evaluate their performance the plot illustrates the amount of energy dissipated 70 seconds after the start of the simulation. In all three protocols the energy dissipated around the network increases as the network size increase. However, the HRSN protocol achieves the lowest dissipation for all the different network sizes.

5.5.1.2 Network's Residual Energy as a Function of Time

Figure 5.15 shows a graphical comparison performance in terms of total residual energy for each of the routing algorithms, LEACH, LEACH-C and the HRSN algorithm when the HRSN is designed in a $100m \times 100m$ area. The plotted results demonstrate that the HRSN protocol outperforms LEACH and LEACH-C in terms of energy management. For example, 120 seconds after running the simulation, the total energy left in the network for the HRSN protocol is approximately 40% more than LEACH-C and 100% more than LEACH, whose energy in the network is almost exhausted at that point.

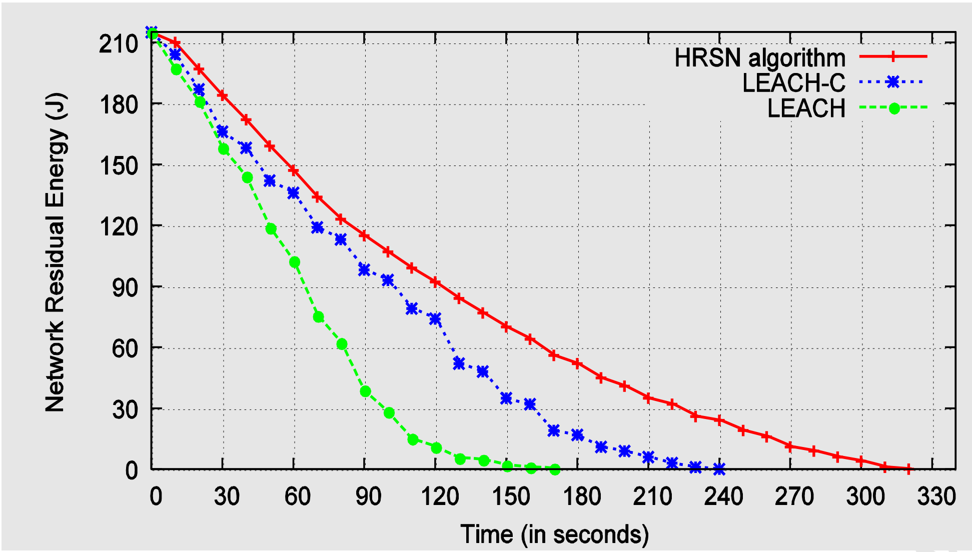

Figure 5.15 A performance comparison of the network's residual energy in an HRSN area of *100m×100m* employing the HRSN algorithm, LEACH and LEACH-C

Figure 5.16 illustrates the performance in terms of the total residual energy when the HRSN is designed on a $1000m \times 1000m$ area.

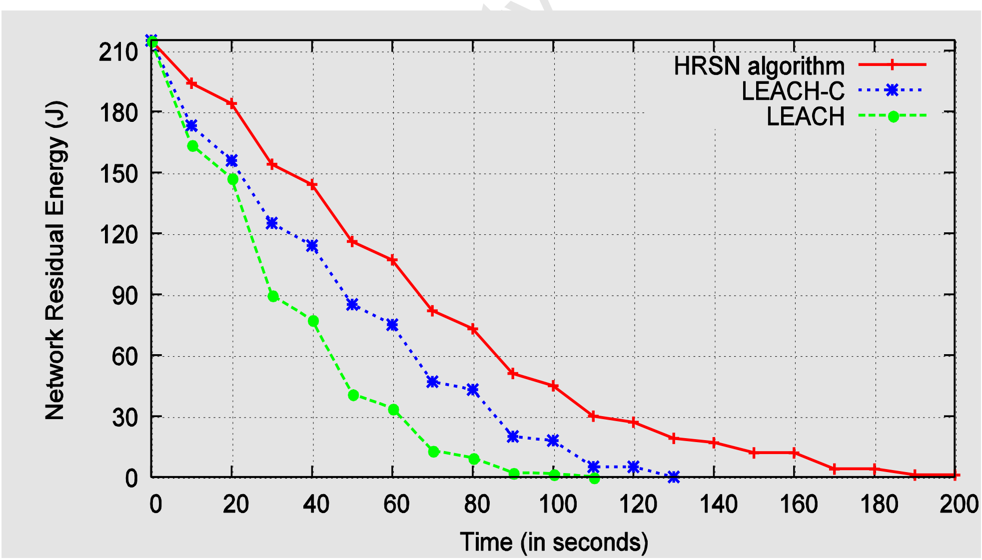

Figure 5.16 A performance comparison of the network's residual energy in an HRSN area of *1000m×1000m* employing the HRSN algorithm, LEACH and LEACH-C

The results demonstrate that the HRSN protocol outperforms LEACH and LEACH-C. For example, 80 seconds after starting the simulation, the remaining energy in HRSN algorithm is 3 times more than the remaining energy in LEACH and about 70% higher than that of LEACH-C.

5.5.1.3 Discussion of Results

The plotted graphs from figure 5.14, figure 5.15 and figure 5.16 demonstrate that performance differences between HRSN algorithm and both LEACH and LEACH-C increases as the size of the network gets larger, HRSN algorithm being the best. However, the amount of consumed energy increases significantly as the size of the network gets larger. For example, 80 seconds through the simulation, in the $1000m \times 1000m$ network, LEACH, LEACH-C and HRSN algorithm have residual energies of only 5J, 35J and 70J respectively. Whereas, in the scenario of the $100m \times 100m$ network, the remaining energies for LEACH, LEACH-C and HRSN algorithm are approximately 60J, 110J and 125J respectively. The higher energy demand is due to longer transmission ranges within clusters and between cluster heads and base station. The outperformance of the HRSN algorithm is because cluster heads in both LEACH and LEACH-C communicate directly to the base station.

Therefore, in a network's area of size $1000m \times 1000m$ the need for forwarding data through more than one hop, proves to be advantageous. In the case of HRSN algorithm, nodes communicate with the base station but only once per round and transmitting only a small message to carry enough information for cluster arrangement.

Furthermore, the total energy dissipated in the network at any given time is balanced throughout its lifetime. The better management of energy of HRSN algorithm is as a result of a more suitable cluster head election process in combination with multi-hopping.

5.5.2 Life Span of All Nodes in the HRSN

The next set of measurements study the relationship between the nodes alive in relation to the network lifetime and network area.

5.5.2.1 Nodes Alive as per Time

Figure 5.17 shows a graphical performance comparison of LEACH, LEACH-C and the HRSN algorithm in terms of average number of nodes alive when the HRSN is designed in a $100m \times 100m$ area.

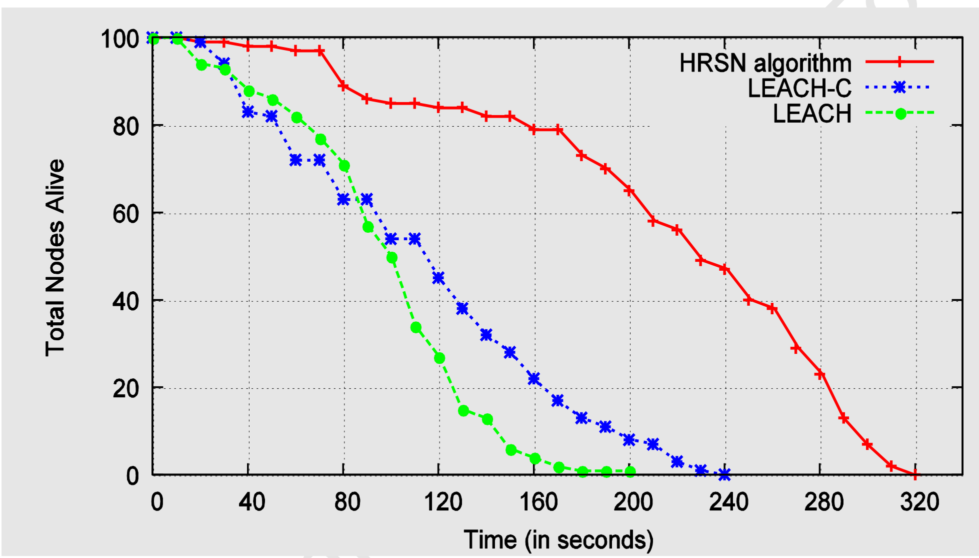

Figure 5.17 A performance comparison of the overall network's lifetime for HRSNs with a *100m×100m* network area, when employing the HRSN algorithm, LEACH protocol and LEACH-C protocol

The results illustrated demonstrate that the HRSN algorithm once again outperforms LEACH and LEACH-C. For example, 160 seconds after the start of the network activity, the average number of nodes alive is 4x 100% and 5x 100% more than the remaining nodes in LEACH-C and LEACH respectively. This is due to a better uniform spreading of cluster heads around the network provided by HRSN algorithm, which prevents cluster heads from being concentrated in one area of the network. This avoids the possibility of some nodes exhausting their power when transmitting their data to faraway cluster heads.

