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Energy Conservation and Lifetime Prolongation Schemes for Distributed Wireless Sensor Network

Zhang, Xiaoguang

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Energy Conservation and Lifetime Prolongation Schemes for Distributed Wireless Sensor Network

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by

Xiaoguang Zhang

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Supervised

by

Dr. Zheng da Wu

Professor of Computer Science

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Abstract

A distributed wireless sensor network is the network composed of sensor nodes, capable of sensing the environment, processing and storing the sensed data and transmitting the data through wireless channels. It can be deployed as a system with static sensors or a system with mobile nodes. As the energy capacity of the node hardware is limited, sensor networks suffer greatly from a severe energy constraint. Furthermore, as many of the environments or objects that need to be monitored, such as volcanoes, bushland, battle fields or animals, are normally difficult to reach, it is very costly or even impossible to renew the energy supply of the sensors or redeploy the nodes. Hence the energy conservation and network lifetime prolongation problem becomes one of the key issues for the deployment of the sensor network.

In this thesis the energy conservation and network lifetime prolongation problem of the sensor network is rigorously examined. Through the investigation of existing works, the design of a non-uniform node deployment scheme for tackling the energy hole problem of the static sensor network is identified to be a vital issue for the prolongation of the network lifetime. Since the non-uniform node deployment mechanism requires a region-by-region routing style, a spatially energy balanced routing strategy for this kind of mechanism is also crucial for the longevity of the network and needs to be studied. For a mobile wireless sensor network, the design of an energy efficient duty cycle scheduling scheme for the node detection is recognised as very important for the energy conservation of the node and thus should be carefully investigated.

Aimed at making progress on these issues, three novel schemes are provided in this thesis. Taking the energy consumptions of nodes, in active mode, without transmitting or receiving data into consideration, the non-uniform node deployment scheme for the event detection sensor network is proposed. This scheme is designed using the analytical results of the impacts of spatial and temporal distribution of

events on the node deployment strategy according to the network lifetime requirement of the application.

Although spatially balanced energy consumption in routing for a network with non-uniform node deployment can be achieved through selecting the neighbour node with maximum residual energy, special equipment is required for obtaining accurate information and the transmission of real-time energy information is costly. Hence it is necessary to design an energy balanced routing strategy without the energy information and the region constraint routing scheme, in accordance with the analytical result of the spatially unbalanced energy consumption for random node selection method, is presented in this thesis for this purpose. By combining the region constraint scheme and maximum residual energy strategy, a hybrid mechanism is also proposed to improve the performance of the maximum residual energy scheme.

Since the sensor nodes in a mobile wireless sensor network must exchange information among each other to increase the probability for data collection, nodes need to detect the existence of each other through beaconing and listening. However the sensors also need to work in very low duty cycle to conserve energy. The low duty cycle of the sensor nodes makes the chance for the nodes to find other neighbours become very low. Thus a duty cycle scheduling strategy that enables nodes to effectively discover other nodes as well as saving the power necessary to fulfil the lifetime demand of applications is required. In this thesis the flock based duty cycle scheduling scheme is presented through the neighbour node number estimation method based on an analytical model.

For all the schemes proposed in this thesis, the experimental results are provided. The results show that the three mechanisms designed in this thesis are capable of improving the performance of the system significantly.

Statement of Originality

All the materials presented in this thesis represent the own work of the author and have not been published previously for a degree or a diploma in any university. To the best of my knowledge, no contents in this thesis have been published or written by any other author except for the supervisor of the author, who is the co-author of the publications arising from this thesis.

Supervisor Signature:

Date:

Author Signature:

Date:

Xiaoguang Zhang

SID: 13000844

E-mail: zfsu3722@hotmail.com

School of Information Technology

Bond University

Gold Coast, QLD, 4229

Australia

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Chapter 1: Introduction

A sensor network is the network system formed by a large number of sensor nodes working together to gather information from the environment and then transmitting this data to a base station for further processing. Developments in processor, memory and radio technology mean that, it is now possible to deploy micro sensor nodes to construct the sensor network system. As a micro node is flexible and can be deployed in locations which are difficult for humans to access, a sensor network system composed of this kind of node can be exploited for a vast variety of applications, for example habitat monitoring, heritage architecture protection, environmental monitoring, soil moisture monitoring for agriculture, maritime monitoring, endangered species protection, animal tracking, pipeline monitoring, glacial monitoring and even epidemic control in human society [1–13].

Sensor network systems can be constructed in two different manners depending on the requirement of the corresponding application. The first method involves setting up a network where the sensor nodes are arranged in fixed positions and is called a static sensor network. In this type of sensor network, each sensor node gathers the relevant information within its sensing range and transmits the data to the base station(the sink node). Since the transmission range of each node is limited, to reach the sink node the data needs to be relayed by other sensors using hop-by-hop data transmssion. Through the exploitation of the static sensor network system, the information gathered from the network can be used to construct a spatial-temporal view of the environment monitored, hence it can be used flexibly in many different fields [1–10]. However, the static network structure is not suitable suitable for some applications. In situations where it is necessary to continuously obtain information from moving objects such as animals or humans, sensor nodes need to be attached directly to objects and move with them [11–13]. In this scenario, which is called a mobile wireless sensor network, the nodes cannot form a steady routing structure in order for the data to be transmitted to the base station and individual nodes rarely encounter the sink node or each other. In order to increase the probability of the data being gathered by the base station, nodes need to replicate information among each other when they are able to communicate.

A micro sensor node is by its nature very small and a battery is the only energy provision currently available as a power source for the device. The capacity of the batteries used in these devices is low and the applications of sensor networks demand a long network lifetime. This restriction in the energy provision of the sensor nodes is one of the most severe problems for system design. In order to conserve the energy of the sensor node and prolong the longevity of the network system so that the requirement of the application can be fulfilled, effective methods for dealing with the energy constraint problem need to be proposed.

This thesis investigates three specific issues concerning the problem of the energy constraint of the sensor network system. These issues are:

- ➢ The design of a non-uniform node deployment strategy that tackles the energy hole problem of the static sensor network system.

- ➢ The establishment of a spatially balanced routing mechanism for solving the spatially unbalanced energy consumption in the routing phase of the static sensor network system with non-uniform node deployment.

- ➢ The construction of an energy efficient duty cycle scheduling scheme for dealing with the non-efficient energy exploitation of the mobile sensor network system.

The energy hole problem is caused by the reverse-multicast data transmission manner of the static sensor network. As the nodes closer to the sink node need to transmit more data, these nodes will use more energy and hence die faster than the sensors further away from the sink node. Therefore the network needs to be deployed non-uniformly to balance the lifetime of the network, so that the longevity of the system can be prolonged. To achieve the proper performance of the non-uniform node deployment strategy, the energy consumption of the nodes in the routing phase needs to be spatially balanced among the nodes. If it is not balanced, the nodes in the part of the network that transmits more data will still die earlier than other sensors. Consequently the design of such a routing scheme is a crucial problem for leveraging the non-uniform node deployment strategy. In a mobile sensor network it is necessary for nodes to exchange information among each other so that the data delivery rate can be increased. However the low duty cycle working style necessary makes it difficult for the nodes to detect each other. Thus a corresponding duty cycle scheduling scheme needs to be proposed so that nodes can effectively discover other neighbours as well as conserving the power required to fulfil the requirement of the application.

The main contributions of this thesis are:

1. The proposal of a non-uniform node deployment scheme for the event detection static sensor network system that considers the energy consumptions of nodes, in active mode, without transmitting or receiving data.

2. The presentation of a spatially energy balanced region-by-region routing scheme for the static sensor network system with non-uniform node deployment.

3. The provision of an adaptive flock detection based duty cycle scheduling scheme that enables nodes to increase the efficiency of energy use as well as conserving power for the mobile sensor network system.

The thesis is organised as follows. In Chapter 2 the essential background on the sensor network system and the energy constraint issues is provided. Chapter 3 contains a review of the literatures that deal with the energy constraint problem of the sensor networks. Through the discussion of related works, the research's objective, methodology and the originality of the schemes investigated in this PhD research are proposed. In the fourth chapter the design of the non-uniform node deployment scheme is presented. Chapter 5 describes the analysis and establishment of a spatially energy balanced routing scheme. In Chapter 6, an adaptive duty cycle scheduling scheme for the mobile sensor network system is proposed. The last chapter concludes the thesis and proposes directions for future works.

Chapter 2: Background

A distributed wireless sensor network system is designed for sensing and processing signals from the environment, such as temperature, humidity and sound and transmitting the sensed data through wireless channels. It is composed of sensor nodes, capable of accomplishing these tasks. The earliest sensor network systems were constructed of high capacity large nodes. However due to their size, these pieces of equipment are very difficult to deploy in some of the areas where sensors are required, such as volcanoes, the bush, battle fields or tracked animals. As processor, memory and radio technologies have developed, the exploitation of micro devices to accomplish these previously difficult goals has become possible. Nevertheless due to limitations with the hardware and the high cost of either renewing the energy supply of the nodes, or redeploying the sensor nodes, the energy and lifetime constraints of this kind of system are severe. This chapter will provide a brief overview of the sensor network system and discuss the energy constraint problems inherent in it.

2.1 Overview of the Sensor Network System

Generally speaking, any network made up of nodes, with the ability of sensing and wireless transmitting can be called a sensor network. One of the first sensor networks deployed in the real world was the ALERT system [14, 15], constructed in the 1970's in the USA. The objective of the ALERT system is to provide real-time rainfall and water level information for evaluating the possibility of potential flooding. In order to obtain the environmental information needed, the system requires large sensing stations equipped with high capacity sensors, such as water level sensors, temperature sensors, wind sensors and even X-band radar. Data gathered by the sensor stations is transmitted through line-of-sight radio communication from the sensor to the base station in real time and processed using a forecast model. A node of the ALERT system is shown in Figure 2-1 [15]. Another similar system is CORIE [16], designed for monitoring the environment of the Columbia River in North America. This system uses both large stationary stations onshore and mobile stations, positioned on a pier or a buoy offshore. The data is also processed centralised by a base station. Other systems such as the watershed environmental monitoring system for investigating the water and air quality [17] and the system for monitoring the microclimate of the grape-yard [18] all use large station nodes to perform the tasks of sensing and transmitting. A node from each system is shown respectively in Figure 2-2 [17] and Figure 2-3 [18]. The figures show clearly the drawbacks of this type of system - as the equipment they rely on is very large and complex, it is difficult to deploy. In some environments, like terrain that is covered with dense vegetation or trees, it is sometimes impossible to construct such a network.

Figure 2-1: A Sensor Station of ALERT System [15]

Figure 2-2: A Sensor Station of Watershed System [17]

Figure 2-3: A Sensor Station for Grape-Yard [18]

With developments in processor, memory and radio technology, the possibility of using small sensor nodes, which are capable of sensing, communicating and computing, to monitor the physical world emerges. Researchers turned to this kind of small and integrated equipments in order to decrease the cost and increase the flexibility of the deployment of the network system. One of the earliest trials is the system constructed on Great Duck Island in Maine for habitat monitoring [1]. This system uses the small and integrated sensor nodes called 'motes' (as shown in Figure 2-4 [1]), which have a limited wireless transmission range, to monitor the habitat of birds on the island. The data gathered by the nodes is periodically transmitted to the base station, which is also called the sink node, through multi-hop routes. Further access to the data can be issued by users through the Internet. Other systems that need to be deployed in places where it is impossible to construct large sensing stations, such as PDOS [3, 4] and LUSTER [5], also use micro devices. Due to the flexibility with their construction, similar systems are employed for a variety of different applications, including maritime monitoring [6], seabed monitoring [7], gas pipelines monitoring [8], soil moisture monitoring [9] and even glacial environment monitoring [10]. In the systems noted above, nodes perform data gathering and transmitting periodically according to certain work cycle.

Figure 2-4: Sensor Motes [1]

Another type of sensor network system is a query-based system such as TinyDB [19]. This system allows users to send a query to the network and the nodes relevant to the query will respond accordingly. Since the requirement of the query is normally a sequence of data gathered in a period of time at certain rate, the system will still work periodically in this scenario.

For some applications such as disaster monitoring, intrusion detection and the discovery of the occurrences of animals, it is necessary for the system to gather information continuously and transmit the information when the event of interest occurs. In order to fulfil the requirements of these applications, the event detection system has been designed [20–23]. Each node in an event detection system has the detection radius for the signals of the events. In order to obtain the degree of accuracy required by the application, the deployment of nodes should meet certain coverage and connection levels. Systems for detecting static events need at least full coverage [23], while for those designed for detecting motion objects [20], partial coverage is adequate.

In addition to the static network deployment, sensor nodes can also be attached to the motion objects and thus form a mobile network system [11–13]. Since the mobile senor network system can be used to continuously obtain information from the objects sensors are attached to, the system is suitable for many applications such as monitoring the motion pattern of whales [11], observing the lifestyle of the zebra [12] or even controlling the spread of epidemics among humans [13]. In order to exploit the information obtained by the network system, the data gathered by sensor nodes needs to be transmitted to a base station for further processing. In [24] the approach of infostation is proposed. In this scheme, nodes within communication range of the base station directly upload data to the base station. However due to the mobility of nodes within the system, occurrences of connections between nodes and the base station are intermittent. Hence a corresponding method is necessary to increase the probability of data delivery. Since a delay for the data arriving at the base station can be tolerated, there is the potential for utilising node mobility to increase the network throughput [25]. By replicating data among the mobile nodes, the probability that the data will be collected by the base station is increased and the delay in transmission will be decreased. This potential leads to the epidemic routing scheme [26]. Nodes using this routing scheme exchange data among each other when they meet. By replicating data among nodes, each node becomes the data relay node of others to form a virtual route to the base station.

2.2 Energy Constraint Problem

Since sensor networks are usually used for monitoring special environments, it is impossible to provide a stable energy supply externally for the sensor nodes most of the time, which makes it necessary for the nodes to contain an energy supply module. Systems composed of large and powerful nodes like CORIE can be equipped with solar power. However, even when fitted with equipment that generates power, this method still suffers from the problem of loss of energy. For the small and integrated devices, this problem is even more serious. Because of the size and deployment difficulty involved in using a solar power board, it cannot be leveraged by the small equipments like motes. Thus the only possible source of energy to operate an integrated micro device is a battery. The life span of the battery of each sensor device is limited which severely constrains the operation of the sensor network [27, 28]. Since most of the applications have special requirements for the network's lifetime that are beyond the capacity of the hardware [1], the lifetime constraint problem is a severe barrier for the deployment of the sensor network system. Therefore, proper schemes must be proposed to tackle this problem so that the exploitation of sensor networks can become practical.

2.3 Specific Issues in Static Sensor Network Systems

2.3.1 The Energy Hole Problem

In a large-scale static sensor network system the majority of the nodes are out of the transmission range of the sink node and need to transmit data to the sink node through multi-hop routes, using other sensors as relay nodes. During this process, the nodes closer to the sink node need to relay the data from other nodes as well as transmitting data they themselves have generated. In this scenario the sensors near the sink node need to transmit more data and thus will die faster than the nodes further away from the sink node. This reverse-multicast data transmission style leads to the unbalanced energy consumption of the nodes in the network. In Figure 2-5, this issue is explained. Nodes in Region 1 are within the communication rage of the sink node and the nodes in Region 2 cannot directly transmit data to the sink node. So the nodes in Region 1 need to relay the data from sensors in Region 2 as well as the data from Region 1 that they have received and will die faster.

After the death of the nodes in Region 1 the rest of the nodes will be disconnected from the sink node and consequently the whole network system will cease to work. However since in this scenario the nodes in Region 2 still have some residual energy in this scenario, the network is actually disconneted by a hole around the sink node. This problem is termed 'the energy hole problem' and has been rigorously analysed using a mathematical model by the authors of [29].

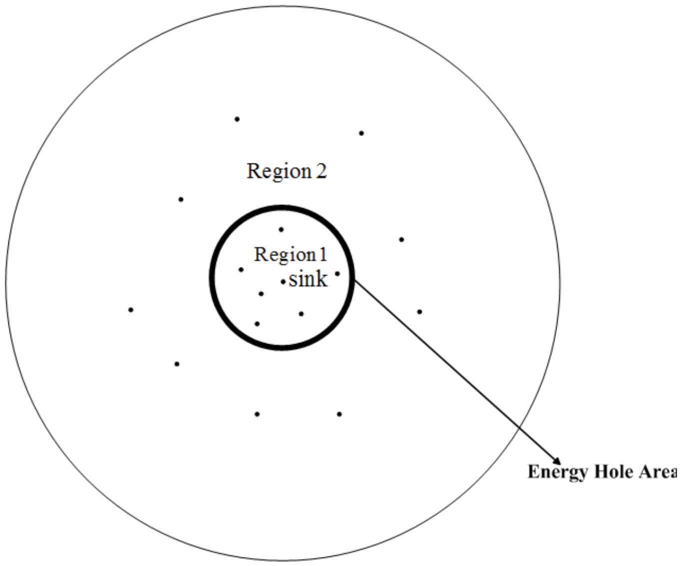

Figure 2-5: The Energy Hole Problem

2.3.2 The Problem of Balancing Energy Consumption in Routing

The energy hole problem can be tackled by non-uniformly deploying nodes around the sink node. In this approach the sensing field is divided into several regions in accordance with the distance from the sink node. Data will be transmitted in a region-by-region style. In order to maintain the proper coverage level of the network and the connection of each part of the network to the sink node, the energy consumption in the routing phase needs to be balanced over each region. Figure 2-6 illustrates this energy balancing issue. Suppose that data from nodes in Region 4 needs to be transmitted through Region 3. If the nodes in Sub Region 3i of Region 3 die faster than the rest of the sensors in the same region, the system will not be able to maintain the coverage in Sub Region 3i and consequently will lose part of the capacity in monitoring the sensing field. In addition since some of the nodes near the outside boundary of Region 4 might only be able to communicate with nodes in the Sub Region $3i$, these nodes will be disconnected from the sink node. With a fixed transmission range of each node of the system, nodes in Sub Region 3i will be covered by more nodes. If the nodes in Region 4 randomly select relay nodes in Region 3, the probability that the sensors in Sub Region 3i will be chosen will be higher. This higher chosen rate will lead to the heavier energy consumption of nodes in Sub Region $3i$. As a consequence, the nodes in the Sub Region $3i$ will die faster than the rest of the nodes in the Region 3. Hence a proper scheme for tackling this problem is a necessity for the sensor network system with non-uniform node deployment.

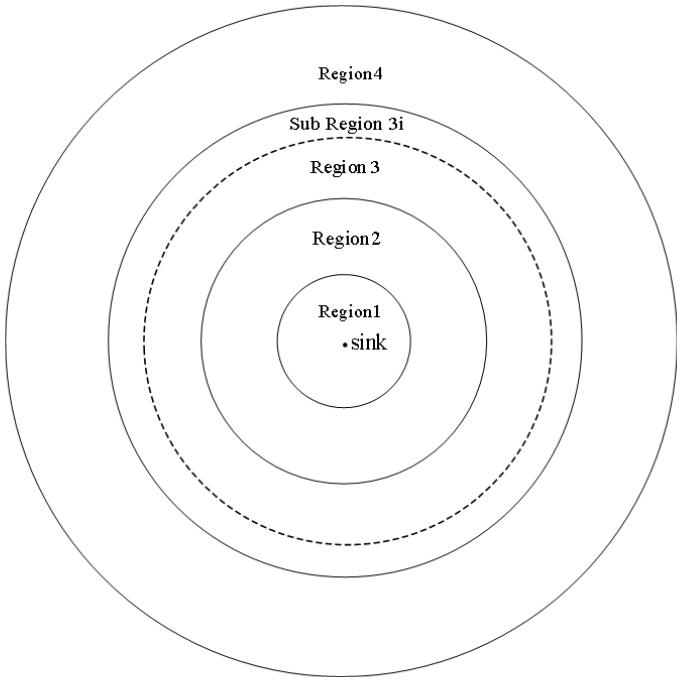

Figure 2-6: Routing Energy Balance Problem

2.4 Specific Issues in the Mobile Sensor Network Systems

2.4.1 The Problem of Duty Cycle Scheduling

In a mobile sensor network system, it is necessary for nodes to replicate data among each other to increase the rate at which the data is delivered to the base station. Since sensor nodes have a severe energy constraint, it is unavoidable that duty cycle scheduling for nodes be exploited to conserve energy when the application has long lifetime requirements. The use of duty cycle scheduling will keep nodes in a low duty cycle to decrease the power consumption. When working in a low duty cycle, nodes will be in the inactive mode for most of the time. A node in the inactive state will turn off their radio transceivers and other onboard equipment to save energy. Hence in this working state, nodes are not able to transmit or receive data. As revealed in [28], in order to ensure the proper lifetime of the node, the duty cycle needs to be lower than 1%. With such a low working cycle, the probability for a node to be able to transmit or receive data will also be extremely low. Since nodes need to detect the existence of each other by transmitting and receiving beacons, successful detection in this circumstance will be very rare. Therefore when a fixed scheduling scheme is used to fulfil the lifetime requirement of applications, nodes cannot effectively discover other neighbouring nodes to replicate data. Consequently the efficiency of the energy use is severely low in this scenario. In order to increase the efficiency of the energy use for a sensor node, it is necessary to develop a new duty cycle scheduling strategy. To increase the efficiency of the energy exploitation, it is essential for the new scheme to adjust the duty cycle of the node in response to changes in the number of the neighbouring nodes. Though it is impossible for a node to detect a change in the number of neighbor nodes in real time under the low working cycle, the estimation of the scale of the neighbouring nodes can be made when the density of network is high. Since animals will occasionally gather together to form flocks with high density, it is possible to design the duty cycle scheduling scheme for *applications composed of mobile nodes with this motion pattern.* In this thesis the duty cycle scheduling problem for the mobile sensor network system will be examined based on the flock motion pattern of the network.

Chapter 3: Literature Review

Schemes that solve the energy constraint problem of the sensor network system by conserving the battery energy of the nodes and thus prolonging the network's lifetime can be designed on different layers as depicted in Figure 3-1. In this chapter the existing studies on these schemes will be reviewed according to this structure of layers. Through a discussion of the existing research, the specifications of the new schemes presented in this thesis will be illustrated. In addition, the objectives and methodologies of the new approaches proposed in this thesis will be described at the end of this chapter.

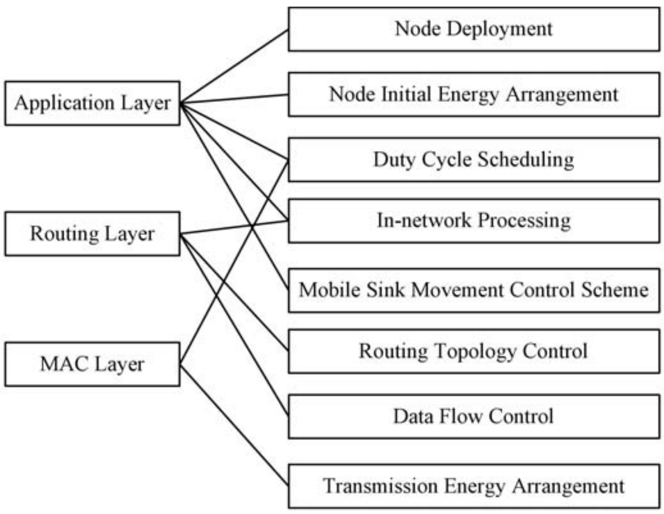

Figure 3-1: Schemes on Different Layers

3.1 Schemes on the Energy Constraint Problem

3.1.1 Schemes on MAC Layer

Since transmitting data through a wireless channel is normally the most energy-consuming behaviour for a sensor node, many researchers have focused on designing the energy efficient transmission control schemes on the MAC layer in order to save the energy of each single node. There are two methods to control the data transmission on the MAC layer: either through exploiting a duty cycle scheduling scheme during transmission or by properly arranging the transmission power of the node. As the schemes on the MAC layer are independent of the network's deployment, these mechanisms can be applied to both the static sensor network system and the mobile sensor network system.

3.1.1.1 The Duty Cycle Scheduling Scheme on the MAC Layer

The objective of the duty cycle scheduling scheme is to properly set the working state of one or many of the nodes' components, for example the CPU or the transceiver. Since each component has different energy consumption level for different working states, energy can be saved by keeping the component in the energy conservation state as long as possible.

In order to reduce the energy consumption of a node, the radio transceiver can be turned off when other nodes are transmitting to avoid the energy waste that normally occurs in some traditional protocols like IEEE 802.11 [30]. To further energy conservation, the communication component can be switched periodically between sleep state and active state. One of the earliest MAC protocols designed for the sensor network system was the S-MAC proposed in [31]. It turns off the radio transceiver of the node for a certain period of time when the node overhears the transmission between other nodes. With this scheme, the radio transceiver of each node will be turned on and off periodically. Through the exchange of a message for synchronisation, the schedules of the neighbouring nodes can be synchronised. The authors of [32] presented a similar protocol, which further modifies the RTS and CTS packet to avoid collision. The energy efficiency of another resembling protocol O-MAC was investigated by [33], which used an explicit packet for ordering the nodes to turn to sleep mode. In the IEEE 802.15.4 protocol for low-rate wireless personal area networks provided in [34], the random backoff method is also used to decrease the transmission conflict and energy consumption. Its contention period is analysed in [35]. In [36] a TDMA-style MAC protocol for sensor networks, without the necessity of global time synchronisation, was described. Nodes using this protocol exchange time slot information through attaching the time slot information of their immediate neighbours and up to two-hop neighbours relative to its own time slot to the data packet head. In this way the time synchronisation can be performed and nodes can arrange their sleep period for energy conservation. The technique discussed in [37] used the transmitter-receiver rendezvous method to carry out the synchronisation. Synchronisation is achieved through the periodic transmission of the frame by the transmitter until it can be received by the receiver. Uisng this method, a node can turn off the transceiver without losing the data transmitted to it. In [38] this scheme was optimised by exploiting the overhearing. When a node hears a frame that has the same destination as its own, it adds the overheard frame to its own frame and interrupts the previous transmission. It then transmits this data and its own data to the determined receiver. This method can decrease data retransmission and consequently reduce energy consumption. The authors of [39] addressed another protocol leveraging two different radio transceivers. One is for data transmission and the other is for waking up the node, which is in low energy consumption. With the waking up capacity, a node is able to stay in a low energy consumption state when there is no data transmission.

3.1.1.2 The Power Arrangement Scheme on the MAC Layer

In addition to the working state, the transmission range is also a contributing factor to the energy consumption level of a radio transceiver. A strategy for deciding the transmission power before node deployment was presented in [40]. It uses the QoS constraint of the maximum tolerable bit error rate at the data destination to derive the optimal transmission power for both decreasing transmission interference and energy consumption. The authors of [41] set out to provide the dynamic and distributed transmission range control scheme for avoiding collisions. Since this scheme tends to reduce the transmission range of nodes, it can reduce the power consumption of a node and consequently conserve its energy.

3.1.2 Schemes on the Routing Layer

Schemes on MAC layer for energy conservation can only control the energy consumption for each single node on transmission. In order to increase the energy efficiency of the whole network, the balance of the energy usage should be further obtained and the unnecessary energy consumption reduced during communication. Therefore it can be noticed that this goal can only be achieved through the mechanisms on higher layer. The schemes on the routing layer are designed to solve this problem.

3.1.2.1 The Data Flow Control Scheme

Controlling the data flow during routing aims to lower energy consumption and network contention by eliminating the unnecessary broadcasting of data. Several studies that deal with this issue for a static network system have been proposed. The authors of [42] demonstrated an energy-efficient data broadcast protocol for network reprogramming. Nodes using this mechanism use limited non-local topology information to decide when to go to sleep as the code is distributed around it. In [43] a scheme based on probabilistic decision making was presented. Nodes decide whether to go to sleep or rebroadcast information by evaluating the probability of keeping active after the active time and the probability of broadcasting. The two probability parameters are designed beforehand in consideration of reliability, latency and energy efficiency. A cross-layer protocol was provided in [44] that exploits the information of the neighbouring nodes, obtained from the lower layers to select the flooding nodes. By this method the retransmission ratio can be adjusted so that the collision and energy consumption can be lowered. An in-network index was constructed in [45] to direct the user's query to the node required, so that the amount of transmission can be decreased. In [46] a similar index tree for the target tracking application was presented for efficiently directing the queries.

With the mobile sensor network system, the issue of controlling the packet replication during the epidemic routing process has also been addressed by many researchers. In [11] a data deletion scheme is proposed based on the estimation of data delivery delay. Through controlling the hop count of the data replication, another mechanism is presented and analysed in [47]. The spray and wait strategy proposed in [48] restricts the data flooding through token based replication number control. Aiming at understanding these schemes further, some works are provided to study performances and trade-off of the mechanisms. In [49] the impact of the replication controlling counter is analysed, based on which a heuristic source control mechanism is proposed. Since the movements of the sensor nodes exhibit certain patterns, it is proper to consider that some nodes will have a higher probability of delivering data to the sink nodes than other sensor nodes. Through this property of the nodes, nodes in the ZebraNet system only choose nodes with higher probability of meeting the sink node as data relay nodes [12]. In [50] a sketch of the delivery probability calculation mechanism is provided.

3.1.2.2 The Routing Topology Control Scheme

Routing topology control schemes are designed to properly form the routing topology of the network so that the energy consumption of the routing phase can be decreased and the efficiency of the data delivery can be increased. To our knowledge, all the mechanisms proposed specifically for the energy constraint sensor network system are constructed for static sensor network system.

The decision-making process for routing topology is energy consuming, because nodes need to exchange information among each other. To reduce this cost, some centralised methods have been addressed. The authors of [51] proposed the protocol with the base station positioned on the edge of the network, providing position information by directional antenna to sensor nodes. Sensor nodes can then use this information to make routing decisions. In [52] another mechanism was discussed. It processes the topology information at the gateway node to form energy efficient download paths and loads them to the sensor nodes when downloading the data.

In addition to the centralised methods, alternative energy-efficient distributed routing schemes were also discussed by other researchers. The authors of [53] proposed a location-based routing protocol that considered the energy cost in addition to the location information. Consequently, it improves the energy-efficiency of some protocols like the one presented in [54] that only considers the location information. In [55] the problem of inaccurate location information was considered and a new energy-efficient routing scheme under this condition was provided. The work issued in [56] modified the proactive routing protocol OLSR [57]. When exchanging the routing information, a node tries to avoid low residual energy nodes in addition to other optimisations on the original OLSR. In [58] the routing strategy exploiting mobile sink nodes was investigated. Through predicting future positions of the sink node that requires the data, the routing can be issued precisely so that the energy waste for the network can be reduced.

The design of an energy balanced routing scheme for static sensor network systems was also examined by a few researchers such as [59], [60], [61], [62], [63], [64] and [65]. In [59] and [60], the strategy of using optimised multiple paths to balance the power usage of data transmission is considered. A parameterised spatial energy balancing routing strategy for wireless networks is proposed in [59], which spreads the data flow for each session in different transmitting paths. In [60] a basestation controlled mechanism is presented to adjust the traffic flow among different data relay routes. A different method of adjusting the transmission range to achieve the balanced energy usage is theoretically analysed in [61]. The mechanisms in [62] and [63] are based on Directed Diffusion [66]. In [62] an algorithm is provided to choose the optimal path in sensor networks for data transmission considering global energy balance and limited delivery delay. The authors of [63] designed the fuzzy next-hop selecting strategy to further balance the energy consumption of Directed Diffusion. The article [64] proposed a swarm intelligence based energy balance routing scheme, based on the neighbour nodes' weight and residual energy. A strategy that trades off the energy consumption and the latency in accordance with the route length is proposed in [65]. None of these works have considered the scenario of deploying sensor nodes non-uniformly in the network *by arranging different node density in different area of the network*. Considering non-uniform node deployment strategy, the mechanism of selecting the node with largest residual energy is provided in [67].

In order to tackle the wasted energy consumption due to the contention of the flat network structure, different clustered methods were presented. For decreasing the contention caused by the routing information exchange of the proactive protocols, the authors of [68]proposed a topology discovery scheme, which divides the network into clusters with the cluster head being in charge of the routing information exchange. In [69] nodes self-organise to form clusters for controlling the traffic flow. The head of the cluster is in charge of evaluating the traffic density and exchanging information between clusters, so that the data rate can be controlled according to the importance of the data flow and congestion can be avoided. In contrast to the supporting row of clusters for the above two protocols, the mechanism exploiting clusters directly for the routing of the data transmission was provided by [70]. Nodes using this protocol periodically select cluster heads through random rotation. The cluster head is in charge of aggregating and transmitting the data directly to the sink node. Due to the limited transmission range of the node, this method cannot be applied in the large scale sensor network system. To tackle this problem an alternative approach was demonstrated in [71]. Leveraging this protocol, nodes select a cluster head according to the residual energy level of the sensors. The data is transmitted to the cluster head for aggregation and then sent to the sink node through the path formed by the cluster heads. By this method, the contention can be reduced and most of the nodes only need to transmit their own data locally to the cluster head node. Consequently the energy can be reserved; however the cluster heads might die quite quickly. The authors of [72] studied the scheme of exploiting a few nodes with limited mobile capacity to tackle this problem. The mobile nodes using this scheme will move to the clusters, in which the energy of the cluster head is used up. For balancing the energy consumption, the work proposed in [73] discussed a centralised method to avoid a hot spot problem by optimising the formation of the clusters according to the information of the location of the node. The authors of [74] designed a distributed protocol for forming the load-balanced transmission framework of clusters. They also considered the working state control of the sensor radio component. Due to the reverse-multicast data transmission manner of sensor networks, the cluster head near the sink node will suffer from bearing a higher burden of traffic flow and die more quickly. Attempting to tackle this problem, another mechanism was addressed in [75]. This strategy forms the clusters with different sizes, in terms of the distance between certain cluster and the sink node. The closer the cluster is to the sink node, the smaller the size of the cluster. This method will provide more nodes to do inter-cluster transmission and in consequence reduce the level of unbalanced energy consumption.

In addition to the hierarchical cluster topology, the flat routing tree structure was also investigated in many studies. The authors of [76] proposed a modified MDST tree, called the DB-MDST tree, to obtain near-optimal tree structure for both minimised height and degree. Experimental results showed that this topology could achieve relatively low delay and an acceptable network lifetime. In [77] an autonomous algorithm for creating and maintaining a routing tree to obtain prolonged network lifetime was presented.

Through working state adjustment, energy-efficient routing topology can also be achieved. The authors of [78] proposed a wave scheduling scheme. This mechanism arranges the working schedules of the nodes to form the routing topology, which decreases the energy consumption of the network by allowing nodes to turn off their radios most of the time. By partitioning the network into cells, this scheduling mechanism can be performed.

3.1.2.3 The In-network Processing Scheme on the Routing Layer

The routing topology control scheme can prolong the lifetime of the sensor network by balancing the energy consumption of the transmissions, decreasing unnecessary transmissions or adjusting the transmission schedule so that nodes can turn off their radio for as long as possible. However, the short network lifetime, caused by the large amount of data that needs to be transmitted in the network, cannot be solved using this method. In order to lower the quantity of the data transmission, the in-network processing scheme for the static sensor network system is proposed. On the routing layer, this scheme is designed focusing primarily on how to aggregate or compress the data during the transmission process. The authors of [79] discussed the routing and aggregation scheme for a multi-sink network. It uses the graph colouring method, which is adaptive to the topology changes, to optimise the time slot assigning for TDMA to avoid network collision. In [80] the scheme used for cluster-based routing topology was considered. It assumes that each node in the cluster uses TDMA protocol to send data to the cluster head. During the transmission process, the node that hears the information sent by other nodes before its transmission and uses this information to compress its own data, exploiting the correlation of the data. A 2D transform compression method was proposed in [81]. This scheme is suitable for any routing tree. It further optimises the routing and transformation, based on the inter-node data correlation and inter-node distance. Since many in-network processing operations have the same energy consumption level as data transmission, in [82] a randomised algorithm was proposed. By choosing the aggregation nodes, this method allows for the construction of a routing tree that jointly optimises energy consumption in consideration of both transmission cost and operation cost. The authors of [83] further considered this problem by proposing an adaptive routing tree, with nodes deciding to aggregate or transmit the data directly. In [84] the data rate allocation scheme for source coding on each node is investigated and an optimised data rate allocation strategy according to the lifetime was proposed.

3.1.3 Schemes on the Application Layer

As an application-specific system, the sensor network system cannot depend solely on the optimisations on the lower layers to obtain expected performance. The requirements of the application need to be taken in consideration; hence it is necessary to exploit the high-level design concerning all the characteristics of the system. On the application layer, all these properties can be considered and thus the full optimisation to the system can be achieved. In this section, the existing mechanisms on the application layer are discussed.

3.1.3.1 The In-network Processing Scheme on the Application Layer

The in-network processing mechanisms proposed on the routing layer of a static sensor network system concentrate on joint optimisation of the routing and compression, thus exploiting the correlations among the sensed values. Some of the schemes deal with the optimisation of routing topology with the capacity of aggregation. However the performances of these methods depend on the characteristics of the data. Using the requirements of the applications, schemes with the better performance can be designed. The TAG presented in [85] is the earliest scheme that leveraged the application's requirements to aggregate the information. It aggregates the data according to certain aggregation function, such as SUM, AVG, MAX or MIN when the data is transmitted through the routing tree rooted by the sink node. The scheme can efficiently fulfil the needs of applications requiring only certain statistics of the data from the sensing field. The authors of [86] discussed the fault tolerant problem and provided a framework with multiple paths for data transmission. Still to tackle the node fault problem, a hybrid method was proposed in [87]. This mechanism uses both tree and gossip algorithms to perform the aggregation processing. Since the sensor network system is intrinsically a distributed system with computation capacity, the idea of exploiting the data processing ability to perform the clustering algorithm for data mining [88] is addressed in [89]. When the data is sparse, the efficiency of a normal routing tree for aggregation is low and the authors of [90] provided a scheme for solving this issue. With this method, nodes with data to report will find the other counterpart that also has information for aggregation. It uses an efficient search method for forming the aggregation tree automatically.