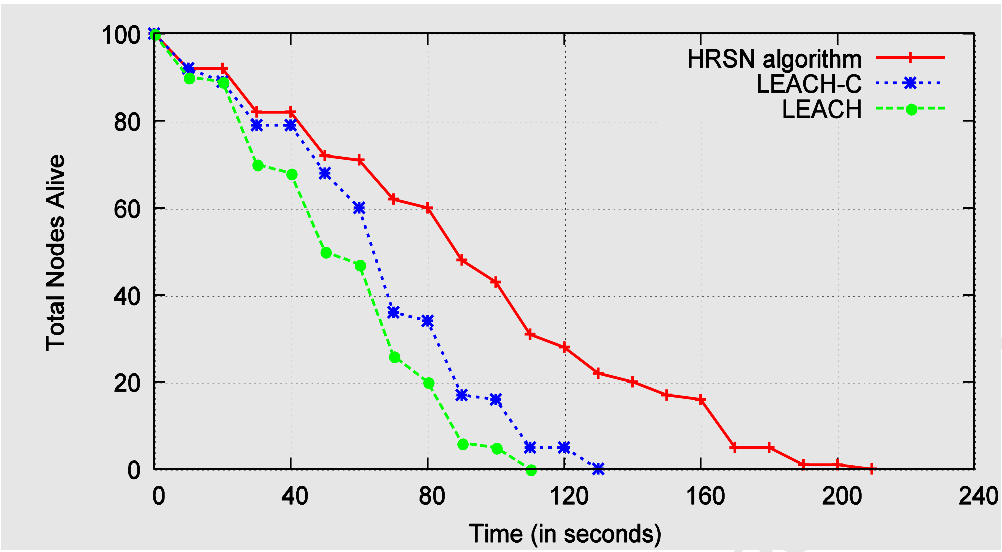

Figure 5.18 A performance comparison of the overall network's lifetime for HRSNs with a *1000m×1000m* network area, when employing the HRSN algorithm, LEACH protocol and LEACH-C protocol

Figure 5.18 illustrates the performance in terms of the total residual energy when HRSN is designed on a $1000m \times 1000m$ area. The advantage of uniformly spreading cluster heads around the network is less appreciable in an scenario like this one, because of the relatively small amount of nodes operating in such a large area. However, HRSN algorithm demonstrates to be the most suitable routing protocol in terms of reducing the rate of death of nodes for HRSNs requiring a large environment. The shame graphs also show that it takes the HRSN algorithm approximately twice as much time to exhaust the power of all nodes achieves an average overall life span of all nodes approximately 100% higher than that of LEACH and approximately 90% higher than LEACH.

5.5.2.2 Nodes Alive per Squared kilometres

Figure 5.19 shows the average number of nodes that remain alive in the network at the end of 50 rounds of activity, as a function of network area. The performances of all three algorithms are compared. The plotted results once again exemplify the effectiveness of HRSN algorithm for HRSN applications that require large network environments.

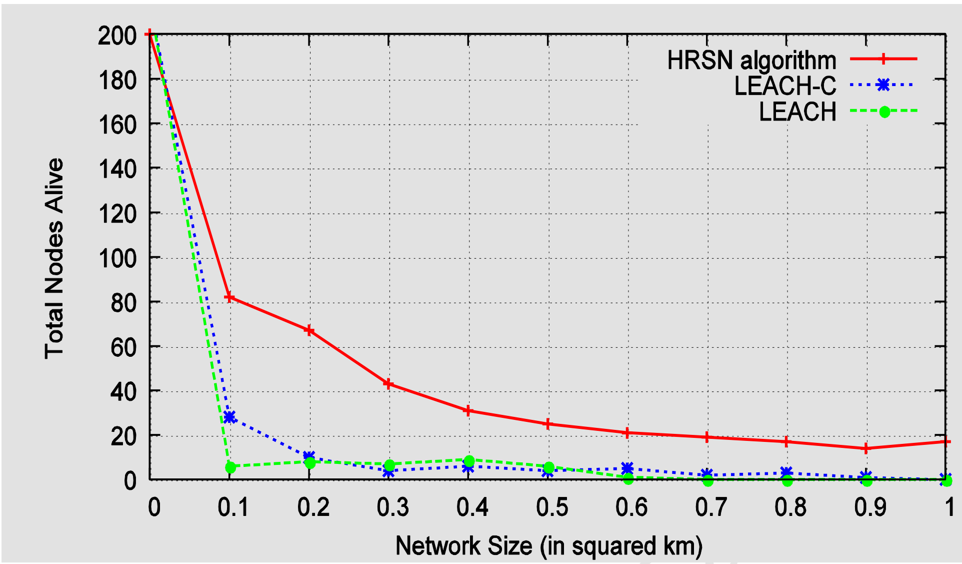

Figure 5.19 A performance comparison of nodes alive per network's area at the end of 50-rounds of simulation activities in 200-node HRSN employing the HRSN algorithm, LEACH and LEACH-C

5.5.2.3 Discussion of Results

The results illustrated in figure 5.17, figure 5.18 and figure 5.19 confirm that the routing algorithm proposed in this research outperforms LEACH and LEACH-C in terms of overall nodes lifetime. The plotted results show that as the network's size increases the performance difference between HRSN algorithm and both LEACH and LEACH-C decreases. However, throughout the experiment HRSN algorithm proves to be the most suitable routing protocol for HRSNs designed in large environments.

5.5.3 HSNs Lifetime

Figure 5.20 compares the performances of the three routing protocols in terms of average number of HSNs alive 70 seconds after the start of the HRSN simulation activity.

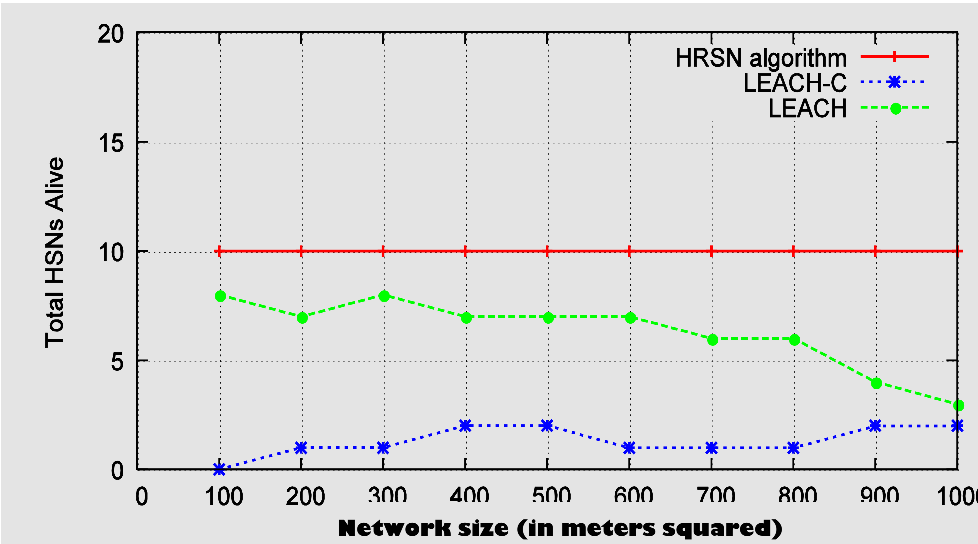

Figure 5.20 A performance comparison of average HSNs alive per network area of HRSN algorithm with LEACH and LEACH-C protocols

The results obtained show that at that time all HSNs remain alive in the network even as the network size increases. In the case of LEACH the number of HSNs alive decreases as the size of the network increases. This is because the cluster head election process of LEACH involves all nodes communicating with each other. Consequently, the longer transmission ranges together with all the messages to process affect the nodes, which in this case are the HSNs. The number of HSNs alive in LEACH-C is not really influenced by the network size. The poorer performance is mainly because of the priority given to HSNs to become cluster heads.

5.5.4 Conclusion

Throughout this experiment, the HRSN algorithm outperforms LEACH and LEACH-C from the smallest network area to the largest area. This is mainly because the two versions of LEACH do not ensure that the cluster heads are placed uniformly across the whole HRSN. As a result, the cluster head nodes in LEACH and LEACH-C can become concentrated in a certain region of the network, in which case nodes from the "cluster head deprived" regions dissipate a considerable amount of energy while transmitting their data to a faraway cluster head.

Therefore, for a better management of energy, higher life span of HSNs and all nodes in general, HRSN algorithm is the most suitable for a large coverage of HRSN.

5.6 Fifth Experiment: Effects of Presence of HSNs

This experiment investigates the effect that increasing the presence of HSNs in the network has on the overall performance of all three routing protocols. The percentage of HSNs in the network is increased from 5% to 40%. The design concept of the HRSN is such that there must be a larger presence of wireless sensor nodes in the network as compared to HSNs. This is the reason for not increasing the amount of HSNs to a higher percentage during the experiment. The simulation environment consists of 100 nodes arranged into 10 clusters through a network area of $100m \times 100m$ with a base station located at (50, 175) m from the network.

In this experiment also 28 different topologies were simulated for each of the different percentages of incorporated HSNs.

5.6.1 Ratio of Consumed Energy as a Function of Total HSNs

Figure 5.21 illustrates the plotted results of the average ratio of energy consumption over the percentage of initial HSNs available for the three routing protocols under study. The results correspond to 150 seconds after starting activity for each of the different scenarios. The plots clearly demonstrate that HRSN algorithm has a much more desirable energy expenditure ratio than those of LEACH and LEACH-C. The percentage of energy consumption increases as the number of HSNs components increases. This is because more high-energy consuming roles are incorporated, which has an effect on the overall energy dissipation.

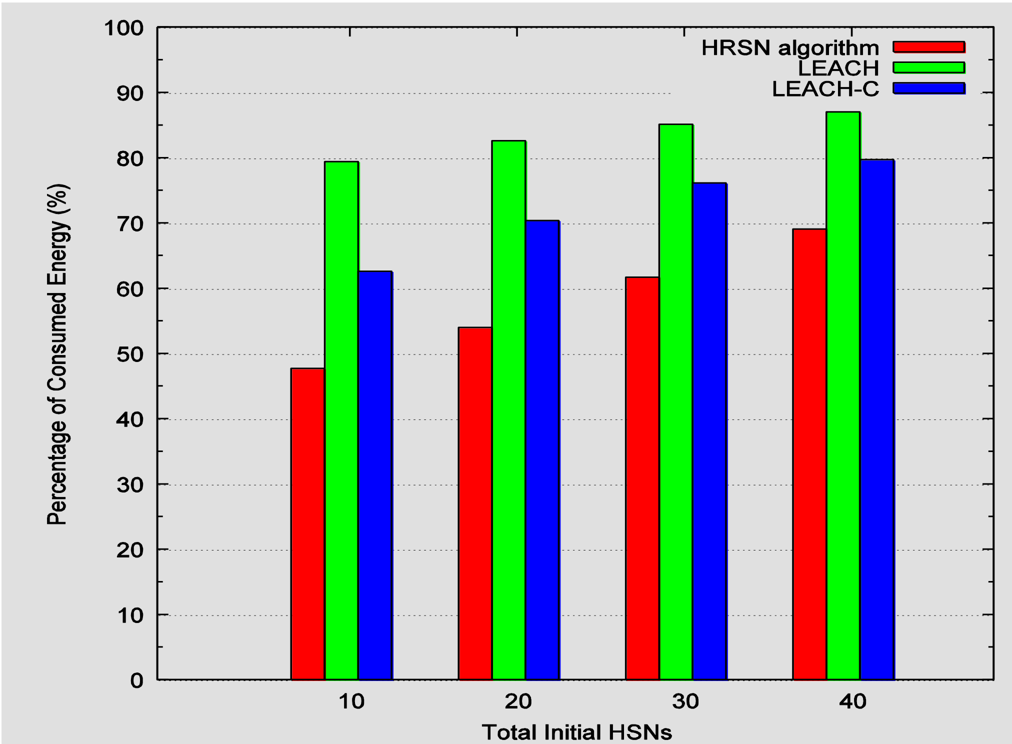

Figure 5.21 Performance comparison of the percentage of energy consumption as the number of HSNs varies in HRSN

5.6.2 Percentage of Alive HSNs as per Initial Number of HSNs

This section investigates the effect that increasing the number of HSNs has on the performance of HSNs themselves. Figure 5.22 illustrates the average percentage of HSNs alive at the end of 50 rounds of activity in the network.

The plotted results demonstrate the advantage that implementing HRSN algorithm has over LEACH and LEACH-C. The performances of both LEACH and LEACH-C significantly increment as the amount of HSNs increases. This is because both LEACH versions allow HSNs to perform a high consuming role such as cluster head, which in addition involves direct communication to the base station. HRSN algorithm alleviates this drawback by incorporating multi-hopping among HSNs and ensuring they are not eligible to act as cluster heads.

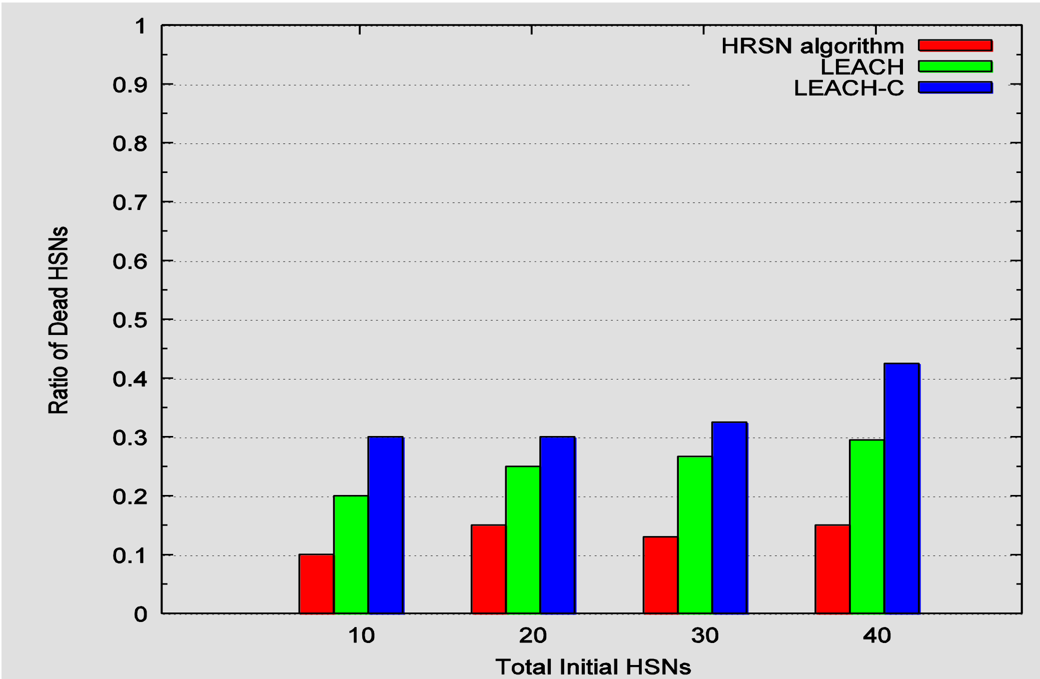

Figure 5.22 A performance comparison of the ratio of HSNs with exhausted power as the number of initial HSNs in HRSN varies

5.6.3 Conclusion

The results obtained throughout this experiment demonstrate that the HRSN algorithm outperforms LEACH and LEACH-C protocols in terms of managing the energy resources of the HSNs. These results reflect the effect that applying multi-hoping in this type of network has on the overall energy efficiency because the superior performance of the HRSN algorithm is more noticeable when the percentage of HSNs in the network is at its highest, 40%. This advantageous performance is due to HSNs not forwarding their data directly to the far base station.