In order to effectively respond to the queries of the users, the in-network storage method is provided, leveraging the storage capacity of the sensor nodes. Through this mechanism, the data can be stored by the nodes and thus the queries can be directed to the sensors with relevant data efficiently. The authors of [91] proposed a hierarchical structure for storing sensed data in different granularities by the exploitation of wavelet transform. The nodes closer to the sink node have the data with less information, while the nodes further away from the sink node contain the more detailed information. Queries can be done in an OLAP [88] fashion. In [92] another method of using the gossip to build the multi-resolution data representations of the sensor data was presented. For the data aggregation, nodes choose to pair for the data exchange according to a probability related to the distance between itself and the counterpart. A distributed hash table scheme was presented in [93]. This method hashes the data according to the demands of users and distributes the data to the corresponding node for storage. The query that requires a certain value can then be directed to the node with the relevant data. It is noted that this mechanism has a hot spot problem due to its single storage point. The clue for this issue was discussed in [94] leveraging a proper replication scheme. The authors of [95] discussed a cluster formation mechanism. With this scheme, the nodes with correlated data will form clusters for a period of time so that only one piece of data needs to be reported each time. Since the network using this method can be regarded as being divided into many virtual storage units, it is categorised as an in-network storage method.

According to trajectories of the motion objects, the in-network processing strategy for motion object tracking is designed. In [96] a tracking tree construction scheme was proposed to detect the motion of an object continuously.

3.1.3.2 The Duty Cycle Scheduling Scheme

Since the energy uses of both the CPU and the transceiver are crucial for the lifetime of a sensor node, it is necessary to arrange the working states not only of the radio transmission device itself, but also of other energy consuming equipments on a sensor node. However as the methods introduced previously can only reduce the power consumption of the radio transceiver, they are not able to decrease the energy consumption of the network effectively. Therefore new duty cycle scheduling schemes need to be proposed for controlling the working states of all the onboard equipments of a node according to the characteristics of the application system.

For the static sensor network system that needs to periodically report data, all the sensors can be kept in sleep mode for conserving energy during the period between the two report processes with the aid of certain time-synchronisation scheme [97]. Existing systems, like the typical one introduced in [1], use this scheduling method. The query-based static sensor network system like the TinyDB presented in [19] can also use this scheme since the report stream for query results is also periodic. The only difference is that this kind of system should keep a working cycle for the queries to be sent to the network. If the issuing of the detection is allowed to be done in cycles by the applications, the in-network storage systems can also use this method. However, for the query-based systems that sense arbitrary events and use in-network storage, no scheduling schemes can be applied, as all the nodes need to be active all the time to detect the event.

When considering energy conservation, it is more important for the static event detection systems to be able to exploit duty cycle scheduling mechanism. Since the occurrences of events are normally sparse, it is proper to directly report the events rather than use in-network storage. In this kind of system, node redundancy can be leveraged to provide duty-cycle arrangement schemes in terms of the demands of the application. In order to achieve level of accuracy of the sensing data, the event detection system needs to retain enough working nodes so that the proper degree of coverage and connection can be obtained. As long as this condition is fulfilled other nodes in the network can switch to the energy conservation mode.

The naive approach is to allow the nodes to switch among different working states randomly following some probabilities. However, the performance of this method needs to be assessed; and many works have analysed this problem. The authors of [98] modelled the performance of such a system in terms of energy consumption, network capacity and data-delivery delay. Through a Markov chain, the trade-offs between the performance metrics and the sensor dynamics in sleep/active mode were investigated by this work. In [99] the possibility of exploiting the uncoordinated scheduling scheme in a sensor network for the applications with serious bonds on latency was examined through percolation theory. The result of the analysis proves that the messages sent by a node can reach the sink with a fixed asymptotic speed. To the coverage capacity, the research issued in [100] analysed the probability of k-coverage of the random schedule scheme. In order to further improve the performance of this mechanism, the authors of [101] formed an optimisation problem to obtain the optimum parameters for the scheduling probability. The presented optimisation problem can be solved using a Markov model. In [102] the issue of the fundamental relationship between the amount of reduction in duty cycle and the amount of deployment redundancy of nodes for the criteria of fixed performance requirement was examined. The random scheduling scheme and coordinated scheduling scheme were provided and compared. This work points out that the performance-energy trade-off lies in some combination of these two schemes depending on the application requirements.

The random scheduling mechanism cannot always promise the expected coverage and connection degree. In order to obtain the determined coverage and connection level, researchers turned to the geometry property of coverage and connectivity for answers. In [103] the intersection coverage property was proven and a coverage scheduling scheme based on this property was proposed to ensure k-coverage for the network. This paper reveals the fact that coverage property being the intrinsic geometric property of the network. Additionally, it also proved that if the transmission range was at least twice the sensing range the network was connected when the network was fully covered. Another coverage scheduling method is proposed by [105] based on the perimeter coverage property presented in [104]. The main contribution of this work is that it loosens the requirement for the relation between coverage radius and transmission range by presenting the direct-neighbour-coverage property. The authors of [106] extended the circular sensing area in the previous works to the polygon and provided the corresponding coverage detection mechanism. In [107] the network was divided into grids and the network coverage scheduling scheme was issued through detecting the coverage level of the grid points. This scheme calculates the scheduling plan in the network initialisation phase and only performs rescheduling when needed. Since these schemes are not able to control the number of the nodes, there will be more nodes than needed. To tackle this problem, the authors of [108] proposed the optimal scheduling scheme, which can effectively reduce the number of active nodes for full coverage. In [109] the lifetime upper-bond for coverage scheduling schemes was estimated. It reveals that the coverage level is closely related to the node density of the network.

In order to further prolong the lifetime of the vehicle detection system described in [20], the work presented in [110] used the partial coverage scheduling scheme proposed in [111]. In this method the active nodes in the network only need to cover part of the sensing field. Due to the mobile characteristic of the vehicles, the objects will be detected on their paths if the schedules of the nodes are properly arranged. The authors of [112] analysed the performance of the partial coverage scheduling mechanism on the motion object detection system according to some important measures, such as average stealth distance, sufficient phase and worst-case stealth distance.

In the mobile sensor network system, the node needs to arrange the duty cycle schedule to effectively perform neighbour node discovery as well as conserving energy to fulfil the lifetime requirement of the application. A scheduling mechanism for this purpose was proposed in [113]. This method leverages the periodic pattern of the node encounters to allocate energy for each time slot.

3.1.3.3 The Node Initial Energy Arrangement Scheme

Most of the research discussed above concentrates on performing energy conservation in accordance with the power supply constraint problem of the single node. Nevertheless the unbalanced energy consumption of the static sensor network system is also another dominant factor for prolonging of the network's lifetime. The authors of [75] attempted to solve this problem through the network topology control scheme. However, with this method the energy use of nodes close to the sink is still higher, since the amount of data for the nodes near the sink node to transmit does not change.

A simple solution is to allocate a higher initial power supply to the nodes near the sink node, so that the network energy consumption can be balanced. The work presented in [114] investigated the relationship between the unbalanced power exploitation and the amount of data that needs to be transmitted by nodes in different part of the network. Through a statistical model, the scenarios for different sink node placements were examined. Based on the analytical results, the non-uniform energy arrangement scheme was proposed.

3.1.3.4 The Mobile Sink Movement Control Scheme

Another method for balancing the energy consumption of the static sensor network system is to deploy mobile sink nodes. This issue has also been examined by many researchers. The earliest one was the data mule approach, which used mobile data collection sinks with random movements to retrieve information from the sensor nodes [115]. In this work an analysis of the performance of the system in terms of the data delivery rate and the buffer use was presented. With the aim of obtaining the optimal sink movement, some scheduling schemes for the motion of the sink nodes have also been proposed. In [116] the movement planning issue was formed into an optimisation problem. It was further proven by this work that the problem was NP-Complete. Practical solutions were also provided by this work. In order to solve the back and forth problem of the schemes provided by [116], a partitioning based mechanism was proposed in [117]. In [118] the sink node movement optimisation method for clustered sensor networks was presented. An alternative to the predetermined movement scheduling method for prolonging the network lifetime is the reactive movement control scheme. The mechanism that calculates the locations of the sinks according to the residual energy of the nodes was demonstrated in [119]. This method controls the movement of the sinks through solving an integer linear programming optimisation problem. In addition to the movement control of the sink node, the corresponding routing scheme also needs to be examined. In [120] the optimal movement scheduling issue and the energy-efficient routing planning problem were formulated as two joint optimisation problems. The results showed that the model provided the optimal solutions to both the problems.

3.1.3.5 The Node Deployment Scheme

Due to the single node energy constraint, the node's initial energy allocation is not practical when high energy level needs to be allocated to a node. The deployment and exploitation of the mobile sink node is also difficult and will lead to high network latency. An alternative method is to deploy more nodes in the areas close to the sink node. The work demonstrated in [121] proposed a non-uniform node deployment strategy in terms of the number of node with the distance to the sink. In [67] it was proven that if all nodes need to transmit data periodically, the ideally balanced energy consumption cannot be obtained. A novel non-uniform deployment strategy was further presented for achieving nearly balanced energy consumption. The authors of [114] turned to the non-uniform node deployment strategy in [122] and presented the node deployment scheme, based on the statistical model of the balance of the network energy consumption. It assumes that the network is scheduled by an ideal scheduling scheme and shows that in this scenario the energy consumption of the network can be balanced. The authors of [123] tried to investigate the new deployment strategy based on the Gaussian distribution. This work analysed the impact of the two Gaussian parameters to the coverage level and network lifetime. The strategies discussed by these works need to divide the network into different regions in terms of the distance to the sink node. In each region, the nodes are deployed uniformly. The data needs to be transmitted region-by-region to the sink node. In these works the energy consumption of the radio transceiver during the data transmission phase was considered as the dominating factor of the network power use. The energy consumed by other working states without data transmission or reception has not been taken into consideration.

3.2 Discussion on Reviewed Schemes

3.2.1 Schemes for Static Sensor Network System

With the unbalanced energy consumption caused by the energy hole problem, the longevity of the static sensor network system will be severely limited by the nodes with a heavy workload that are close to the sink node. Exploiting the schemes on the MAC layer, the energy of the single node can be saved and thus the lifetime of the node will be prolonged. However since nodes with more data to transmit will still die faster, the energy of the whole network will still be seriously wasted. Consequently the system cannot achieve the expected lifetime due to the power constraints of the node.

The data flow control methods on the routing layer focus on the energy efficient data broadcast from sink node to sensor nodes. Therefore these mechanisms are not able to balance the energy consumption of the network. Through controlling the routing topology, the unnecessary waste of the energy use in the routing phase can be decreased. Furthermore by the exploitation of the clustered schemes, the extra power used due to contention can be reduced and with the special design of the size of the cluster, the relatively balanced energy consumption can be achieved. However the effectiveness of the clustered schemes depends on the performance of the data aggregation or data compression. If the amount of data for the cluster head to transmit cannot be decreased, the cluster heads close to the sink node will still die faster and consequently the balanced energy consumption will not be obtained. The in-network processing schemes on the routing layer suffer from the same problem. When the data aggregation or data compression process cannot efficiently reduce the size of data, the energy hole problem will occur. Consequently the mechanisms on routing layer are not capable of effectively achieving the balanced energy consumption of the system.

According to the requirement of the specific application, the in-network processing schemes are able to significantly reduce the amount of data for transmission. In this occasion the amount of data for the nodes close to the sink node to transmit will not dramatically increase according to the increase of the scale of the network; hence the energy hole problem is not serious for the application. However this kind of method cannot be applied for all the applications. For the systems that need to process all the information gathered from the sensor nodes centrally, these schemes cannot be exploited. Leveraging the mobility of the sink node, the balance of the energy consumption can be achieved; but this mechanism will lead to a low data rate and high cost of the construction of the system. The natural solution for balancing the energy consumption in this scenario is to arrange more energy to the nodes near the sink node. Nevertheless due to the intrinsic restriction of energy provision of the single node, it is not practical to issue this method in the system. The applicable resolution for the energy hole problem is the non-uniform node deployment scheme. Since it is possible to design the proper scheduling scheme according to the sensing field coverage requirement and inter-node transmission connection requirement of the application, the redundancy of the node deployment close to the sink node can be exploited to balance the energy consumption of the network. With a proper scheduling scheme, the sensor nodes of the network can be regarded as working in groups to maintain the required level of coverage and connection. Thus the deployment of the redundant nodes will be equivalent to the arrangement of the additional energy to the single node. The existing works on the non-uniform node deployment strategy only consider the energy consumption of the radio transceiver during the data transmission and reception phase. However for some applications such as fire detection, it is necessary to keep the nodes in the working state(inter-changeable with the term active state) with on-board equipments on for monitoring the sensing field continuously. In this circumstance the energy consumed by a node during the working period without transmitting and receiving data is also crucial for the longevity of the node and thus cannot be ignored in the design of the node deployment strategy. *According to the review of the existing works on the non-uniform node deployment strategy, no work has considered the energy consumption of the node in the active mode without data transmission and reception. Hence the design of the existing strategy cannot achieve the proper node deployment for applications* *requiring the continuous monitoring of the sensing field.*

The system using a non-uniform node deployment scheme needs to transmit data region-by-region to the sink node. If the workload of the data transmission cannot be distributed evenly throughout a certain region, nodes in another part of the region with more data to transmit will be out of work earlier than other nodes in the same region. When the data relay node in the region is randomly chosen, the probability for nodes covered by more sensors to be selected as the data relay node will be higher. In this occasion, the workload for these nodes will be heavier and thus these nodes will die faster. Among the reviewed energy balanced routing schemes, only the highest residual energy node selection strategy proposed in [67] is capable of keeping the balance of workload in certain region. Nevertheless in order to obtain the accurate information of the energy of the node, a special piece of equipment [124] is necessary and the complexity and cost of the system will be increased. Even the systems with the energy information available will still suffer from spatially unbalanced energy consumption. When there are multiple nodes with the same residual energy, it is more probably that the sensors covered by more nodes will be selected. In addition as the transmission of the real-time energy information from the potential data relay nodes to the data sender will place a heavy burden on the network, the practical method to disseminate the information is through the cyclic broadcasting. With the decrease of the frequency of energy information synchronisation, the inaccuracy of the information will increase. Since the practical information propagation cycle for different systems might vary, this effect will also have impact on the performance of the routing scheme. *As no energy balanced routing scheme discussed previously has considered the issue of spatially balancing the energy consumption of a system without the energy information of the nodes, the existing schemes are not applicable in the scenario of the unavailability of the energy information of the nodes and a new scheme without the necessity of the energy information of the nodes need to be designed. Furthermore the design of such a method can also be combined with the maximum residual energy selection mechanism to improve the performance of the system.*

3.2.2 Schemes for Mobile Sensor Network System

In mobile sensor network systems, it is important for nodes to conserve energy so that the longevity requirement of the application can be fulfilled. Schemes on the MAC layer can be exploited for energy conservation by adjusting the energy consumption of the radio transceiver. However since the power use of all the components of the sensor is essential for the lifetime of the node, the effectiveness of the mechanisms on the MAC layer is limited.

The data flow control scheme for mobile sensor network systems on the routing layer is designed to control the packet replication during the epidemic routing process. Exploiting this method the energy consumption of nodes can be decreased through the reduction of the amount of data transmitted by each single node. As the decrease of the power consumption through this mechanism is also achieved by reducing the energy use of the radio transceiver, the data flow control scheme still cannot effectively perform the energy conservation for the node in mobile sensor network system.

Due to the ability of turning all the units of a sensor node into energy conservation state, the duty cycle scheduling scheme on the application layer can be leveraged efficiently for the energy conservation of a node in mobile sensor network systems. However since sensors also need to be capable of detecting other nodes to exchange data with for obtaining the proper data delivery rate, the suitable duty cycle scheduling scheme for the system also needs to consider the issue of increasing the rate of node discovery. As a node needs to detect other nodes through transmitting and receiving beacons, a sensor cannot discover the existence of the other node when it is working in the inactive state. As a consequence the probability of the node discovery will be unacceptable when the node is working in extremely low duty cycle. Hence the naive fixed scheduling scheme without the consideration of this problem is not suitable for mobile sensor network systems. Among all the reviewed works, only the scheduling strategy proposed in [113] has specifically considered this issue. *Nevertheless this scheme can only be exploited for the network with periodic motion pattern. Since many motion objects such as wild birds cannot be expected to exhibit periodic gathering behaviours, these motion objects show the motion pattern of non-periodic gathering. For the network with this kind of non-periodic motion pattern, this method is not applicable.*

3.3 New Approach on Non-Uniform Node Deployment

3.3.1 Objective

Due to the intrinsic restriction on the energy provision of a single sensor node, the energy consumption of a node in the active working state without data transmission and reception is still critical for the longevity of the node. For the static sensor network system with the necessity of continuous sensing, a certain number of nodes should be kept in active mode in order to fulfil the coverage and connection requirements. Thus the power use in the active mode cannot be ignored in the design of the non-uniform node deployment strategy. However to the best of our knowledge, no work on the non-uniform node deployment scheme has considered this issue. Hence in this thesis a new approach will be proposed in consideration of this problem.

Since the density of the occurrence of the events will influence the frequency of data transmission, it will consequently have an impact on the energy consumption of the data transmission. Additionally, the spatial density of the events in the sensing field will also affect the amount of the data that needs to be transmitted and thus will impact the power use of the data delivery. If the spatial density or the temporal density of the occurrence of the events is high, the energy consumption in data transmission will be the dominant factor of the all the power use of the system. In this scenario, the energy hole problem will be serious. As a consequence the network needs to be deployed highly non-uniformly. On the other hand when the density of the occurrence of the events is low, the energy consumed during data transmission will not be the major factor for the power use of the system and the impact of the energy hole problem on the longevity of the network will be minor. In this circumstance it is not necessary for the network to be deployed very non-uniformly. The objective of the new approach on the non-uniform node deployment strategy of this thesis is to investigate the impact of the spatial and temporal density of the occurrence of events to the deployment of the network in terms of the lifetime requirement of the application. Since many sensor network systems use a deterministic requirement of the network lifetime measured by time units, it is practical to assume that the network lifetime requirement is predetermined by the application in this thesis. Through the result of the analysis a new non-uniform node deployment scheme will be proposed.

3.3.2 Methodology

As the occurrences of many natural events such as rainfall [125] can be modelled as Poisson processes spatially and temporally, the spatial and temporal distributions of the occurrences of events can be leveraged to propose the analytical model for non-uniform node deployment scheme. Through regarding the spatial distribution of the occurrence of the events as a Poisson process, a statistical model of the impact of the spatial density of events on the amount of data for the network to transmit can be derived. Since the temporal distribution of the events can also be generalised as a Poisson process, the theoretical model of the effect of the frequency of the occurrence of the events can be obtained. Exploiting these two models, the node deployment density of each region of the sensing field for balancing the energy consumption of the network can be achieved according to the lifetime requirement of the application. The numerical results of the analytical model will be calculated through MATLAB. In order to further validate the strategy, the network simulation will also be issued through the Java based network simulator J-SIM [126–128].

3.4 New Approach on Energy Balanced Routing

3.4.1 Objective

Without the aid of the residual energy information, the random node selection routing will lead to the spatially unbalanced energy consumption of the sensor network system using non-uniform node deployment scheme. This effect is due to the uneven transmission coverage for nodes of certain region. Since nodes near the outer boundary of the region are closer to the sensors in the adjacent region, these nodes will be within the transmission range of more sensors. Hence the probability for these nodes to be selected as the relay nodes will be high and thus the energy consumption of the region will be skewed. Even with the information of the residual energy, the energy consumption will still be unbalanced among the nodes with the same residual energy level, thus the maximum residual energy node selection scheme will also suffer slightly from the spatially unbalanced energy consumption problem. Furthermore due to the variable practical residual energy information dissemination frequency, the accuracy of the residual energy information will also influence the balance of the energy consumption of the network.

Aiming at solving these issues, the analysis on the issue of balancing the energy consumption spatially during the data routing process will be investigated in this thesis. Through the analysis, the constraint of the node selection region for each sensor with data to transmit can be determined. Based on the analytical result the region constraint node selection scheme without the need of the residual energy information will be proposed. Further combining the region constraint scheme and the maximum residual energy scheme, the hybrid scheme will also be presented to improve the performance of the maximum residual energy node selection scheme.

3.4.2 Methodology

Since the spatial distribution of nodes in each region can be regarded as a Poisson process, the theory of the stochastic geometry [129] can be applied to the analysis. Exploiting the theorem presented in [130], the statistical model for the energy consumption of each region under random node selection strategy can be obtained. With the modification on this analytical model, the theoretical model for the region constraint node selection strategy can be derived. The results of the analytical models can be obtained through MATLAB and the results of the simulations can be achieved through network simulation experiments leveraging J-SIM. By comparing the two sets of results the correctness of the analytical models will be proved. The performance of both the region constraint scheme and the hybrid scheme will also be tested through simulations issued by J-SIM.

3.5 New Approach on Duty Cycle Scheduling

3.5.1 Objective

In order to increase the data delivery rate, nodes in mobile sensor network systems need to exchange data with each other. The reviewed works on the data flow control schemes for mobile sensor network systems all focused on the low energy cost data replication strategy to achieve the proper data delivery rate with reduced power consumption. Since nodes need to discover each other through transmission and reception of beacons, a node discovery can only be performed in the active mode. However in order to fulfil the lifetime requirement of applications, nodes need to work in low duty cycle to conserve energy. In this occasion, the probability for nodes to find each other under fixed duty cycle scheduling will be extremely low. Therefore a proper duty cycle scheduling scheme that enables the effective node detection is a necessity for the mobile sensor network. Though in [113] a mechanism for the network with periodic motion pattern was proposed, the strategy for the network with non-periodic motion pattern still needs to be examined.

The most efficient method for a duty cycle scheduling is to adjust the duty cycle according to the number of neighbouring nodes. Nevertheless working in low duty cycle nodes cannot properly detect the change the number of the neighbouring nodes. Thus it is necessary to exploit some other pattern of the network with non-periodic motion pattern. It has been revealed by previous research on the motions of animals that the movements of these objects all follow the pattern of forming flocks [131–133]. It can also be noted that humans will occasionally gather together to form an area with high density of people. During the flocking period, the number of the neighbouring nodes for a certain node is relatively stable, hence in this period it is possible for the node to discover the existence of a flock even when the work cycle is low. Consequently nodes will be able to adjust the duty cycle according to the size of the flock for effectively performing node discovery. The objective of the new approach on the duty cycle scheduling for mobile sensor network systems in this thesis is to design a flock detection based duty cycle scheduling scheme for nodes to perform node discovery efficiently as well as conserving energy, in applications with mobile nodes following the pattern of forming flocks.

3.5.2 Methodology

Through configuring the duty cycle of a single node as a temporal Poisson process by generating random numbers following exponential distribution, the duty cycles of several nodes combined together can also be regarded as a temporal Poisson process. Therefore the model for the estimation of the number of the neighbouring nodes can be derived through the detected beacon arrival rate in terms of the Poisson process. Based on the neighbour node number estimation, the flock detection method can be established. By a flock detection method, a duty cycle adjustment scheme can be constructed according to the size of the flock. The configuration of the parameters for the scheme can be determined through the analysis and simulations. In order to measure the performance of the mechanism, the simulation experiments will be performed. All the numerical results of the analysis will be calculated by MATLAB and the simulations will be carried out leveraging J-SIM.

Chapter 4: Non-Uniform Node Deployment

4.1 Introduction

As discussed in Chapter 3, one practical method for tackling the energy hole problem is the non-uniform node deployment scheme. The fundamental approach of this scheme is to deploy more nodes in the area with the higher energy requirements near the sink node, thus balancing the lifetimes of the different areas of the sensing field. However existing non-uniform node deployment strategies have only considered the energy consumption of the data transmission and reception. For the systems that require continuous sensing of the field and only issue data transmission at the occurrence of the specific events they are monitoring for, this kind of strategy will lead to an unnecessarily high deployment density in the regions near the sink node. This problem can be illustrated with an example. Suppose that it is necessary to keep three nodes in active mode within the transmission range of the sink node. Outside this region, there are nine nodes performing the sensing task. When the energy consumption of the data transmission and reception is the only factor considered, 12 nodes should be deployed in the area within the transmission range of the sink. However, if the energy consumption for one node to transmit its own data is only 10% of the total energy consumed by the node in the whole lifetime, the lifetime of the three nodes within the transmission range of the sink node will be shortened by 30%. Therefore statistically only an extra 30% more energy is necessary for the direct transmission region of the sink. In order to fulfil the requirement of the *coverage of the sensing field*, six nodes needed to be deployed in this region. It is noted that the energy hole problem is directly caused by the unbalanced work load of the reverse-multicast data transmission. Thus if the nodes do not need to perform data transmission, the energy hole problem will not occur. With the increase of the amount of essential data transmission of the network, the energy consumption in the data transmission will rise and the severity of the energy hole problem will consequently increase. To solve this problem, the network needs to be deployed more non-uniformly. For sensor network systems in charge of event detection, the spatial and temporal distribution of the events will determine the amount of data transmission necessary for the network. Consequently, it is essential to consider the energy consumption of the node in active mode without data transmission and reception in the design of the non-uniform node deployment scheme for event detection sensor network systems. Furthermore, for the construction of the node deployment strategy it is also necessary to take into account the spatial and temporal distribution of the events.

In this chapter, a novel non-uniform node deployment strategy for static sensor networks that takes into consideration the energy consumption of a node in an active working state *without the data transmission and reception* will be presented. By investigating the level of unbalanced energy consumption in the network according to the spatial and temporal distributions of events, an estimation of the network lifetime in terms of the deployment density of each region can be derived. Based on this result, a deployment strategy that is in accordance with the network lifetime requirement of the application can be obtained.

The chapter is organised as follows. The system model is presented in Section 4.2. Based on the network model, a mathematical model that determines the amount of data transmission will be proposed in Section 4.3. Exploiting the result of the amount of data transmission derived by this model, the lifetime estimation method will be presented in the following section, Section 4.4. This section also describes the non-uniform node deployment strategy that leverages the network lifetime estimation. The arrangement of the region width required in order to maintain the connectivity of the network will be analysed in Section 4.5. To evaluate the feasibility of the strategy shown in this chapter, a numerical and experimental study is proposed in Section 4.6. The last section will conclude this chapter.

The main contributions of this chapter are: the volume of the amount of data transmission of the network is derived and then analysed, taking into consideration the spatial distribution of the events; a model that estimates the lifetime of a network, taking into account both energy consumptions for active mode and transmitting/receiving modes is presented, based on the results of the amount of data transmission of the network; and a non-uniform node deployment strategy is presented, leveraging the derived network lifetime estimation model.

4.2 System Model

The desired sensing field is assumed to be a circle region with radius r_D, i.e. the area of the network is πr_D^2. The sink node is located at the centre of the network. The sensing nodes in the network are assumed to be homogenous with sensing range r_s (shown in Figure 4-2) and communication range r_t. In other words, each sensor can sense each event that occurs within its sensing field, which is a circular region with the area of πr_s^2. A node can communicate with all of the nodes in the circular region of πr_t^2. Within the distance of r_t from the sink node, nodes can communicate directly with the sink node. Out of this region nodes transmit data to the sink node through multi-hop paths. Sensing nodes originate and forward a unit of information of m bits about an event they sense to the sink. Since this chapter focuses on a large scale sensor network, the radius of the network is assumed to be far larger than the transmission range ($r_D \gg r_t$). The sink node is assumed to be a super node without energy constraints. In addition, the transmission of a node is assumed to be error free with the speed of a constant value γ bit/s.

Nodes in the network are assumed to be scheduled by a proper scheduling scheme, so that the density of active nodes can be maintained to be a constant value λ_n for a proper coverage degree (at least full coverage) [109], which can fulfil the application's coverage requirement. In this way, all nodes can work alternatively to conserve energy, which leads to the prolongation of network lifetime.

As the occurrences of many natural events such as rainfall [125] can be modelled as Poisson processes spatially and temporally, the occurrences of events are regarded as two independent Poisson processes on the spatial dimension and the temporal dimension. The densities of these two processes are λ_s and λ_t respectively.

The network is divided into several circular regions which have the same centre, which is the sink node. Except for the first region, the widths of all the other regions are the same with the value of r'_t ($r'_t \leq r_t$), which can ensure the communication between two nodes in adjacent regions. The first region is composed of nodes that can communicate with the sink directly, therefore it has the width of r_t. The network division model used in this chapter is shown in Figure 4-1. In this chapter the adjacent region of a region closer to the centre of the network is called the inner-region of the region. The adjacent region of a region further from the centre of the network than the region is called the outer-region of the region. For example the inner-region of Region 2 is Region 1 and the outer-region of Region 2 is Region 3. The boundary of a region closer to the centre of the network field is called the inner-boundary of the region and the other boundary further away from the centre of the network is called the outer-boundary of the region. Since nodes in the inner-most region can communicate directly with the sink node, the width for this region is the transmission range r_t. The nodes in other regions need to transmit their information to the sink node through relay nodes in the next inner-circular region. Each node has the same initial energy of e_{ini}. The energy consumption model for

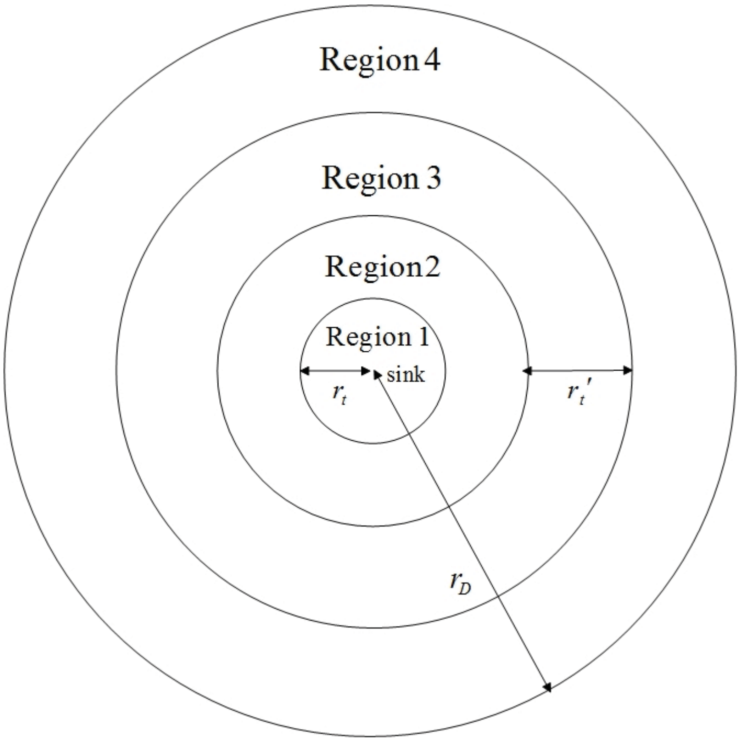

Figure 4-1: The division of the network

radio transmission is assumed to be the first-order radio model as follows [70]

$$e_{tx} = e_{elec} + e_{amp}d^{\beta} \tag{4-1}$$

This model shows the energy consumption for transmitting one bit. The parameter e_{elec} is the energy consumed by activating the circuit of radio transceiver and the e_{amp} is the energy used by the transceiver amplifier for communication. d is the distance for transmission. The energy for receiving one bit is just the energy consumed by the transceiver circuit. Thus we have

$$e_{recv} = e_{elec} \tag{4-2}$$

Energy consumed per unit time for a node in the active state is assumed to be a constant value e_{act}. The cost for a node in sleeping mode is neglected.

4.3 Volume of Data Transmission

Nodes in the network need to transmit data via multiple-hop paths. In this scenario, nodes in the inner-region of the network need to relay the packets that come from all of the nodes from the outer-regions. Thus in order to obtain the relationship between lifetime and node deployment density, the amount of data transmitted by each region needs to be calculated first. In this section the amount of data transmission is derived by considering the coverage effects, the density of the active nodes and the density of events on spatial dimension.

In order to calculate the amount of data transmission, it is necessary to examine the impacts of events on the amount of data generated by a certain region. As revealed in Figure 4-2, each region will be affected by events from three different influences. Events in iner-inf Region K of Region K will lead to the data generation of nodes in both Region K and Region $K+1$. For example the event $e2$ will influence each sensor node in the area A_{iinf} of Region $K+1$ to generate a packet. It will also cause data generation from the sensor nodes in Region K within its impact circular region with radius r_s. Similarly the occurrence of an event such as $e1$ will influence sensor nodes in the region A_{oinf} within Region $K-1$. Events happening in the rest areas of Region K like $e3$ will only cause the nodes in Region K to generate data packets. Utilising the density of the active sensor nodes, the number of nodes influenced by a certain event can be calculated according to the area of the impact of the event. Furthermore the total number of data packets generated by each type of the influence can be achieved through the spatial density of the events. The first three subsections of this section will determine the data generation amount of the three types of influence respectively. Based on these results the data generation amount of each region will be derived in the last part of this section.

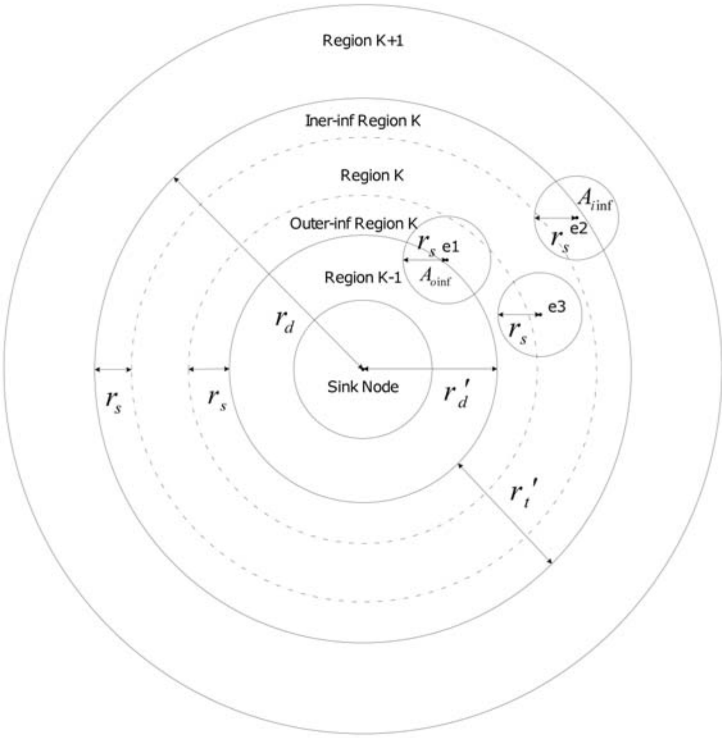

Figure 4-2: The Influence of Events

4.3.1 The In-Region Data Origination Amount

The radius of the inner-boundary for a certain region is denoted as r'_d. The occurrence of events influencing only the nodes inside this region are in the area started from the circle having the radius $r'_d + r_s$ with the width $r'_t - r_s$. The total number of packets that are generated by the occurrences of events in this area, M_{in}, can be calculated as

$$M_{in} = \int_0^{r'_t - 2r_s} N_{in} \lambda_s 2\pi (r'_d + r_s + r'_s) dr'_s \tag{4-3}$$

where N_{in} is the number of nodes influenced by the whole coverage area of the occurrence of a single event r'_s away from the circle with the radius $r'_d + r_s$. It can be derived through the density of active nodes λ_n as

$$N_{in} = \pi r_s^2 \lambda_n \tag{4-4}$$

For the convenience of the derivations in section 4.3.4, we define the function

$$M_{in}(r'_d, r, \alpha) = \int_0^{\alpha} N_{in}\lambda_s 2\pi(r'_d + r + r'_s)dr'_s \tag{4-5}$$

4.3.2 Outer-influence

Considering the coverage effects, the occurrence of events out-side the outer-boundary of a region might cause the origination of information in this region. It can be noted that only the events in a certain region with the distance in the range $(0, r_s)$ from the inner-boundary of the region can influence the inner region. For example in Figure 4-2, only the events occurring within the area formed by the two boundaries with radius r'_d and $r'_d + r_s$ respectively in Region K can influence the sensor nodes in Region $K-1$. Thus the total number of packets that generated by this outer-influence effect can be calculated as

$$M_{oinf} = \int_0^{r_s} N_{oinf}\lambda_s 2\pi(r_d + r'_s)dr'_s \tag{4-6}$$

where r_d is the radius of the outer-boundary of certain region. In the formula above, the number of nodes that are influenced by a single event, denoted by N_{oinf}, can be obtained as

$$N_{oinf} = \lambda_n A_{oinf} \tag{4-7}$$

where A_{oinf} is the area of the region influenced by the event. For the convenience of the derivations in Section 4.3.4, the following function is defined

$$\Delta M_{oinf}(r_d, \alpha) = \int_0^{\alpha} (N_{in} - N_{oinf})\lambda_s 2\pi(r_d + r'_s)dr'_s \tag{4-8}$$

4.3.3 Inner-influence

Similar to the outer-influence effects, the occurrences of events in the inner-region of one region can also influence the data origination of the region. Suppose the radius of the outer-boundary of the inner-region of a certain region is r_d. Events occurring in the area bounded by the two boundaries with radius $r_d - r_s$ and r_d will have this effect. For example in Figure 4-2, events in the area bounded by the boundaries with radius $r_d - r_s$ and r_d respectively in Region K will influence the nodes in Region $K+1$. The total number of packets that generated by this effect can be calculated as

$$M_{iinf} = \int_0^{r_s} N_{iinf} \lambda_s 2\pi (r_i' + r_s') dr_s' \tag{4-9}$$

where $r_i' = r_d - r_s$ and N_{iinf} is the number of nodes that are affected by one event, occurring r_s' away from the circle with the radius of r_i'. N_{iinf} can be derived as

$$N_{iinf} = \lambda_n A_{iinf} \tag{4-10}$$

where A_{iinf} is the area that the event covers the outside outer-region. For the convenience of the derivations in Section 4.3.4, we define the two functions

$$M_{iinf}(r_d, r_i', \alpha) = \int_0^{\alpha} N_{iinf} \lambda_s 2\pi (r_i' + r_s') dr_s' \tag{4-11}$$

$$\Delta M_{iinf}(r_d, r_i', \alpha) = \int_0^{\alpha} \Delta N \lambda_s 2\pi (r_i' + r_s') dr_s' \tag{4-12}$$

where $\Delta N = N_{in} - N_{iinf}$.