Chapter 6

Summary of Contributions and Future Work

6.1 Introduction

This chapter discusses the main contributions made in this research based on the conclusions drawn in the previous chapter and recommends some future work that can be done on this research topic. Following this introduction, Section 6.2 provides a summary of this thesis; Section 6.3 lists the achievements of the research work. Section 6.4 discusses the shortcomings experienced in the study, and makes recommendations for future work.

6.2 Summary of this Research

This research proposed a framework for integrating the RFID and sensor technologies in hybrid networks aiming at identifying objects and sensing their environments, to provide services to different users in ubiquitous sensing environments. Building upon the integration of conventional wireless sensor nodes, sensor-tags, hybrid RFID/sensor nodes (HSNs) and a base station into the same networking environment, a new routing protocol referred to as HRSN algorithm was also proposed. The proposed routing protocol uses a centralized-based routing mechanism to solve the energy imbalances arising in hybrid sensing/identification networks. This is achieved by having the base station selecting cluster heads based on their sensing energy properties, residual energy, and position in the network. Using simulation based on extensions of the NS2 simulator, the efficiency of the HRSN algorithm was evaluated and compared to LEACH and LEACH-C; two of the most widely known clustering based protocols in WSNs. The different simulation results revealed that, the HRSN algorithm achieves the best energy management, higher network lifetime and longest HSNs life span. This is due to a better load balancing scheme implemented by the HRSN through multi-hopping and an improved spreading of cluster heads around the network. The obtained results were discussed in the previous chapter. In that chapter, various conclusions were drawn based on the obtained results.

The following sections present the contributions that can be drawn from the discussed observations and conclusions of the previous chapter.

6.3 Summary of Contributions

The results obtained in the various simulation tests presented in the previous chapter demonstrated that the models designed in this thesis make important contributions in the field of integration of RFID and WSN networks. These contributions are summarized below.

This thesis has proposed a novel architecture for integrating RFIDs and WSNs into one hybrid network named HRSN. A common characteristic of previously proposed architectures in this research field is the communication limitation among the different components as discussed in Chapter 2. The architecture proposed for the HRSN improves this limitation by allowing communication among conventional wireless sensor nodes, sensor-tags and integrated RIFD readers. This is achieved through the HSNs, who interact with the conventional sensor nodes and the sensor-tags.

The HRSN was compared to traditional WSN, and the results showed energy efficiency improvements between an imbalanced HRSN and a balanced HRSN. A balanced HRSN achieves better energy performance than WSN. This was achieved through the implementation of the proposed routing protocol named HRSN algorithm. The improved energy balanced when using the HRSN algorithm is the result of a combination of features. For instance, the HRSN algorithm introduced a method for denominating cluster heads based on the sensing properties of each node. The simulation test results demonstrated that with this feature the HRSN algorithm increases the life span of the high-energy consuming nodes, HSNs, by approximately 100%. In addition, results obtained also showed that the energy dissipated throughout the lifetime of the network does not fluctuate, resulting in an improved energy balancing. The advantages of this feature when combined with multihopping, demonstrate further improvements of the energy efficiency for a network with a number of HSNs that are almost half of the total nodes in the network. In such environment, the HRSN algorithm also improves the life span of the HSNs and the results showed an approximately 100% reduction death rate of HSNs.

The clustering process of hierarchical routing protocols designed for this type of network was improved. The HRSN algorithm combined the improved election of cluster heads that exclude HSNs from playing this role, with a spreading technique that determined a cost factor involving the residual energy of the node as well as their position in the network. This unique combination of features proved to be advantageous in the plotted results, as the HRSN algorithm demonstrated up to 90% increase of the overall network lifetime. These improvements proved to be even more significant in networks with large number of nodes where the network lifetime experienced an increase of 100%.

Therefore, it can be concluded that the routing method introduced by the HRSN algorithm is the most efficient in managing the energy resources of a network with characteristics similar to HRSN. However, despite these important contributions, the work presented in this research experienced some limitations. The following section discusses these limitations.

6.4 Recommendations for Future Work

The algorithm proposed in this research proves to be a promising solution to energy imbalances experienced in hybrid networks, but there is room for improvement to make the solution more efficient and widely deployable. The following paragraphs describe some areas where the proposed algorithm might need improvements.

- *Investigate the QoS.* This research focuses on investigating performances the HRSN algorithm in terms of energy efficiency. Further experiments can be conducted to study the performance in terms of Quality of Service (QoS).

- *Make the HRSN algorithm efficient for critical event driven applications.* The properties of the HRSN routing algorithm are more suitable for a periodic event based type of applications. A network designed for an event driven application may find some delay if using this routing algorithm. The delay will be caused by the TDMA implemented in the algorithm because TDMA allows each cluster member to send its data to the cluster head only during its allocated slot. Consequently, information about an event detected by a node will arrive with delay to the base station if the node sensed such data after its transmission slot. Therefore, for this type of application a different Medium Access Control (MAC) protocol such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) may need to be considered, such that nodes only transmit data after detecting an event. This will not only improve delay but also save more energy for these applications.

The investigation of mitigation solutions that may trade between efficiency, delays, and routing overheads is an avenue for future research.

- *Optimization of the centralized technique used in the HRSN algorithm.* It is widely known that centralized routing algorithms lead to global network optimization and subsequent operation efficiency. However, these algorithms tend to also increase the routing overheads by generating extensive signaling messages forth and back from a central entity used to compute the algorithm. The solution proposed in this project is based on a centralized algorithm that may inherit similar overhead inefficiencies at implementation. Therefore, another avenue for future research work is the design of an efficient protocol extended from the HRSN algorithm to achieve optimization while reducing the signaling overheads.

- *Materialization of the HRSN for real network applications.* Finally, since the technology is already available, it would be interesting to build a prototype of the HRSN for an application such as the one described in Chapter 3. Furthermore, the performance of the HRSN can be compared to other hybrid networks of similar application. This has also been reserved for future research work.

References

[1] L. Zhang and Z. Wang, "Integration of RFID into Wireless Sensor Networks: Architecture, Opportunities and Challenging Problems," *in Proc. of the 5^th^ International Conference on Grid and Cooperative Comp. Workshops.*, pp 463-469 Oct. 2006.

[2] J. Cho, Y. Shim, T. Kwon, Y. Choi, S. Pack, and S. Kim, "SARIF: A Novel Framework for Integrating Wireless Sensor and RFID Networks," *in Proc. of the IEEE Transactions on Wireless Communications*, Vol. 14, no. 6, pp. 50-56, Dec. 2007.

[3] F. Dressler, A. Awad, S. Dengler, and R. German, "Integrated RFID and Sensor Networks for Smart Homes". In Book: *in RFID and Sensor Networks: Architectures, Protocols, Security and Integrations, Wireless Networks and Mobile Communications*, Yan Zhang, Laurence T. Yang and Jiming Chen (Eds.), Auerbach Publications, CRC Press, Taylor and Francis Group, LLC 2010, pp. 537-558.

[4] H. Liu, M. Bolic, A. Nayak, I. Stojmenovic, "Taxonomy and Challenges of Integration of RFID and Wireless Sensor Networks," *IEEE Network*, Vol. 22, no. 6, pp. 26-32, 2008.