4.3.4 Region Data Transmission Amount

The amount of data that needs to be transmitted by each region can be calculated using the results presented in previous sections. Suppose there are G regions in the sensing field. Region G is the region farthest from the centre of the network. Sensor nodes in Region i need to transmit all of the data they have generated and the data that originated in its outer-regions. Thus the packets of the data transmitted by the nodes in Region i include those generated solely inside the area formed by the inner-boundary of Region i and the outer-boundary of Region G, m_{in}. Additionally, except for the first region, the inner-influence of events in Region $i-1$ on Region i, m_{iinf}, also needs to be considered. Due to the inner-influence effect to the area outside of the network near the outer-boundary with the radius r_D on Region G and outer-influence effect to the Region $i-1$ close to inner-boundary of Region i, the packets generated by the two effects need to be excluded. The exclusions are performed by two variables Δm_{oinf} and Δm_{iinf}. r_{di}' is denoted as the radius of the inner-boundary of Region i and r_{di} as the radius of the outer-boundary of Region i.

The total number of packets that need to be transmitted by Region i $(1 < i \leq G)$, M_i , is

$$M_i = m_{in} + m_{iinf} + \Delta m_{iinf} + \Delta m_{oinf} \tag{4-13}$$

where

$$m_{in} = M_{in}(r'_{di}, r_s, r_D - r_s) \tag{4-14}$$

and

$$m_{iinf} = M_{iinf}(r_{di-1}, r_{di-1} - r_s, r_s) \tag{4-15}$$

and

$$\Delta m_{iinf} = \Delta M_{iinf}(r_{dG}, r_{dG} - r_s, r_s) \tag{4-16}$$

and

$$\Delta m_{oinf} = \Delta M_{oinf}(r_{di-1}, r_s) \tag{4-17}$$

As Region 1 does not have an inner-region, the number of the packets to be transmitted in Region 1 can be expressed by

$$M_1 = m_{in1} + \Delta m_{iinf} \tag{4-18}$$

where

$$m_{in1} = M_{in}(0, 0, r_D - r_s) \tag{4-19}$$

The amount of data for region i to transmit, D_i, is

$$D_i = M_i \cdot m, \ i = 1, 2, \cdots G \tag{4-20}$$

where M_i is defined in (4-13) and m is the number of bits for a packet.

4.4 Deployment Strategy

Using the results of the amount of data transmission for each region, obtained in the previous section, the network lifetime for each region can be estimated, based on the density of events on the temporal-dimension. The estimation is achieved according to the energy use of all the sensor nodes of a region throughout the time and the total energy available for the nodes. This result will be achieved in this section. Exploiting the estimation, a measure will then be defined to analyse the energy waste for the uniform node distribution strategy. There are different definitions for the lifetime of sensor network [109, 122]. In this chapter the network lifetime is defined as the period of time during which the network can keep the certain density of sensor nodes required by the application. Utilising the lifetime analysis, the non-uniform node deployment strategy will be proposed at the end of this section.

4.4.1 Network Lifetime Estimation

If the density of events occurrences on the temporal dimension is λ_t, the average waiting time for the occurrence of events is $1/\lambda_t$. Except for the first waiting period, the duration $1/\lambda_t$ can be divided into two durations: transmission duration and active duration, as shown in Figure 4-3. In the active duration, the onboard equipments of sensor nodes will be turned on to monitor the sensing field without data transmission. In the transmission duration, sensor nodes will perform data transmission.

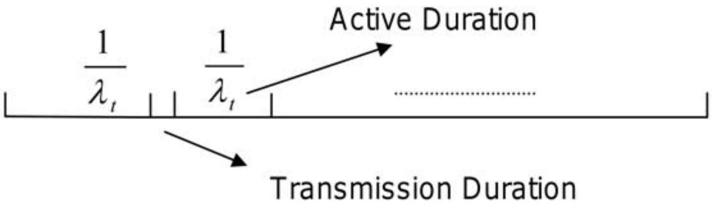

Figure 4-3: The Working Sequence of a Certain Region

The average energy consumption in the waiting period for the first occurrence of events is denoted as e_{w1}. e_{trans} and e_{active} are the energy consumptions for the transmitting duration and active duration respectively. The energy balancing equation for Region j can be derived as follows

$$e_{all} = e_{w1} + k_j \left(e_{trans} + e_{active}\right) \tag{4-21}$$

e_{w1} can be obtained by the density of active nodes λ_n and the energy consumed per unit time for a node in the active state e_{act} as

$$e_{w1} = \frac{1}{\lambda_t} e_{act} A_j \lambda_n \tag{4-22}$$

where A_j is the area of Region j. Since nodes in Region j need to receive the data from nodes in Region $j+1$ and transmit all the data including the data they receive and the data generated by themselves, the derivation of e_{trans} can be obtained according to (4-20)

$$e_{trans} = D_j \cdot e_{tx} + D_{j+1} e_{recv} \tag{4-23}$$

Also e_{active} can be calculated by (4-21) as

$$e_{active} = e_{act} A_j \lambda_n \left(\frac{1}{\lambda_t} - \frac{D_j + D_{j+1}}{\gamma A_j \lambda_n}\right) \tag{4-24}$$

Let ν_j stand for the deployment node density for Region j. The e_{all} can be obtained as

$$e_{all} = \nu_j A_j e_{ini} \tag{4-25}$$

Through (4-21) the parameter k_j can be resolved as

$$k_j = \frac{e_{all} - e_{w1}}{e_{trans} + e_{active}} \tag{4-26}$$

The estimated lifetime for the Region j, T_j, can be derived as

$$T_j = (k_j + 1)\frac{1}{\lambda_t}, \; j = 1, 2, \cdots G \tag{4-27}$$

4.4.2 Lifetime Waste Ratio

In this section, lifetime waste ratio is defined to estimate the energy waste for the uniform node deployment strategy. For the uniform node deployment strategy, it is assumed that the node density is a constant value ν for the whole network. In this situation the network lifetime is dominated by the first region. Also since the nodes in the G_{th} region do not need to relay data generated by nodes in other regions, the G_{th} region is the region with the longest lifetime. Hence the lifetime waste ratio can be defined as follows

$$\Psi = \frac{T_G - T_1}{T_G} \tag{4-28}$$

Exploiting (4-27) it can be further derived as

$$\begin{aligned} \Psi &= \frac{(k_G + 1)/\lambda_t - (k_1 + 1)/\lambda_t}{(k_G + 1)/\lambda_t} \\ &= \frac{k_G - k_1}{k_G + 1} \end{aligned} \tag{4-29}$$

4.4.3 Deployment Density for Non-uniform Node Deployment

Using the analysis from the previous sections, the non-uniform node deployment strategy can be designed, according to the lifetime requirement of the application. Each region can then be deployed according to the estimated node density. Given a certain lifetime requirement T_{req}, the network density for each region can be calculated through the lifetime estimation. For fulfilling the lifetime requirement of T_{req}, the node deployment density for Region j can be derived in terms of (4-27) as

$$\nu_j = \frac{(T_{req}\lambda_t - 1)\xi + e_{w1}}{A_j e_{ini}}, \ j = 1, 2, \cdots G \tag{4-30}$$

where ξ is

$$\xi = e_{trans} + e_{active} \tag{4-31}$$

The detail of the derivation is presented in Appendix A.

4.5 The Arrangement of Region Width

The key assumption for a non-uniform deployment mechanism, as proposed in this chapter, is that multi-hop data delivery can be done in a region-by-region manner. However if the width of a region is set too large, the area covered by the transmission region of a node far away from the outer-boundary of the inner-region will be too small to ensure the existence of at least one node in the area. As a consequence, it is difficult to fulfil the assumption of region-by-region routing. In this section, the problem of adjusting the region width will be investigated.

When the density of active nodes in a network is scheduled to be λ_n, the probability for a node in certain region to have at least one neighbour node in its inner region is defined as the route-able probability P_γ. Since the distribution of active nodes is assumed to be a Poisson distribution, the route-able probability can be derived as

$$P_\gamma = 1 - e^{-\lambda_n A_c} \tag{4-32}$$

where A_c is the area formed by the intersection of the transmission area of the node and the next inner-region. It is clear that the probability increases with the enlargement of A_c. Thus, if a node at the outer-boundary of a region has a large enough value of P_γ, all the other nodes in the same region will have a larger router-able probability. r_Δ is defined as the ratio of the transmission radius and the region width. It is

$$r_\Delta = \frac{r_t}{r_t'} \tag{4-33}$$

The value of A_c is able to be calculated through r_Δ. Consequently by adjusting this ratio, the appropriate route-able probability can be obtained. Figure 4-4 shows the numerical result for the route-able probability P_γ as a function of the ratio r_Δ for three different regions, under the condition of $r_t = 40$. This result reveals that when r_Δ is over 1.3 the reasonable P_γ can be obtained, given $r_t = 40$. Figure 4-5 shows the numerical results of Region 2 for P_γ as a function of r'_t under different values of r_Δ. The results indicate that with the increase of r_Δ the region width required for achieving a proper route-able probability decreases and the required transmission range r_t required also decreases accordingly. Using these results the proper region width for the network can be set according to the transmission range of the sensor node.

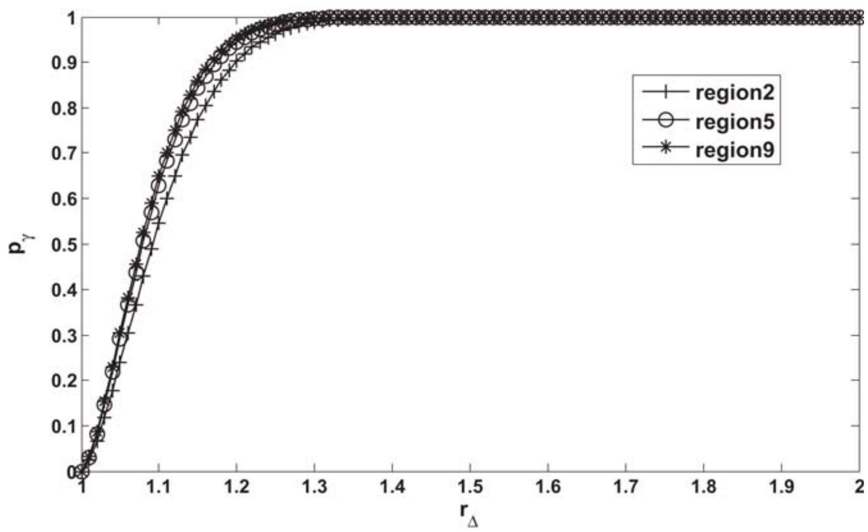

Figure 4-4: r_Δ versus P_γ

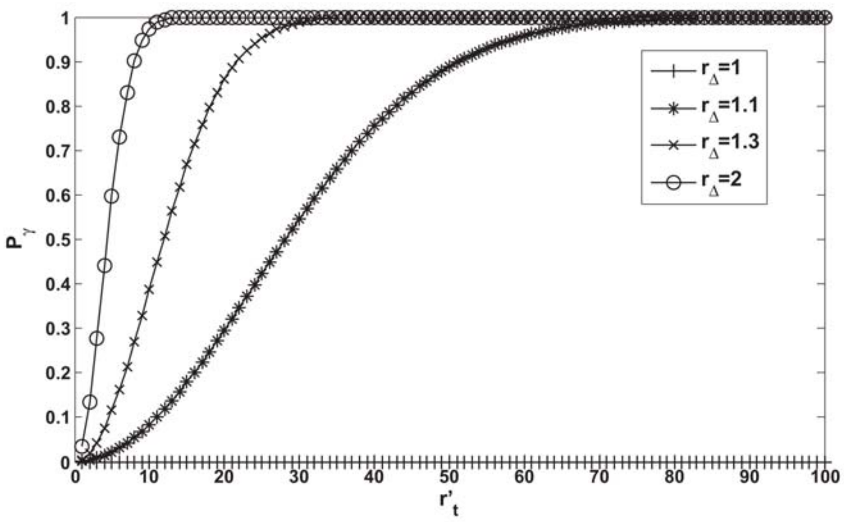

Figure 4-5: r'_t versus P_γ

4.6 Experimental Results

In this section both numerical results based on the proposed mathematical model and experimental results, obtained through simulation, are presented in order to evaluate the feasibility of the mathematical model, presented in the previous sections.

Firstly, the estimated lifetime of each region will be calculated through numerical results according to different spatial and temporal densities λ_s and λ_n of the events. The simulation results will then be provided to further illustrate the performance of the mathematical model, by comparing the results achieved from simulations with those of the mathematical model, under certain conditions.

In order to demonstrate the impacts of the spatial and temporal distributions of the events on the unbalanced energy consumption degree of the network, the lifetime waste ratio will also be evaluated, through the calculation of the mathematical model. Again simulation results will be provided to validate the theoretical results.

At the end of this section, the simulation results for the non-uniform node deployment strategy, provided in this chapter, will be presented, thus demonstrating the feasibility of the strategy.

The simulations are performed by the Java based network simulator J-SIM. It is extended to support node deployment and simulation time evaluation for issuing the experiments. The simulation model follows the system model presented in Section 4.2. In the experiments each node selects the neighbouring node with the largest residual energy in the next inner-region as the data relay node.

4.6.1 Parameter Settings

The parameter settings for the experiments are listed in Table 4-1. The sensor hardware parameters, such as energy consumption parameters, transmission speed parameters and transmission range parameters are selected similar to the Motes [27,28]. The topology of the network is formed by region-by-region routing. Region width is set to be $30m$ for achieving a reasonable router-able probability. The total number of regions of the network is set to 10.

Table 4-1: Parameter Settings

Parameter Name	Value
e_{ini}	$2J$
e_{act}	$1.25 \times 10^{-5} J/s$
e_{elec}	$5.0 \times 10^{-11} J/bit$
e_{amp}	$1.0 \times 10^{-11} J/bit$
β	2
γ	$250kbit/s$
r_D	$300m$
r_t	$40m$
r'_t	$30m$
m	$640bits$

4.6.2 Lifetime of Regions

The numerical results for the estimation of lifetime of different regions, in terms of temporal density are shown from Figure 4-6 to Figure 4-9. From the results, it can be seen that with the decrease of the temporal density of events, the lifetime of each region increases accordingly and the level of unbalanced consumption of network falls, as the temporal density decreases. When the density is very low, the energy usage is nearly balanced, even for the uniform distribution, while in the situation of high event temporal density, the energy consumption is highly unbalanced. The results also reveal that the lifetime of each region is approximately proportional to the network node density ν. The numerical results indicate that the level of unbalanced energy consumption depends on whether the energy consumption of the data transmission is the dominant factor of energy utilization of the network. If more energy is used for data transmission, the energy consumption of the network will be more unbalanced. Furthermore the lifetime decreases when the spatial density of events increases. Figure 4-10 and 4-11 show the comparison between the estimated lifetime and simulation results for lifetime of two different regions. The results show that the numerical results match the simulation results with only minor distortions. The largest difference in Figure 4-10 is 1.676% and the largest difference in Figure 4-11 is 0.322%. This shows that the estimation scheme proposed in this chapter is accurate enough.

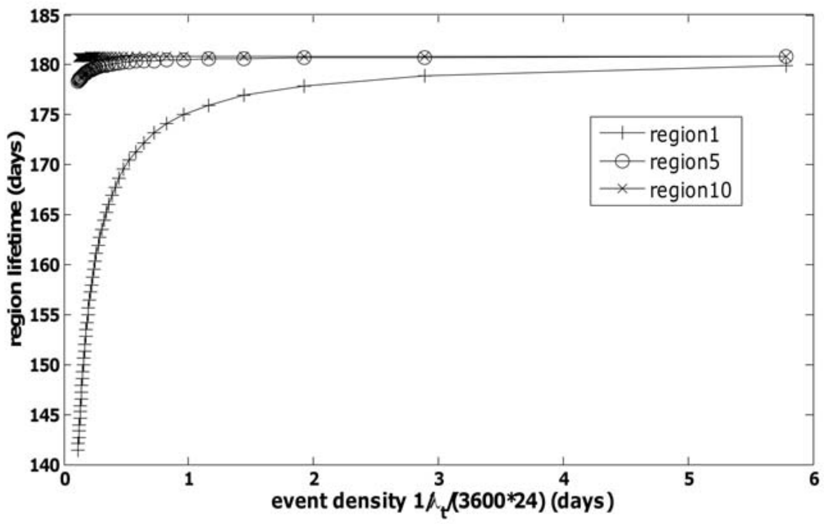

Figure 4-6: Lifetime of Regions by λ_t ($\nu = 2,\ \lambda_n = 0.02\ and\ \lambda_s = 0.2$)

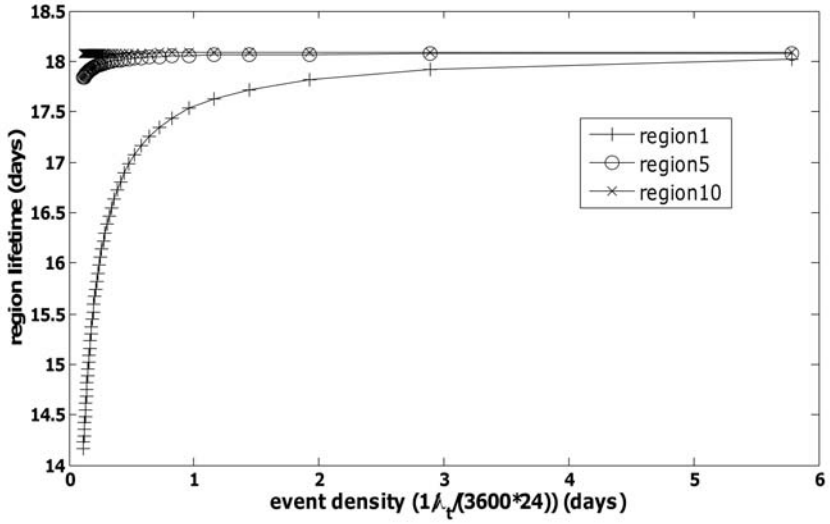

Figure 4-7: Lifetime of Regions by λ_t ($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_s = 0.2$)

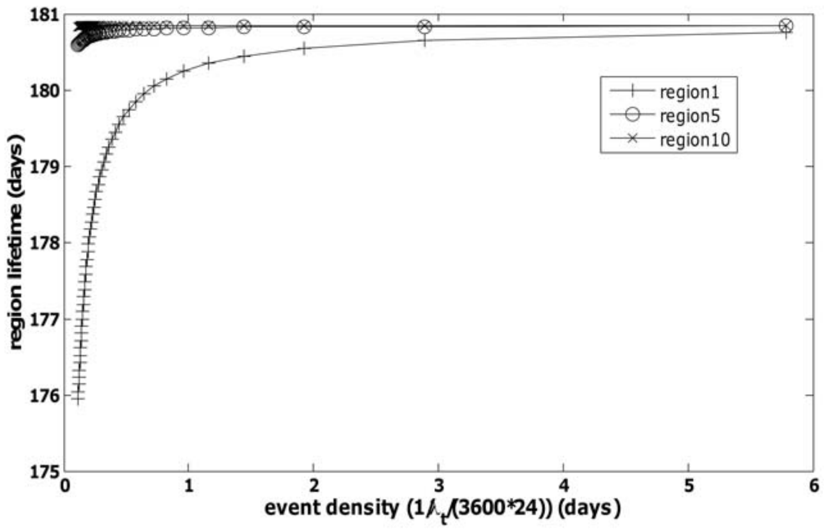

Figure 4-8: Lifetime of Regions by λ_t ($\nu = 2,\ \lambda_n = 0.02\ and\ \lambda_s = 0.02$)

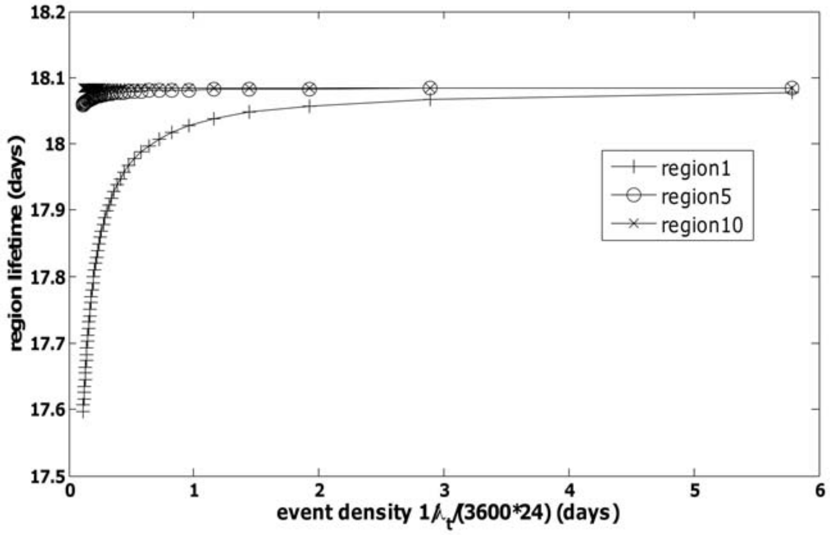

Figure 4-9: Lifetime of Regions by λ_t ($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_s = 0.02$)

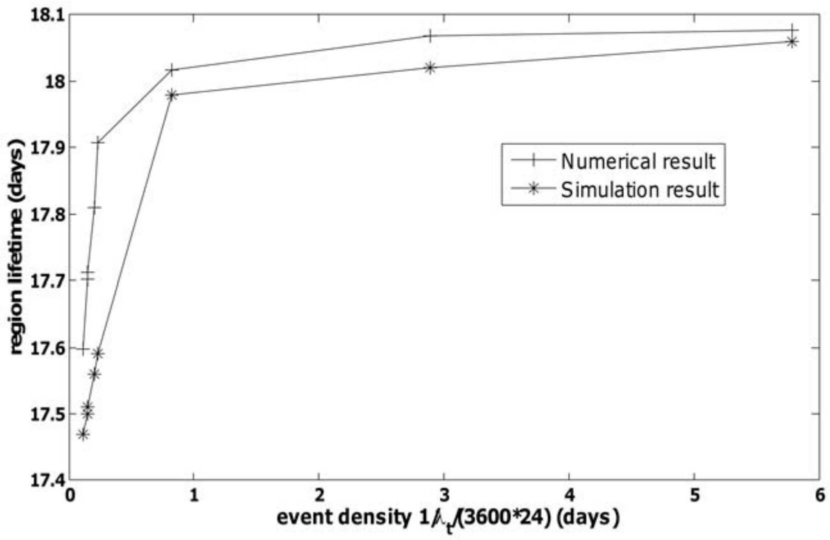

Figure 4-10: Lifetime of Region 1 by λ_t ($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_s = 0.02$)

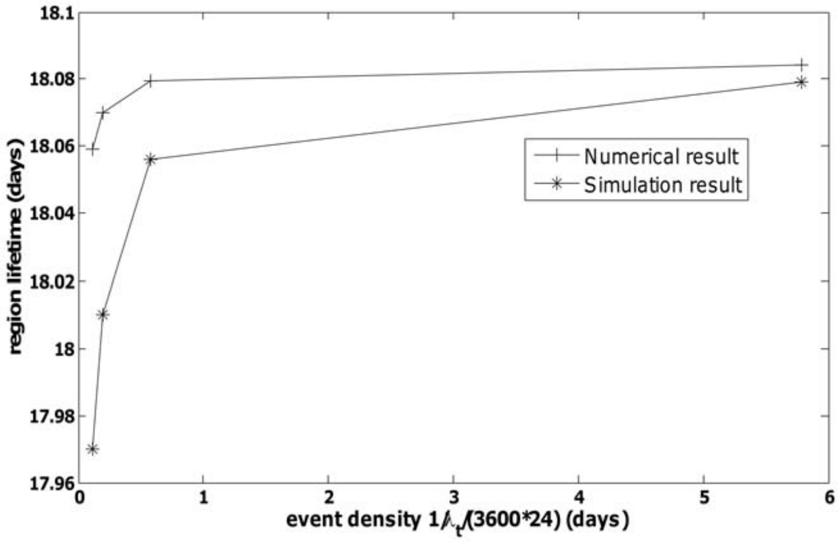

Figure 4-11: Lifetime of Region 5 by λ_t ($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_s = 0.02$)

The results for estimated lifetime according to the spatial density of events are displayed in Figures 4-12 to 4-15. The results imply that the network lifetime of each region is negatively proportional to the spatial density of events. Similar to the previous results, it can also be seen that lifetime of each region is approximately proportional to the sensor node density ν. Since nodes in Region 1 need to transmit the most amount of data, the lifetime of Region 1 is the shortest among all the regions. Figures 4-16 and 4-17 show the simulation results in comparison with the numerical results for the lifetime of two regions in terms of the spatial density of events. The largest differnece in Figure 4-16 is 2.0702% and the largest difference in Figure 4-17 is 0.5534%.The results also indicate the accuracy of the lifetime estimation proposed in this chapter.

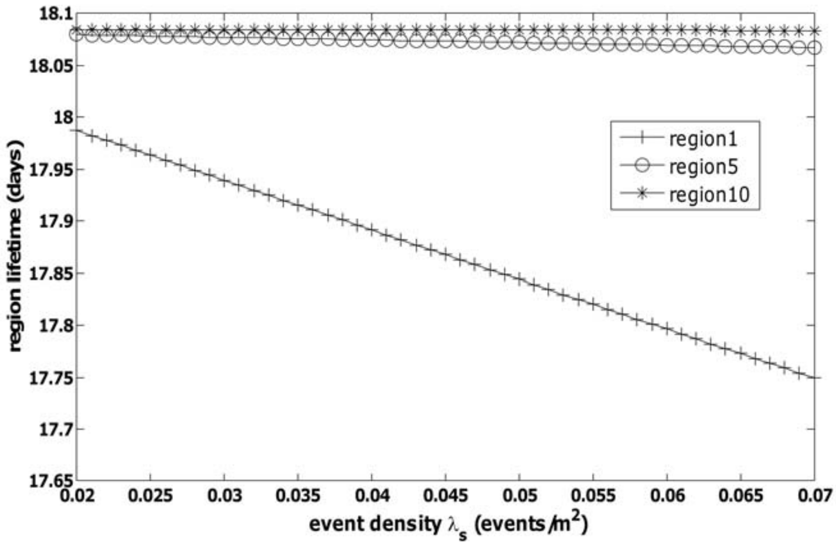

Figure 4-12: Lifetime of Regions by λ_s ($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_t = 2 \times 10^{-5}$)

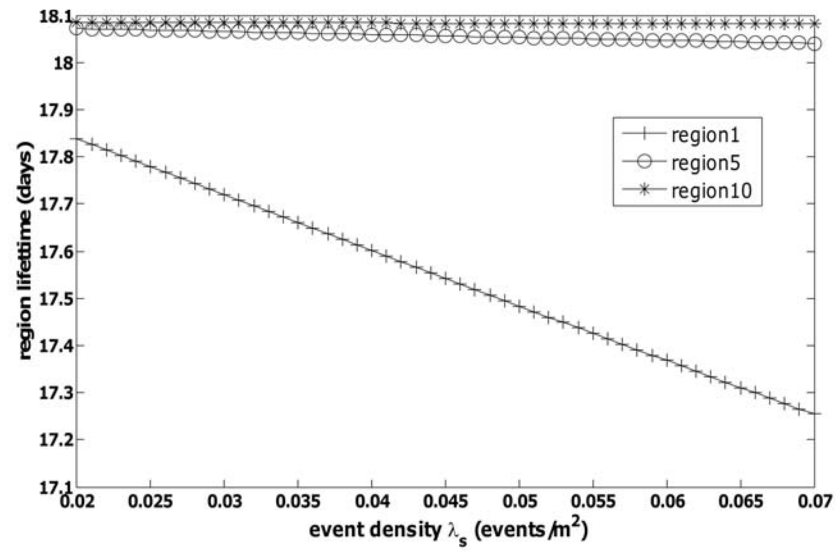

Figure 4-13: Lifetime of Regions by λ_s ($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_t = 5 \times 10^{-5}$)

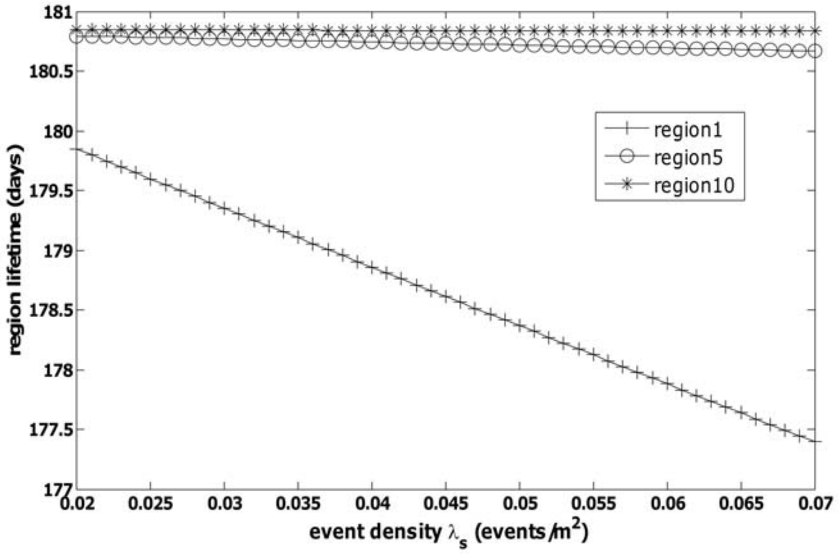

Figure 4-14: Lifetime of Regions by λ_s ($\nu = 2,\ \lambda_n = 0.02\ and\ \lambda_t = 2 \times 10^{-5}$)

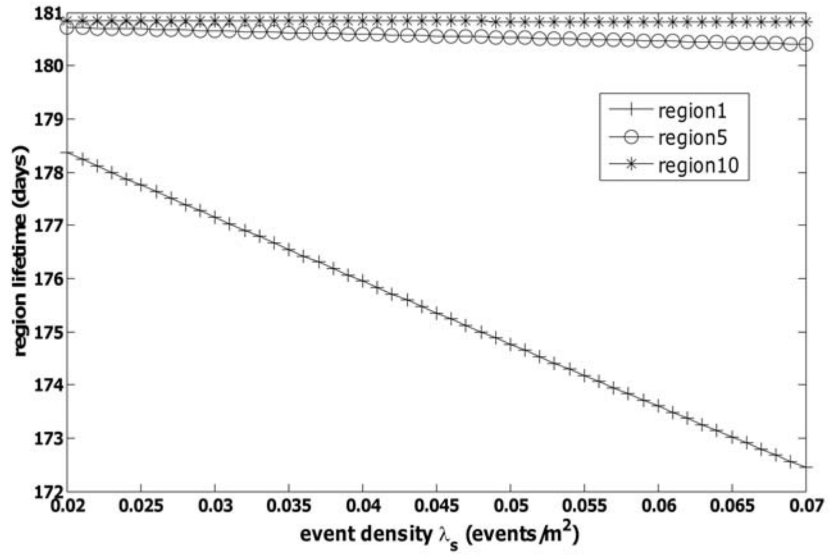

Figure 4-15: Lifetime of Regions by λ_s ($\nu = 2,\ \lambda_n = 0.02\ and\ \lambda_t = 5 \times 10^{-5}$)

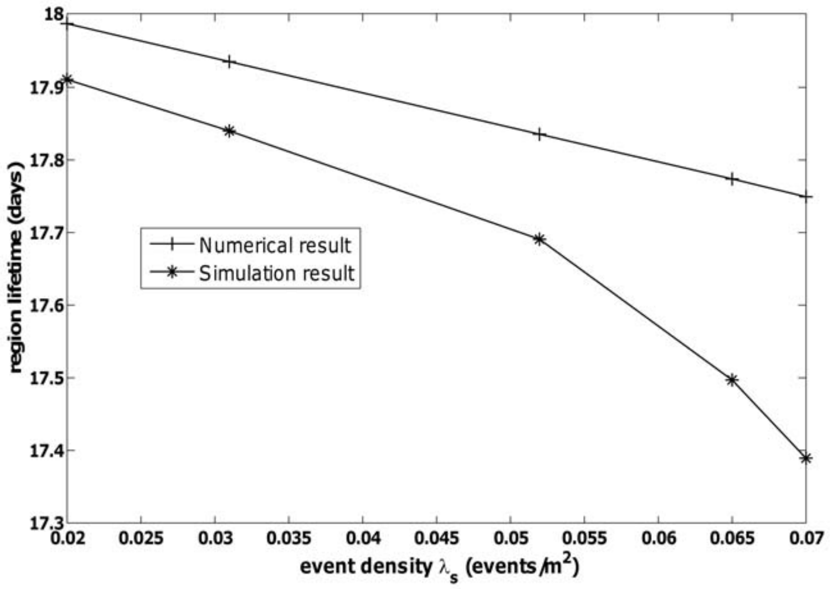

Figure 4-16: Lifetime of Region 1 by λ_s ($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_t = 2 \times 10^{-5}$)

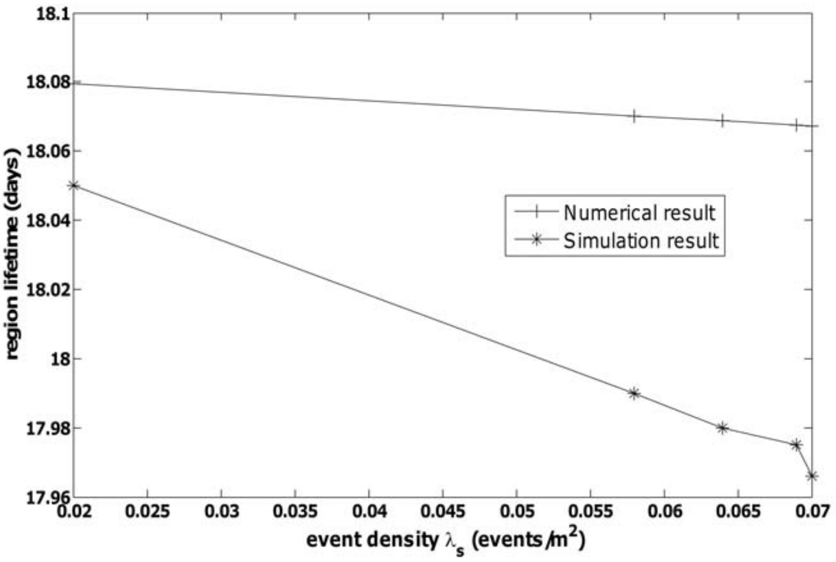

Figure 4-17: Lifetime of Region 5 by λ_s ($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_t = 2 \times 10^{-5}$)

4.6.3 Lifetime Waste Ratio

Figures 4-18 and 4-19 show the numerical results of lifetime waste ratio for different spatial densities of events, given the temporal density of events. These results again imply that energy hole problem will be more serious when the spatial and temporal densities of the events are higher. It is also noticed that the node deployment density ν approximately has no impact on this ratio. The simulation results in Figure 4-20 show the accuracy of theoretical approximation. Results in Figures 4-21 and 4-22, which are the numerical results of lifetime waste ratio in terms of spatial density of events, show the same trend for the degree of unbalanced energy consumption. The simulation results in Figure 4-23 show that the numerical results for the lifetime waste ratio match the simulation results well.