[5] A. Mitrokotsa, C. Douligeris. Chapter: "Integrated RFID and Sensor Networks: Architectures and Applications", In Book: *RFID and Sensor Networks: Architectures, Protocols, Security and Integrations*. Wireless Networks and Mobile Communication Series, pp. 511-535. Auerbach Publications, CRC Press, Taylor and Francis Group, LLC 2010, ISBN: 978-1-4200-4288-7.

[6] U.S. Government Accountability Office (GAO), "Radio Frequency Identification Technology in the Federal Government," *Report To Congress To Congressional Requesters,* May 2005. Available from: http://epic.org/privacy/surveillance/spotlight/0806/gao05551.pdf Last accessed: 15/09/2011.

[7] I.F. Akyildiz, S. Weilian, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Communications Magazine*, Vol. 40, no. 8 pp 102-114, August 2002.

[8] J. Jeong, X. Jiang, and D. Culler, "Design And Analysis of Micro-solar Power Systems for Wireless Sensor Networks," *in Proc. of the 5th Intl Conference on Networked Sensing Systems (INSS)*, pp. 181–188, June 2008.

[9] W. Seah, Z. Eu, and H. Tan. "Wireless sensor networks powered by ambient energy harvesting (WSN-HEAP) – Survey and challenges" in *Proc. of Wireless VITAE*, pp. 1-5, May 2009.

[10] W.R. Heinzelman, J. Kulik, and H. Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," *Proc. 5th ACM/IEEE Mobicom Conference* (MobiCom '99), pp. 174-185, Aug. 1999.

[11] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: a scalable and robust communication paradigm for sensor networks," *Proceedings of ACM MobiCom'00*, pp. 56-67, 2000.

[12] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient

communication protocols for wireless microsensor networks," in *Proceedings of the Hawaii International Conference on Systems Sciences*, pp. 1-10, Jan. 2000.

[13] S. Lindsey and C.S. Raghavendra, "PEGASIS: Power-Efficient Gathering In Sensor Information System," *in IEEE Aerospace Conference*, pp. 1125-1130, March 2002.

[14] F. Xiangning, S. Yulin. "Improvement on LEACH Protocol of Wireless Sensor Network," *in Proc. of the International Conference on Sensor Technologies and Applications (SENSORCOMM 2007),* pp. 260-264, 2007.

[15] M. Ye, C. Li, G. Chen, and J. Wu, "EECS: An Energy Efficient Clustering Clustering Scheme in Wireless Sensor Networks," *in Proc. of IEEE International Performance Computing and Communications Conference,* pp. 535-540, 2005.

[16] J. N. Al-Karaki and A.E. Kamal, "Routing techniques in wireless sensor networks: a survey"' *IEEE Trans. on Wireless Communications*, Vol. 11, no. 6, pp. 6-28, 2004.

[17] W. B. Heinzelman and A. P. Chandrakasan, "An application-specific protocol architecture for wireless microsensor networks", *IEEE Trans. Wireless Commun*., Vol. 1, no. 4, pp. 660-670, Oct. 2002.

[18] S. Jain and S.R. Das, "Collision Avoidance in a Dense RFID Network", in Proceedings of *the 1st international workshop on Wireless network testbeds, experimental evaluation \& characterization (WiNTECH'06)*, pp. 49-56, Sept. 2006.

[19] A.G. Ruzzelli, Raja Jurdak and Gregory M.P. O'Hare, "On the RFID wake-up impulse for multi-hop sensor networks," *In Proceedings of 1st ACM Workshop on Convergence of RFID and Wireless Sensor Networks and their Applications (SenseID) at the 5th ACM Conference on Embedded Networked Sensor Systems (ACM SenSys 2007)*, Sydney, Australia, November, 2007.

[20] S. Kim, S. Lee and S. An, "Reader Collision Avoidance Mechanism in Ubiquitous Sensor and RFID Networks," in Proceedings of *the 1st international workshop on Wireless network testbeds, experimental evaluation \& characterization (WiNTECH'06)*, pp. 101-102, Sept. 2006.

[21] J. Waldrop, D.W. Engels, and S.E. Sarma, "Colorwave: An Anticollision Algorithm for the Reader Collision Problem," in *IEEE International Conference on Communications*, vol. 2, 2002, pp. 1206-1210.

[22] G.P. Joshi and S.W. Kim, "Survey, Nomenclature and Comparison of Reader Anti-collision Protocols in RFID," *IETE Technical Review*, Vol. 25, no. 5, 2008.

[23] T.S. López, D. Kim, G. H. Canepa, K. Koumadi "Integrating Wireless Sensors and RFID Tags into Energy-Efficient and Dynamic Context Networks", *The Computer Jounal, Oxford University Press,* Vol. 52, pp. 240-267, 2009.

[24] A. G. Ruzzelli, R. Jurdak and Gregory M.P. O'Hare, "On the RFID wake-up impulse for multi-hop sensor networks," *In Proceedings of 1st ACM Workshop on Convergence of RFID and Wireless Sensor Networks and their Applications (SenseID) at the 5th ACM Conference on Embedded Networked Sensor Systems (ACM SenSys 2007)*, Sydney, Australia, November, 2007.

[25] H. Ramamurthy, B.S. Prabhu, R. Gadh and A.M. Madni, "Wireless industrial monitoring and control using a smart sensor platform," *IEEE Sensor Journal,* Vol. 7, no. 5, pp 611–618, 2007.

[26] Z. Li, H. Shen, B. Alsaify: "Integrating RFID with Wireless Sensor Networks for Inhabitant, Environment and Health Monitoring", in *Proc. of 14th IEEE International Conference on Parallel and Distributed Systems*, pp 639 – 646, 2008.

[27] G. Yang, M. Xiao, and C. Chen, "A simple energy-balancing method in RFID sensor networks," in *Proc. of 2007 IEEE International Workshop on Anti-Counterfeiting, Security, Identification*, pp. 306–310, April 2007.

[28] G. Virone, A. Wood, L. Selavo, Q. Cao, L. Fang, T. Doan, Z. He, R. Stoleru, S. Lin, and J.A. Stankovic, "An advanced wireless sensor network for health monitoring," *Transdisciplinary Conference on Distributed Diagnosis and Home Healthcare (D2H2)*, April 2006.

[29] V. Dyo, S. A. Ellwood, D. W. Macdonald, A. Markham, C. Mascolo, B. Pasztor, N. Trigoni, and R. Wohlers, "Poster abstract: Wildlife and environmental monitoring using RFID and WSN technology," in *Proceedings of ACM Sensys'09*, 2009.

[30] J. Kulik, W.R. Heinzelman, and H. Balakrishnan, "Negotiation-based protocols for disseminating information in wireless sensor networks," *Wireless Networks*, Vol. 8, no. 2, pp. 169-185, 2002.

[31] R. Verdone, D. Dardari, G. Mazzini, and A. Conti, "Wireless Sensor and Actuator Networks: Technologies, Analysis and Design," *Academic Press*, pp. 163-192, Jan. 2008. ISBN: 978-0-12-372539-4.

[32] A. Wang, W. Heinzelman and A. Chandrakasan, "Energy-scalable protocols for battery-operated microsensor networks," i*n Proc. of the IEEE Workshop Signal Processing Systems (SiPS 99)*, pp. 483-492, Oct. 1999.

[33] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks," in *Proc. of the Sixth ACM Annual International Conference on Mobile Computing and Networks (ACM MOBICOM)*, pp. 56-67, Aug. 2000.

[34] C. S. Mani and M. B. Srivastava, "Energy efficient routing in wireless sensor networks," *in Military Communications Conference Proceedings on Communications for Network-Centric Operations: Creating the Information Force*, pp. 357–361, Oct. 2001.

[35] R.C. Shah, and J. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," in *Proc. of the IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 350-355, March 2002.

[36] T.H. Cormen, C.E. Leiserson, and R.L. Rivest. Chapter 16: "Greedy Algorithms." In: "Introduction to Algorithms" 2nd ed. McGraw-Hill Book Company, 2001. ISBN: 0-07-013151-1.

[37] H. Karl and A. Willig, "Protocols and Architectures for Wireless Sensor Networks." Willey Interscience, 2007.

[38] A. Savvides, C-C Han, and M. Srivastava, "Dynamic fine-grained localization in Ad-Hoc

networks of sensors," in *Proc. of the Seventh ACM Annual International Conference on Mobile Computing and Networking (MobiCom),* pp. 166-179, July 2001.

[39] S.M. Jung, Y.J. Han and, T.M. Chung, "The concentric clustering scheme for efficient energy consumption in the PEGASIS," in *Proc. of the 9th International Conference on Advanced Communication Technology*, pp. 260 – 265, Feb. 2007.

[40] S. Lindsey, C.S. Raghavendra, K. Sivalingam, "Data gathering in sensor networks using the energy*delay metric," in *Proc. of the IPDPS Workshop on Issues in Wireless Networks and Mobile Computing*, pp. 2001–2008, April 2001.

[41] N.M. Abdul Latiff, C.C. Tsimenidis, and B.S. Sharif, "Performance comparison of optimization algorithms for clustering in wireless sensor networks," in *Proc. IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS 2007),* Oct. 2007.

[42]].N. Israr and I. Awan, "Multihop clustering algorithm for load balancing in wireless sensor networks," *Internat. J. Simul. Systems Sci. Technol*. Vol. 8, No. 1, pp. 13–25, 2007.

[43] J. J. Lotf, M. Hosseinzadeh, and R. M. Albuliev. "Hierarchical routing in wireless sensor networks: a survey," in Proc. *2nd International Conference on Computer Engineering and Technology*, Vol. 3, pp 650 – 654, April 2010.

[44] G.L. Stuber and G.L. Ster Ber Chapter 9: "Spread Spectrum Techniques" In Book: "Principles of Mobile Communications," 2nd ed. by Kluwer Academic Publishers, pp 459 – 507, 2001. ISBN: 0-7923-7998-5.

[45] H. Shen, *Finding the k Most Vital Edges with Respect to Minimum Spanning Tree*, Proc. IEEE National Aerospace and Electronic Conference, Vol. 1, pp. 255-26, July 1997.

[46] S.D. Muruganathan, D.C.F. Ma, R.I. Bhasin, and A.O. Fpojuwo, "A Centralized Energy-Efficient Routing Protocol for Wireless Sensor Networks," *IEEE Communication magazine*, IEEE, vol. 43, no. 3, pp. S8-S13, 2005.

[47] U. Karthaus and M. Fischer; "Fully integrated passive UHF RFID transponder IC with 16.7 μW minimum RF input power," *IEEE Journal of Solid-State Circuits*, Vol. 38, No. 10, pp. 1602-1608, Oct. 2003.

[48] SlimTrak™ Intelligent UHF RFID Reader with Integrated Computer, by EPCglobal. Data sheet available at: http://www.ventureresearch.com/PDF/IntelligentSlimTrakSlicksheet.pdf Last accessed: 29/09/2011

[49] D. M. Pozar, "Microwave and RF Wireless Systems," John Wiley & Sons, 2001. ISBN: 978-0-471-32282-5.

[50] Y.P. Chen, A.L. Liestman, and J. Liu, "A Hierarchical Energy-Efficient Framework for Data Aggregation in Wireless Sensor Networks," *IEEE Transactions on Vehicular Technology*, Vol. 55, no. 3, pp. 789-796, May 2006.

[51] MachineTalker, iRFID—Intelligent radio frequency identification device, *Q3 2006*, *Preliminary Specification*, Available at: www.machinetalker.com/pdf/iRFID-Q3-2006-Spec.pdf, Last accessed: 07/08/2011.

[52] NS Manual. *Available online at:* http://www.isi.edu/nsnam/ns/ns-documentation.html Last

accessed: 08/07/2011

[53] J. Pan, "A Survey of Network Simulation Tools: Current Status and Future Developments" *Available online at:* http://www1.cse.wustl.edu/~jain/cse567-08/ftp/simtools.pdf, Last accessed: 08/07/2011

[54] OPNET: User Manual, Sept. 2004. Available at: http://www.opnet.com/university_program/teaching_with_opnet/textbooks_and_materials/materials/OPNET_Modeler_Manual.pdf, Last accessed: 15/09/2011.

[55] OMNET++ User Guide. Available at: http://www.omnetpp.org/doc/omnetpp40/UserGuide.pdf, Last accessed: 15/09/2011.

[56] GloMoSim User Manual, Available at: http://pcl.cs.ucla.edu/projects/glomosim/GloMoSimManual.html, Last accessed: 15/09/2011.

[57] JiST User Guide, Available at: http://jist.ece.cornell.edu/docs/040319-jist-user.pdf Last acessed:15/09/2011

[58] SWANS User Guide, Available at: http://jist.ece.cornell.edu/docs/040319-swans-user.pdf Last accessed: 15/09/2011

[59] D. Albesseder, "Comparision of Network-Simulators" *Available online at:* http://ti.tuwien.ac.at/ecs/people/albeseder/simcomp/simcomp Last accessed: 08/07/2011.

[60] OMNeT vs NS-2: A Comparison, Available at:

[61] The Network Simulator ns-2: Tips and Statistical Data for Running Large Simulations in NS. *Available at:* http://www.isi.edu/nsnam/ns/ns-largesim.html Last accessed: 08/07/2011

[62] Ke Liu's NS2 Code, Available at: http://www.cs.binghamton.edu/~kliu/research/ns2code/#speedup, Last accessed: 09/07/2011

Appendix A: Additional Simulation Results

This section provides additional findings from three of the different conducted experiments.

A.1 Third Experiment: Assessment of Netw0rk Scalability

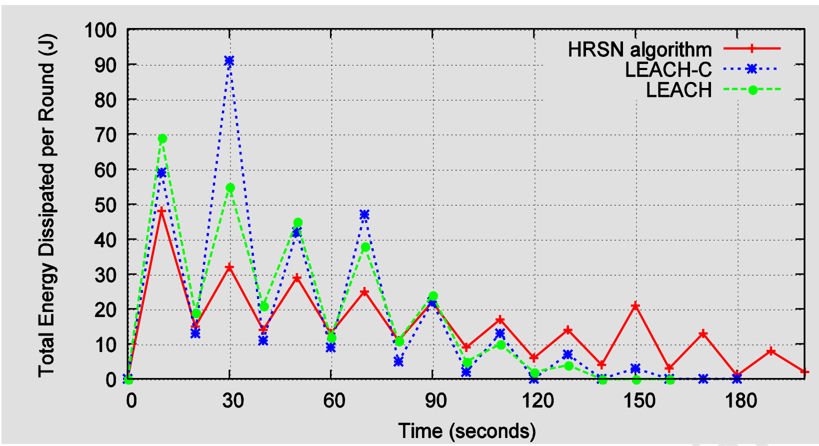

Figure A. 1 A comparison of HRSN algorithm energy consumption per round with LEACH and LEACH-C when there are 150 nodes in the HRSN

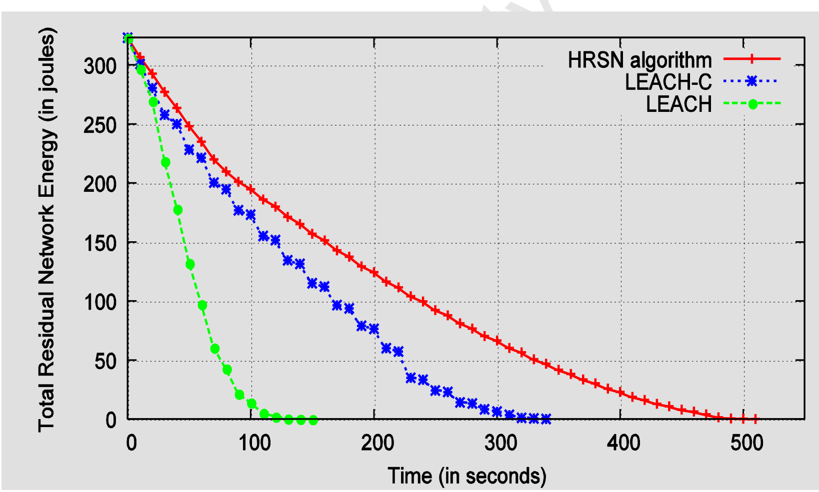

Figure A.2 A performance comparison of the network residual energy of HRSN algorithm with LEACH and LEACH-C when there are 250 nodes an HRSN