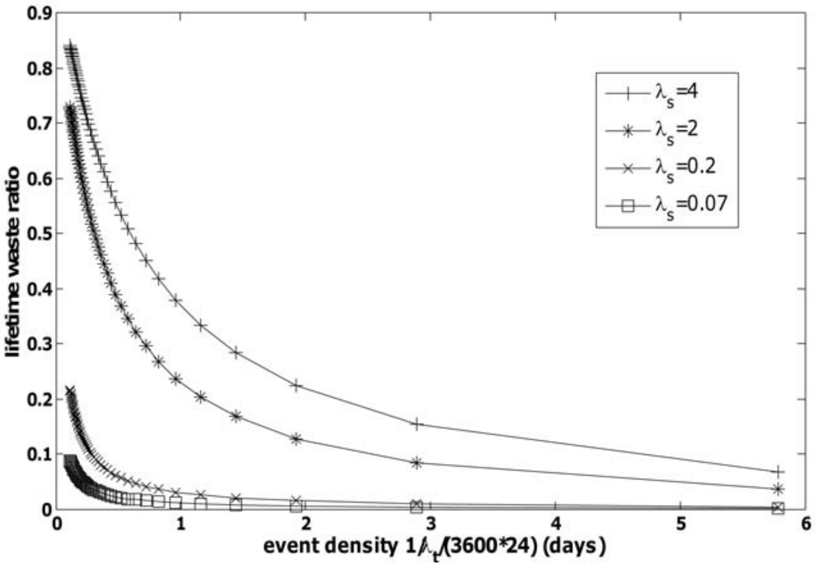

Figure 4-18: Lifetime Waste Ratio by λ_t ($\nu = 0.2,\ \lambda_n = 0.02$)

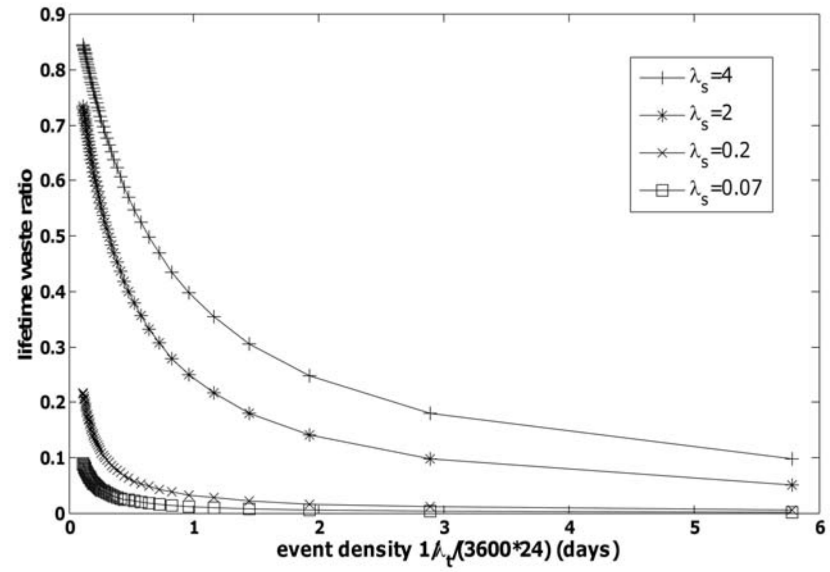

Figure 4-19: Lifetime Waste Ratio by λ_t ($\nu = 2,\ \lambda_n = 0.02$)

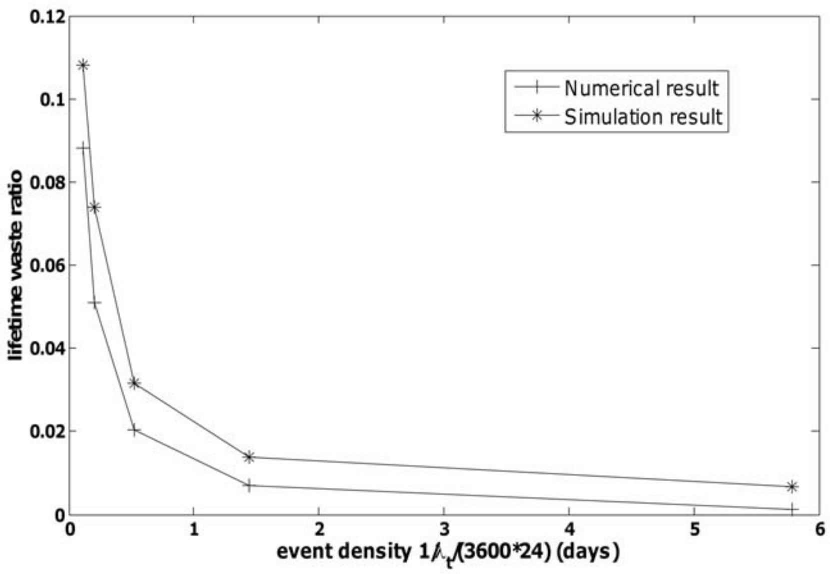

Figure 4-20: Lifetime Waste Ratio Comaprison by λ_t
($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_s = 0.07$)

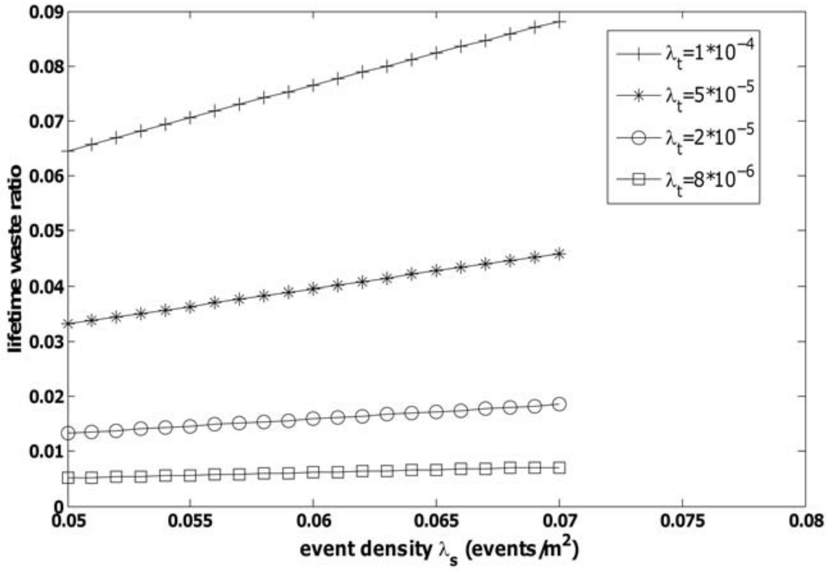

Figure 4-21: Lifetime Waste Ratio by λ_s ($\nu = 0.2,\ \lambda_n = 0.02$)

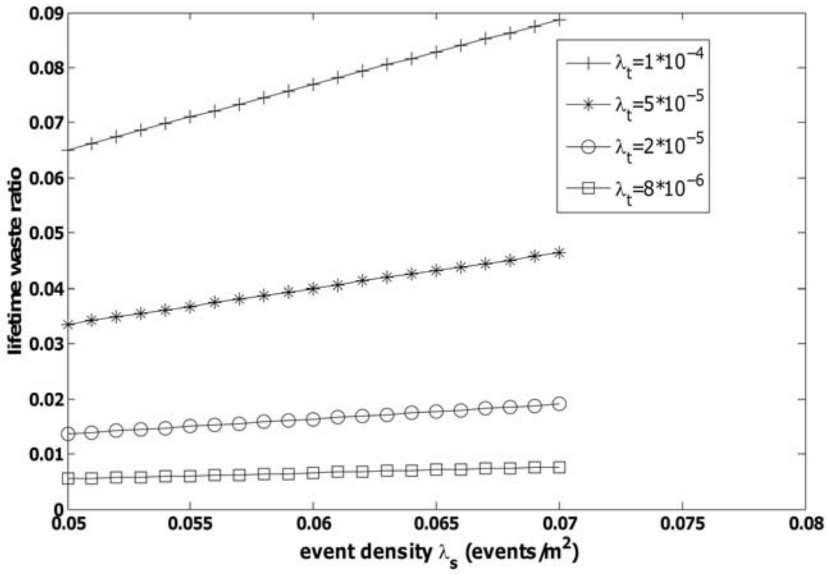

Figure 4-22: Lifetime Waste Ratio by λ_s ($\nu = 2,\ \lambda_n = 0.02$)

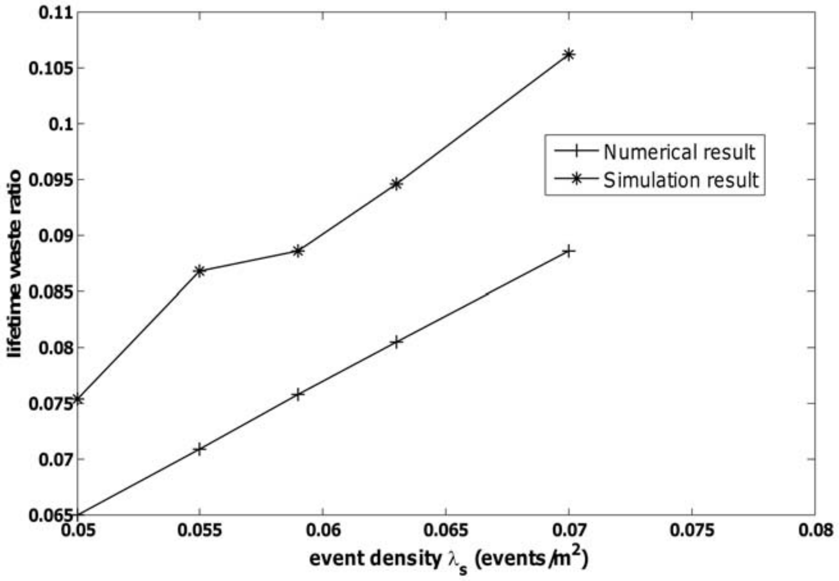

Figure 4-23: Lifetime Waste Ratio Comparison by λ_s
($\nu = 0.2,\ \lambda_n = 0.02\ and\ \lambda_t = 0.0001$)

4.6.4 Performance of the Non-uniform Deployment Scheme

For the evaluation of the performance of the non-uniform deployment strategy, proposed in this chapter, two ratios are used. The first ratio is the lifetime waste ratio, defined in Section 4.4.2, which indicates the degree of unbalancing in energy usage in the network. Although this measure has been previously presented for the circumstance of uniform deployment, it can also be used for evaluating the simulation results for non-uniform deployment strategy.

The second measurement, lifetime expectation ratio, is defined as

$$\omega = \frac{T_{sim}}{T_{req}} \tag{4-34}$$

where T_{sim} is the simulation result for the network lifetime.

In Figure 4-24 the simulation results for lifetime waste ratio of the network with non-uniform deployment and uniform deployment, in terms of temporal density of events are shown. These results show that when using the non-uniform deployment strategy presented in this chapter, the energy consumption of the network is greatly balanced. Figure 4-25 illustrates the lifetime expectation ratio for the same simulation. The results also prove that the non-uniform deployment strategy discussed in this chapter can achieve good performance. In Figure 4-26 the results for lifetime waste ratio according to spatial density of the events are shown. Figure 4-27 provides the results of lifetime expectation ratio for the same simulation. From these results, it is noted that the non-uniform node deployment scheme can provide the stable lifetime performance of the network in all the occasions examined, despite the minor distortions of the experiments. The occurrence of spikes of the curve in Figure 4-27 is due to the high resolution of 0.1% of the Y-axis. The largest distortion in the results of Figure 4-27 is 1%. Therefore these results further prove the feasibility of the non-uniform deployment strategy provided in this chapter.

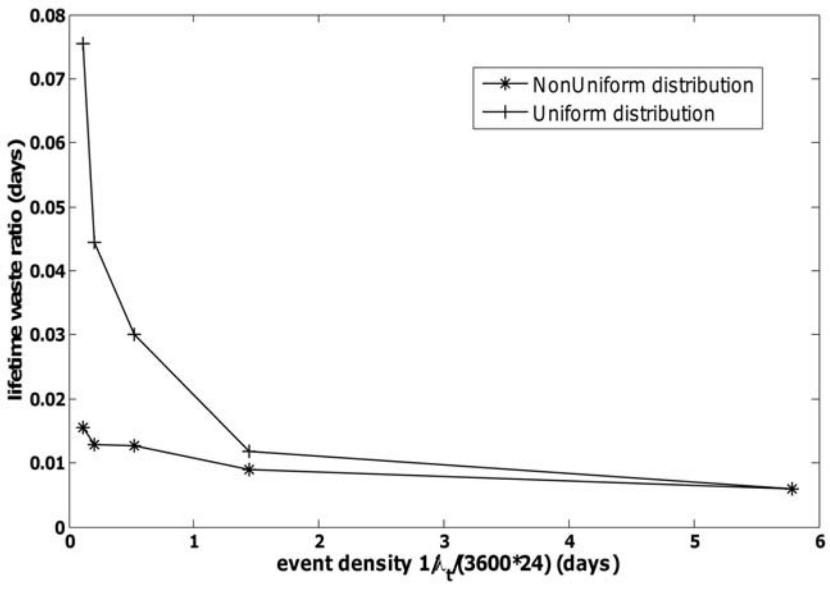

Figure 4-24: Lifetime waste ratio by λ_t ($\lambda_n = 0.02,\ \lambda_s = 0.05\ and\ T_{req} = 19\ days$)

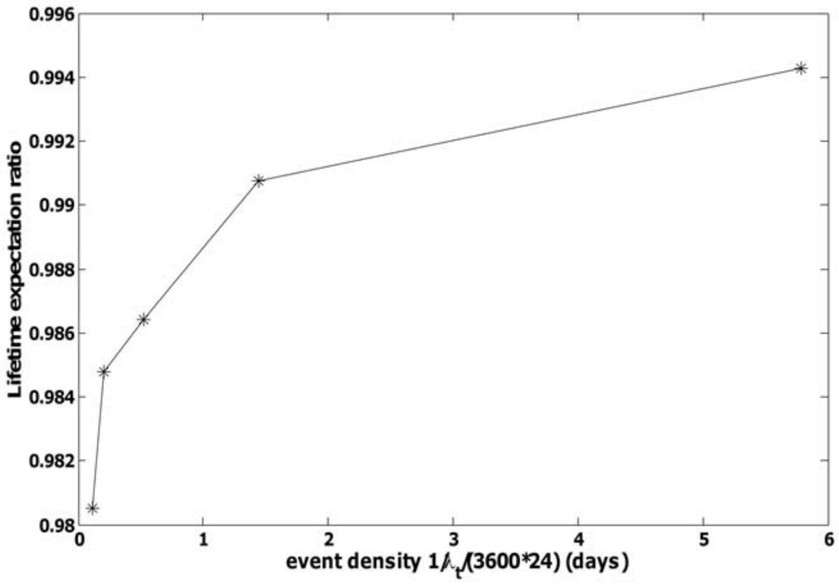

Figure 4-25: Lifetime expectation ratio by λ_t
$(\lambda_n = 0.02,\ \lambda_s = 0.05\ and\ T_{req} = 19\ days)$

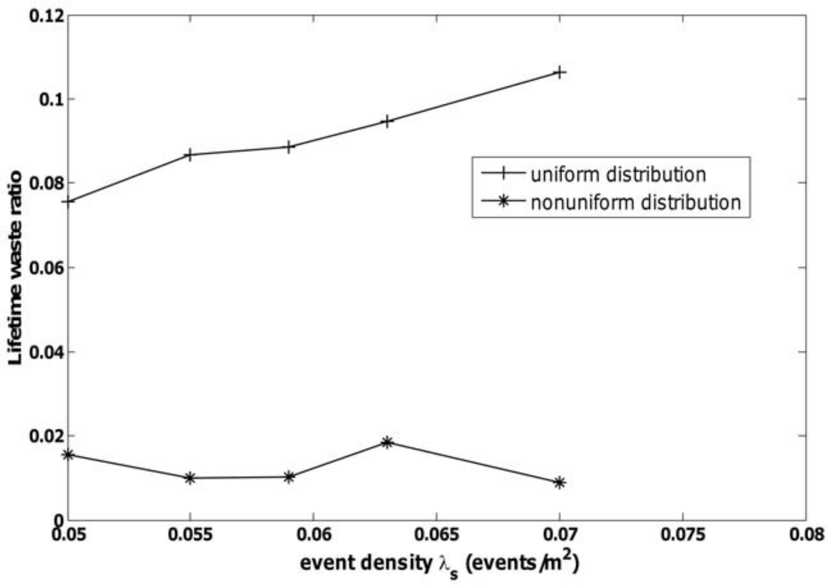

Figure 4-26: Lifetime waste ratio by λ_s
$(\lambda_n = 0.02,\ \lambda_t = 0.0001\ and\ T_{req} = 19\ days)$

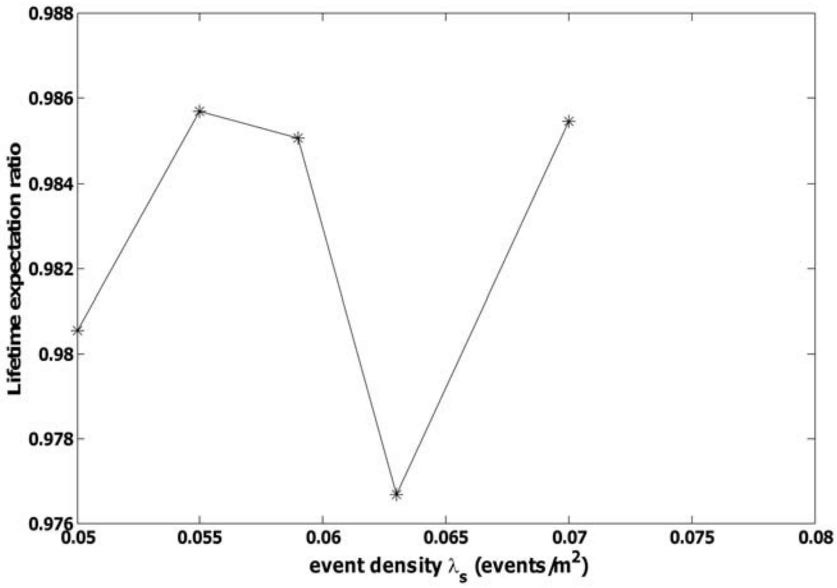

Figure 4-27: Lifetime expectation ratio by λ_s
($\lambda_n = 0.02,\ \lambda_t = 0.0001\ and\ T_{req} = 19\ days$)

4.7 Summary

As discussed in the first section of this chapter, the amount of data to be transmitted by sensors has significant impact on the design of the non-uniform node deployment strategy for sensor network systems that need to monitor the sensing field continuously. In this situation, the energy consumed by nodes in the active state without data transmission and reception needs to be taken into consideration. As demonstrated by the results on lifetime waste ratio, when only the energy consumption for data transmission and reception is considered, the deployment strategy causes unnecessarily more nodes to be used and thus leads to the waste of sensor nodes. Since the spatial and temporal distribution of the occurrence of events will influence the amount of data transmission, in this circumstance the design of a proper non-uniform node deployment strategy needs to be based on the spatial and temporal distribution of the occurrence of events. In this chapter, the design of such a non-uniform node deployment scheme for continuous event detection sensor network systems is investigated taking into consideration the energy consumptions of nodes without transmitting and receiving data, according to the spatial and temporal distribution of events. The analytical models for estimating the lifetime and the degree of the unbalanced energy consumption level are given. Based on the estimation of network lifetime, a non-uniform node deployment strategy is proposed.

Both numerical and simulation results prove that the provided lifetime estimation model and the presented non-uniform node deployment strategy are feasible. The results indicate that the spatial and temporal distributions of events greatly influence the strategy of the node deployment for balancing the energy consumption of the network. This chapter also shows that the energy consumption for nodes in active mode without transmitting or receiving should be considered when designing the network node deployment.