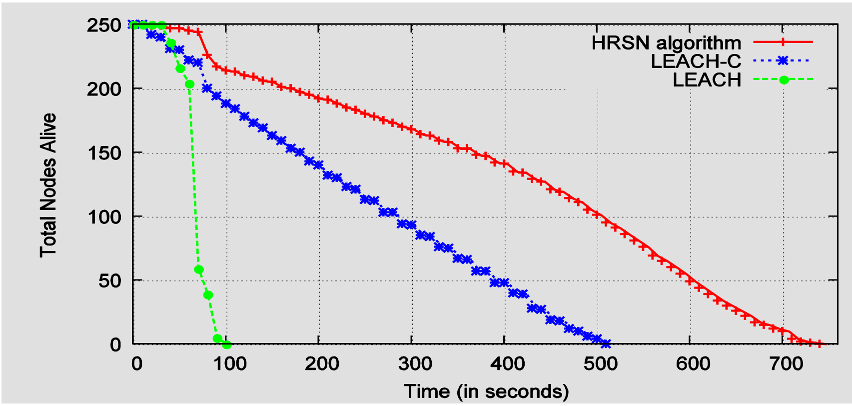

Figure A3 A performance comparison of the nodes lifetime of HRSN algorithm with LEACH and LEACH-C when there are 250 nodes in a $100m \times 100m$ HRSN

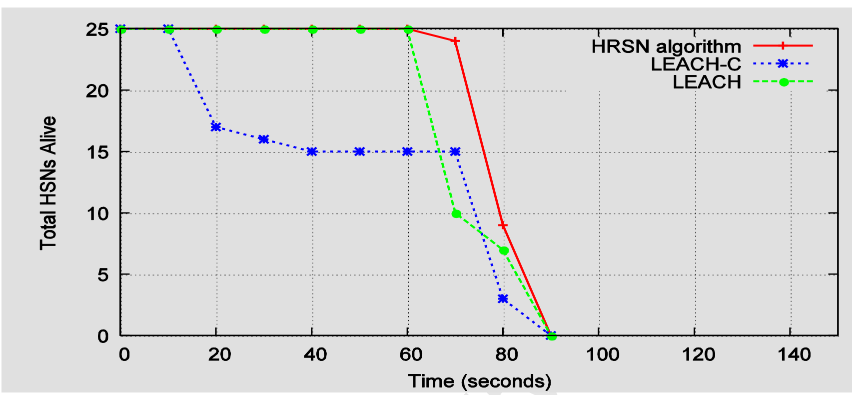

Figure A.4 A performance comparison of the HSNs life span of HRSN algorithm with LEACH and LEACH-C when there are 50 nodes in a $100m \times 100m$ HRSN

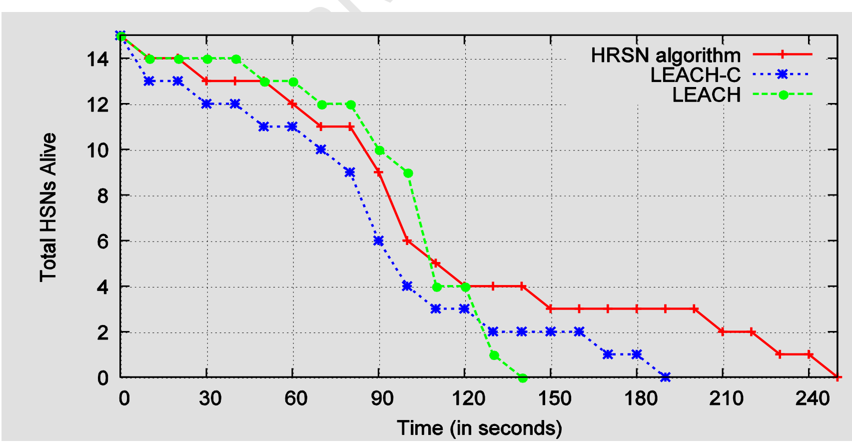

Figure A.5 A performance comparison of the HSNs life span of HRSN algorithm with LEACH and LEACH-C when there are 150 nodes in the HRSN

A.2 Fourth Experiment: Analysis of HRSN Coverage

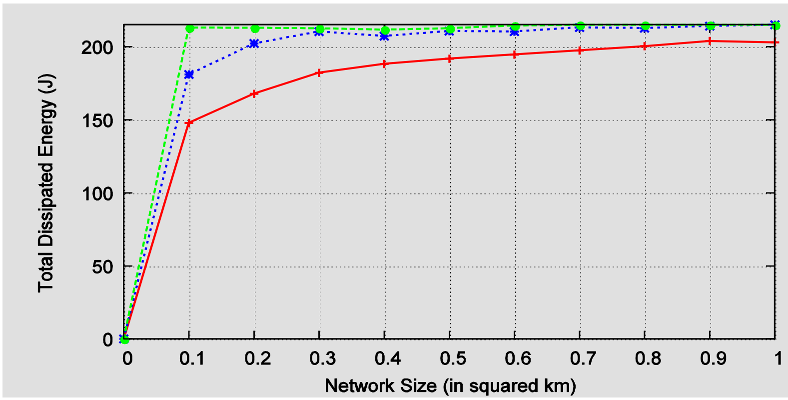

Figure A. 6 A performance comparison of the overall energy dissipation in the HRSN after 120 seconds of simulations as the area size increases

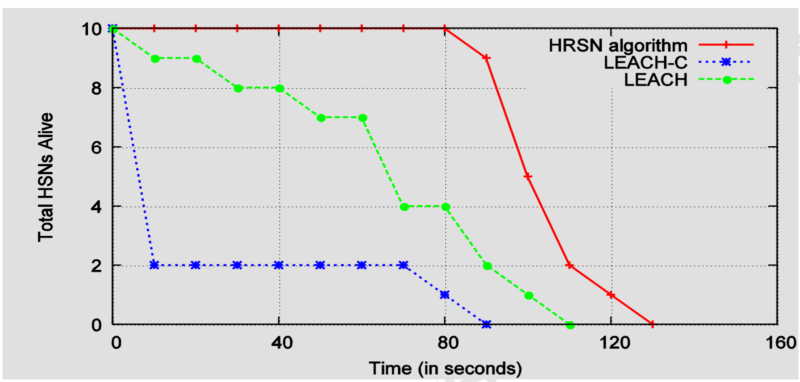

Figure A. 7 A performance comparison of the HSNs life span of HRSN algorithm with LEACH and LEACH-C when there are 100 nodes in a $900m \times 900m$ HRSN

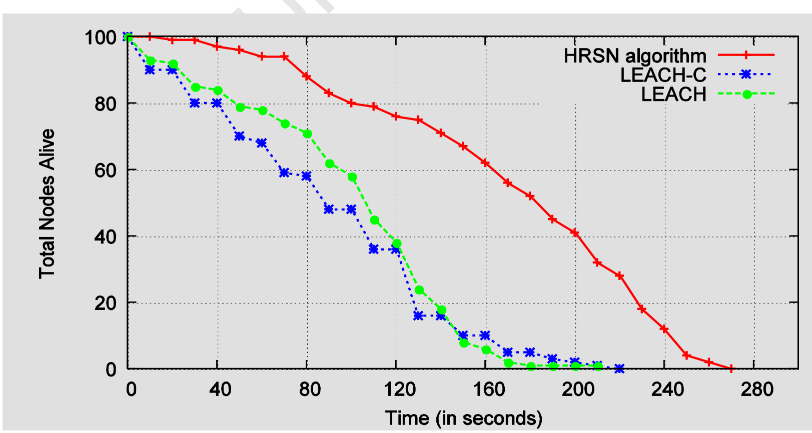

Figure A. 8 A performance comparison of the nodes lifetime of HRSN algorithm with LEACH and LEACH-C when the HRSN is $200m \times 200m$ large

A.3 Fifth Experiment: Effect of Presence of HSNs

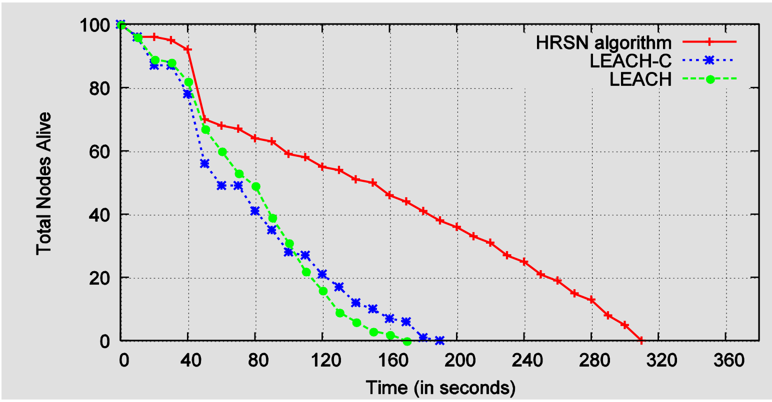

Figure A. 9 A performance comparison of the nodes lifetime of HRSN algorithm with LEACH and LEACH-C when 25% of nodes are HSNs with same initial energy

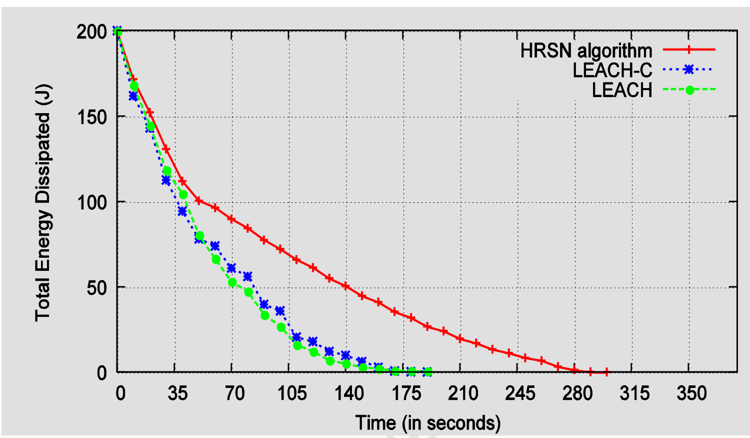

Figure A. 10 A performance comparison of the network's energy dissipation of HRSN algorithm with LEACH and LEACH-C when 35% of nodes are HSNs with the same initial energy

Appendix B: Installation of NS2

Installation of NS2.27 on Ubuntu 9.10 is not a straight forward process, mainly because of the required adjustment of packages on NS2.27 no longer compatible with Ubuntu 9.10 because of being old. This section is the result of various internet websites and forums. The aim is to document the steps and programming codes required for the installation of this version of NS2.

Files you will need:

ns-allinone-2.27

ns-allinone-2.34

Before starting, please download the g++-3.3 packages required for installation. You can get them from the following link
http://packages.ubuntu.com/hardy/g++-3.3

The names of the packages are:

cpp-3.3_3.3.6-15ubuntu4_i386.deb

g++-3.3_3.3.6-15ubuntu4_i386.deb
gcc-3.3_3.3.6-15ubuntu4_i386.deb

gcc-3.3-base_3.3.6-15ubuntu4_i386.deb
libstdc++5-3.3-dev_3.3.6-15ubuntu4_i386.deb

Step 1: In the terminal type:

sudo apt-get install libx11-dev libxmu-dev libxmu-headers libxt-dev libtool

Step 2:

Edit the file in ns-allinone-2.27/ns-2.27/Makefile.in line 36-37 to:
CC = gcc-3.3
CPP = g++-3.3

and in ns-allinone-2.27/nam-1.10/Makefile.in line 44-45:

Do the same.

Step 3:

sudo dpkg -i \
cpp-3.3_3.3.6-15ubuntu4_i386.deb g++-3.3_3.3.6-15ubuntu4_i386.deb \
gcc-3.3_3.3.6-15ubuntu4_i386.deb gcc-3.3-base_3.3.6-15ubuntu4_i386.deb \
libstdc++5-3.3-dev_3.3.6-15ubuntu4_i386.deb

Step 4:

Having ns-allinone-2.27/ and ns-allinone-2.34/ in the same directory
e.g. /home/"username"/ns2/

Type the following commands to link ns-allinone-2.27 and ns-allinone-2.34:

cd ns-allinone-2.27/
mv otcl-1.8/ back-otcl-1.8
mv tcl8.4.5/ back-tcl8.4.5
mv tclcl-1.15/ back-tclcl-1.15
mv tk8.4.5/ back-tk8.4.5

ln -s ../ns-allinone-2.34/tcl8.4.18/
ln -s ../ns-allinone-2.34/tcl8.4.18/ tcl8.4.5
ln -s ../ns-allinone-2.34/tk8.4.18/
ln -s ../ns-allinone-2.34/tk8.4.18/ tk8.4.5
ln -s ../ns-allinone-2.34/otcl-1.13/
ln -s ../ns-allinone-2.34/otcl-1.13/ otcl-1.8
ln -s ../ns-allinone-2.34/tclcl-1.19/
ln -s ../ns-allinone-2.34/tclcl-1.19/ tclcl-1.15

mkdir include
cd include/
ln -s ../tcl8.4.18/generic/tclInt.h

ln -s ../tcl8.4.18/generic/tclIntDecls.h

(These two links may already be present.)

Apply the tk-8.4-lastevent.patch in tk8.4.14.

Apply the otcl-113-configure.in.patch in otcl-1.13

Then: ./install in the ns-allinone-2.27/ top directory.

Step 5: For the installation of leach obtain the mit.tar.gz package at

http://www.internetworkflow.com/downloads/ns2leach/mit.tar.gz

Step 6: Place the mit.tar.gz package into the ns-allione-2.27/ns-2.27 directory and type the following commands in the terminal

cd ns-allione-2.27/ns-2.27

gunzip mit.tar.gz

tar -xvf mit.tar

Step 7:

Edit the file in ns-allione2.27/ns-2.27/Makefile.in

Add –DMIT_uAMPS to the DEFINE list

Add -I./mit/rca –I./mit/uAMPS to the INCLUDE list

Add the following just prior to the line that says gaf/gaf.o \

mit/rca/energy.o mit/rca/rcagent.o \

mit/rca/rca-ll.o mit/rca/resource.o \

mac/mac-sensor-timers.o mac/mac-sensor.o mit/uAMPS/bsagent.o \

Edi the file in ns-allione-2.27/ns-2.27/mit/uAMPS/sims/uamps.tcl

Replace lines #12 to 15 with these lines:

source mit/rca/ns-ranode.tcl

source mit/uAMPS/ns-bsapp.tcl

source mit/uAMPS/extras.tcl

source mit/uAMPS/stats.tcl

Replace lines #20 to 22 with these lines:

source mit/rca/resources/ns-resource-manager.tcl

source mit/rca/resources/ns-energy-resource.tcl

source mit/rca/resources/ns-neighbor-resource.tcl

Follow the same logic of replacing $**env**(RCA_LIBRARY) and $**env**(uAMPS_LIBRARY) with mit/rca and mit/uAMPS correspondingly in the following files:

ns-allione-2.27/ns-2.27/mit/uAMPS/sims/leach.tcl

ns-allione-2.27/ns-2.27/mit/uAMPS/sims/leach-c.tcl

Step 8:

cd ns-allione-2.27/ns-2.27/

./configure

make clean

make

./validate

./leach-test

Check in ns-allione-2.27/ns-2.27/mit/leach_sims/leach.err if the file reports any errors

Check the simulation outputs in ns-allione-2.27/ns-2.27/mit/leach_sims/leach.out