Chapter 5: Spatially Energy Balanced Routing

5.1 Introduction

In order to achieve the performance expected from the non-uniform node deployment method, nodes need to transmit data to the sink node by selecting a node in the adjacent inner-region. Since the nodes near the outer-boundary of a region will be covered by more sensors, the random selection method will cause the unbalanced energy consumption problem. This issue is illustrated in Figure 5-1. The node $n3$ in the sub-region $K1$ of Region K is covered by both node $n2$ and node $n1$ in Region $K+1$. The node $n4$ in Region K is only covered by the node $n1$ in Region $K+1$. As a consequence if nodes in Region $K+1$ select their next relay node in the region K randomly, the probability that the node $n3$ will be chosen rather than the node $n4$ is greater due to the higher coverage level. Hence the energy consumption of the network in the routing process is not balanced spatially in this occasion and nodes with higher coverage will die earlier. Though the maximum residual energy selection strategy is able to balance the spatial energy consumption of the region-by-region routing, the requirement of a piece of special equipment [124] for obtaining accurate energy information will increase the cost of the system. Therefore a spatially energy balanced node selection method without the need for the residual energy information of sensor nodes needs to be proposed. Figure 5-1 also demonstrates that when the two nodes $n3$ and $n4$ have the same energy level, the node $n3$ also has the higher probability of being selected. In this scenario, the node $n3$ will consume more energy. When the energy of the node $n3$ has decreased, it will still be chosen by the node $n2$. Due to the extra energy consumption of node $n2$ for the transmission of data from node $n1$, the energy consumption is still slightly spatially unbalanced. Thus the maximum residual energy node selection scheme also needs to be improved. Furthermore since the real-time dissemination of the residual energy information of nodes is expensive, a practical approach is to broadcast this information periodically.

Due to the varied achievable broadcast periods of different applications, the accuracy of the information will vary. Consequently the impact of the accuracy of the energy information on the performance of the routing strategy also needs to be investigated taking into consideration the broadcast period. In this chapter, this issue is rigorously studied and a region constraint selection scheme will be proposed based on the analytical result. Through combining the region constraint strategy and the maximum energy node selection mechanism, a hybrid scheme will be presented that improves the performance of the maximum residual energy method. The impact of the accuracy of the energy information on the performance of the routing strategy will be examined through simulation experiments. Exploiting the numerical results obtained from the analytical model and the simulation results achieved form the network simulation experiments, the improvements of the region constraint scheme over the random scheme will be discussed. Additionally, the simulation results will also demonstrate the better performance of the hybrid mechanism in comparison to the maximum energy node selection scheme.

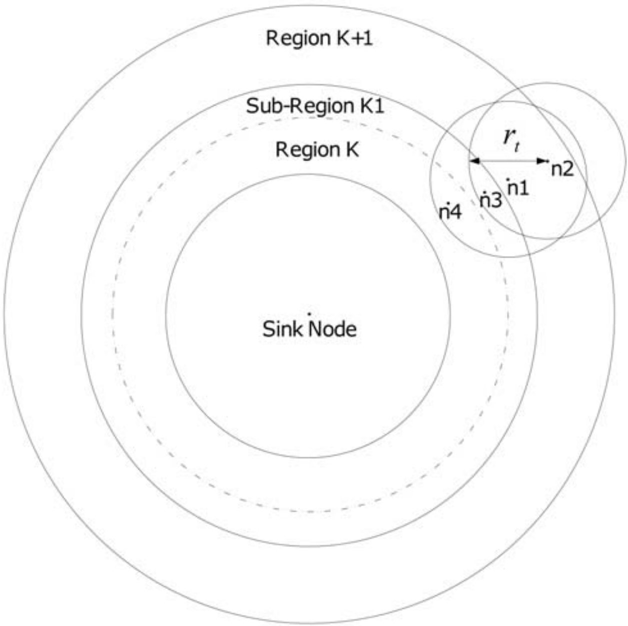

Figure 5-1: Unbalanced Routing Coverage

This chapter is organised as follows. Section 5.2 provides the network model, the fundamental assumptions and the notations used in this chapter. In the following section, Section 5.3, the mathematical model for the spatially unbalanced energy consumption issue due to the random node selection is proposed, based on which the region constraint strategy is given in Section 5.4. Section 5.5 describes the hybrid scheme. The experimental results are presented in Section 5.6 and Section 5.7 states the conclusions drawn in this chapter.

The major contributions of this chapter are: the development of an analytical model for the spatially unbalanced energy consumption of the random node selection scheme; The proposal of a region constraint mechanism; the proposal of a hybrid scheme combining the region constraint strategy and the maximum energy node selection scheme; and the impact of the inaccuracy of the energy information on the node selection mechanisms are examined through simulations.

5.2 System Model

Most of the configurations of the system model used in this chapter is the same as thoes in Chapter 4. However, in order to maintain the integrity of this chapter, they are further addressed in this section. The sensing field of a sensing network is assumed to be a circular region with radius r_D. Therefore the area of the network is πr_D^2, with the sink node located at the centre of the network. The sensing nodes in the network are assumed to be homogenous with communication range r_t, so that one node can communicate with any other node within the circular area of πr_t^2 centred at the node. In this chapter, if a sensor can communicate with a node, the sensor covers the node. Nodes can communicate directly with the sink node within the distance of r_t from the sink node. Outside this region nodes transmit data to the sink node via multi-hop paths. Since statistically the data transmission of the network can be generalised as a periodic pattern, it is also assumed that each node generates a data unit of l bits in the period of τ seconds to the sink node. Since this chapter primarily focuses on the large-scale sensor networks, the radius of the network is assumed to be far larger than the transmission range ($r_D \gg r_t$). The sink node is assumed to be a super node without energy constraints. It is also assumed that an ideal MAC protocol is used, so that the collision can be tackled and overhearing can be avoided [31]. The data transmission is assumed to be error free.

Nodes in the network are assumed to be scheduled by a proper scheduling scheme, so that the density of working nodes can be maintained to be a constant value λ_n to fulfil the coverage requirement of the application [109]. This assumption of the constant density value implies that the distribution of the nodes follows the Poisson distribution. Based on this assumption, the network can be statistically considered as working in groups with nodes distributed uniformly. In this circumstance, the node density is constant and the spatially unbalanced energy consumption problem is independent of the non-uniform deployment strategy. Thus it is proper to solely consider the scenario of uniform distribution in the analysis of the spatially unbalanced energy consumption problem in the following sections. It is also practical to suppose that each node knows its own position and that a sensor also has the information about the positions of all the nodes within its transmission range through an information exchange stage.

The network is divided into several circular regions, all of which have the sink node at their centre. Except for the first region, the widths of all the other regions are the same with a value of r'_t ($r'_t \leq r_t$), which ensures the communication between two nodes in adjacent regions. The first region is composed of the nodes that can communicate with the sink directly, therefore it has the width of r_t. Sensors in other regions need to transmit data through multi-hop routes in a region by region fashion, which only allows a node to select a relay node from the adjacent inner region. This postulate is proposed to ensure that the network lifetime can be lengthened through a non-uniform node deployment scheme. For the purpose of the research in this chapter, each region is further divided into several sub-regions with width δ. Figure 5-2 shows the network division model used in this chapter, where $\Xi(3, i)$ represents the ith sub-region of Region 3. Since the focus of this chapter is on the energy balance of the routing scheme, only energy consumed by the data transmission is considered in this chapter.

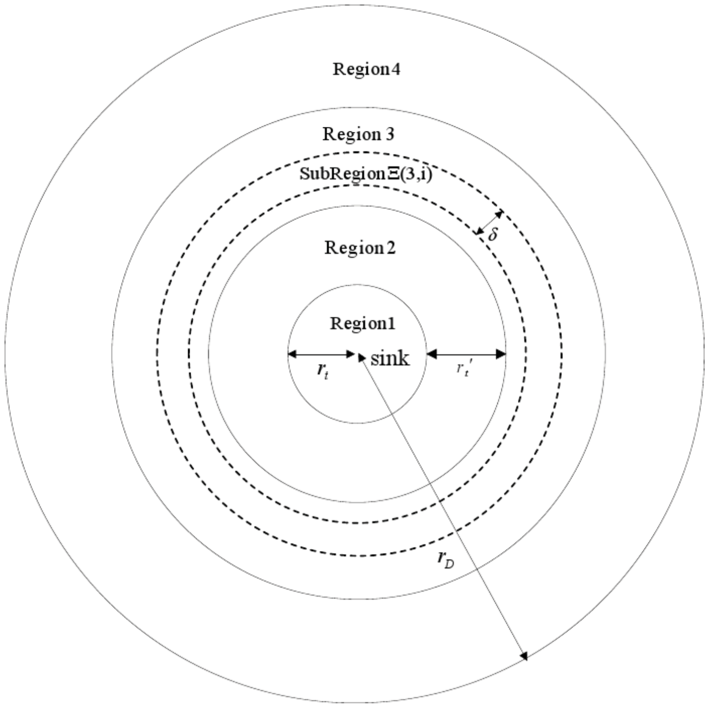

Figure 5-2: The Division of the Network

The notations most frequently used for the analysis in this chapter are listed in Table 5-1. Others will be explained when they first appear in the chapter.

5.3 Random Selection Scheme

The fundamental strategy when the relay node is selected is to randomly choose one neighbour node in the adjacent inner-region. In this section, the balance of the energy use of this node selection strategy is analysed. Firstly, the probability for a node to be chosen as the data relay node will be calculated in terms of the spatial density of active nodes of the network. Based on this result, the probability of a certain number of the nodes choosing sensors in a certain sub-region will be constructed as a binomial distribution. Through an estimation of the number of potential nodes that can be chosen in a certain region, this probability will be obtained. Exploiting these results, the amount of data for nodes in a certain sub-region to transmit can be estimated. At the end of this section a measure for the spatial balance of the energy consumption of the routing phase will be proposed.

Table 5-1: Notations

Notations	Definitions
$\Xi(i,k)$	The sub-region k of Region i.
δ	The width of a sub-region
λ_n	The density of active nodes in the network
N	The total number of nodes in the network
l	The amount of data that is generated by a node in each cycle
G	The total number of regions in the sensing area
r_t	The transmission range of a sensor node
r'_t	The width of Region $i (2 \leq i \leq G)$ in the network
M_i	The total number of sub-regions for the Region i
$\delta_{l(i)}$	The width of the last sub-region of Region i

5.3.1 Node Selection Probability

In order to evaluate the performance of the random selection scheme, the first step is to calculate the probability of a node in the sub-region $\Xi(i+1,m)$ choosing a certain node in the sub-region $\Xi(i,k)$, which is denoted as $\rho_{(i+1,m,k)}$.

Suppose that a node in sub-region $\Xi(i+1,m)$ can totally cover $\Phi_{(i+1,m)}$ nodes in Region i and in sub-region $\Xi(i,k)$, the node has $\phi_{(i+1,m,k)}$ sensors in the contact range. The probability, $\rho_{(i+1,m,k)}$, can be calculated by

$$\rho_{(i+1,m,k)} = \frac{\phi_{(i+1,m,k)}}{\Phi_{(i+1,m)}} \tag{5-1}$$

In accordance with the Poisson distribution of sensor nodes, the value of $\Phi_{(i+1,m)}$ and $\phi_{(i+1,m,k)}$ can be derived as

$$\Phi_{(i+1,m)} = \lambda_n \Omega_{(i+1,m)} \tag{5-2}$$

$$\phi_{(i+1,m,k)} = \lambda_n \Omega_{(i+1,m,k)} \tag{5-3}$$

where $\Omega_{(i+1,k)}$is the area covered in Region i by a node in $\Xi(i+1,k)$, and $\Omega_{(i+1,k,m)}$ represents the area covered in $\Xi(i,m)$ by a node in $\Xi(i+1,k)$. Also the area Ω can be obtained by a function of the distance r between the node and the sink node, expressed below as

$$\Omega = g(r) \tag{5-4}$$

If the width of a sub-region δ is small enough, all the nodes can be approximately regarded as being on the curve with the same value of r. In this occasion it is practical to estimate the value of Ω for any node in $\Xi(i+1,m)$ according to the expectation of minimum value of r, $E(min(r))$, as

$$\Omega = g(E(min(r))) \tag{5-5}$$

We denote $F_r(x)$ as the cumulative distribution function of $min(r)$ and also define the following notations:

$r_{(i,j)}$ - the radius of the inner boundary of $\Xi(i,j)$.

$A_{(i,j)}$ - the area of $\Xi(i,j)$.

$A_{(i,j)}(x)$ - the area, which is formed by the inner boundary of $\Xi(i,j)$ and the circle with the radius $(r_{(i,j)}+x)$ centred at the sink node.

According to the Poisson distribution of sensor nodes, the following relation holds [129]

$$F_r(x) = 1 - e^{-\lambda_n A_{(i+1,m)}(x-r_{(i+1,m)})} + e^{-\lambda_n A_{(i+1,m)}} \tag{5-6}$$

Denote $r'_{(i+1,m)}$ as the distance between a node in $\Xi(i+1,m)$ and the sink node. Thus $E(min(r'_{(i+1,m)}))$ can be calculated as

$$E(min(r'_{(i+1,m)})) = \int_{r_{(i+1,m)}}^{r_{(i+1,m)}+upper_{(i+1,m)}} \varphi(r)dr \tag{5-7}$$

where $\varphi(r) = 2r^2\lambda_n\pi \cdot e^{-\lambda_n\pi(r^2-r^2_{(i+1,m)})}$ and

$$upper_{(i,j)} = \begin{cases} \delta & \text{if } 1 \le j \le M_i - 1 \\ \delta_{l(i)} & \text{if } j = M_i \end{cases} \tag{5-8}$$

Where $\delta_{l(i)}$ is the width of the last sub-region of Region i. Exploiting the value of $E(min(r'_{(i+1,m)}))$, the probability $\rho_{(i+1,m,k)}$ can be calculated as

$$\rho_{(i+1,m,k)} = \frac{g_{(i+1,m,k)}(E(min(r'_{(i+1,m)})))}{g_{(i+1,m)}(E(min(r'_{(i+1,m)})))} \tag{5-9}$$

where $g_{(i+1,m)}$ is the function for $\Omega_{(i+1,m)}$, and $g_{(i+1,m,k)}$ is the function for $\Omega_{(i+1,m,k)}$.

5.3.2 Sub-Region Selection Probability

Based on the node selection probability derived in Section 5.3.1, in this section the probability that a certain number of the nodes will choose sensors in a certain sub-region will be obtained.

Suppose that all the nodes in $\Xi(i,j)$ have $\eta_{(i,j,k)}$ nodes within the communication range in $\Xi(i+1,k)$. Let random variable, $m_{(i,j,k)}$, represent the number of nodes in $\Xi(i+1,k)$ that choose nodes in $\Xi(i,j)$ for relaying data. Thus, $m_{(i,j,k)}$ is considered as a binomial random variable with parameters $(\eta_{(i,j,k)}, \rho_{(i+1,k,j)})$. The probability for $m_{(i,j,k)}$ to be m is given by

$$P_r(m_{(i,j,k)} = m) = \begin{pmatrix} \eta_{(i,j,k)} \\ m \end{pmatrix} \rho^{m}_{(i+1,k,j)} \cdot \rho_{\varsigma} \tag{5-10}$$

where $\rho_{\varsigma} = (1 - \rho_{(i+1,k,j)})^{\eta_{(i,j,k)}-m}$. In order to fully achieve this probability, the parameter $\eta_{(i,j,k)}$ needs to be estimated.

The estimation of this value needs the support of following result presented in [130]: if the probability for a point being in one circle is a constant value p, the expectation value for the total area of κ circles intersecting the plane domain with area B can be calculated as

$$E(X) = B(1 - (1-p)^{\kappa}) \tag{5-11}$$

Let $X_{(i,j,k)}$ represent the area of the region that formed by the intersection of the circle with radius r_t, centred at some node in $\Xi(i,j)$, and sub-region $\Xi(i+1,k)$. Also, the probability for a point locating in $X_{(i,j,k)}$ is denoted as $p_{(i,j,k)}$. It can be derived as

$$p_{(i,j,k)} = \frac{X_{(i,j,k)}}{A_{(i+1,k)}} \tag{5-12}$$

As a result $X_{(i,j,k)}$ can be expressed as following function

$$X_{(i,j,k)} = f_{\delta(i,j,k)}(x_{\delta(i,j)}) \tag{5-13}$$

where $x_{\delta(i,j)}$ is the distance between a node and the inner-boundary of $\Xi(i,j)$. When the value of δ is small enough, it can be estimated through the expectation of the maximum value of $x_{\delta(i,j)}$, $E(max(x_{\delta(i,j)}))$.

Denote $F(x)$ as the cumulative distribution function of $max(x_{\delta(i,j)})$. Since no sensor exists inside $\Xi(i,j)$, in the area further away from the circle, with the radius of the distance from the node with $max(x_{\delta(i,j)}$ to the sink node, $F(x)$ can be given by

$$F(x) = (1 - e^{-\lambda_n A_{(i,j)}(x)}) \cdot e^{-\lambda_n (A_{(i,j)} - A_{(i,j)}(x))} \tag{5-14}$$

Hence $E(max(x_{\delta(i,j)}))$ can be calculated as

$$E(max(x_{\delta(i,j)})) = \int_0^{upper_{(i,j)}} x e^{\alpha(x)} \cdot (2x + \lambda_n \pi) dx \tag{5-15}$$

where $\alpha(x) = -\lambda_n \pi (2r_{(i,j)} \cdot (upper_{(i,j)} - x) + upper^2_{(i,j)} - x^2)$. Leveraging this result, the value of $p_{(i,j,k)}$ can be estimated by

$$p_{(i,j,k)} = \frac{f_{\delta(i,j,k)}(E(max(x_{\delta(i,j)})))}{A_{(i+1,k)}} \tag{5-16}$$

Let $\kappa_{(i,j)}$ represent the number of nodes in $\Xi(i,j)$. According to the Poisson distribution of the sensor nodes, $\kappa_{(i,j)}$ can be calculated as

$$\kappa_{(i,j)} = \lambda_n A_{(i,j)} \tag{5-17}$$

Denote $A_{(i,j,k)}$ as the total area formed by the intersections of the transmission regions of all the nodes in $\Xi(i,j)$ and the sub-region $\Xi(i+1,k)$. Based on (5-11), $A_{(i,j,k)}$ can be derived as

$$A_{(i,j,k)} = A_{(i+1,k)} \cdot (1 - (1 - p_{(i,j,k)})^{\kappa_{(i,j)}}) \tag{5-18}$$

Exploiting this estimation, the value of the number of nodes in $\Xi(i+1,j)$, which can choose the nodes in $\Xi(i,k)$ as data relay nodes, $\eta_{(i,j,k)}$, can be finally calculated as

$$\eta_{(i,j,k)} = \lambda_n \cdot A_{(i,j,k)} \tag{5-19}$$

5.3.3 Estimated Sub-Region Data Amount

The expected amount of data transmission of each sub-region in each region will be derived in this section using the results obtained in the previous sections.

In accordance with the binomial distribution of $m_{(i,j,k)}$, the expectation of this random variable can be derived as

$$E(m_{(i,j,k)}) = \eta_{(i,j,k)} \cdot \rho_{(i+1,k,j)} \tag{5-20}$$

Let $m_{(i,j)}$ be the number of nodes that select nodes in $\Xi(i,j)$ as relay nodes. The expectation of $m_{(i,j)}$ can be obtained as

$$E(m_{(i,j)}) = \sum_{k=1}^{\Delta_{(i,j)}} E(m_{(i,j,k)}) \tag{5-21}$$

where $\Delta_{(i,j)}$ stands for the largest sub-region number in Region $i+1$ that can use the nodes in $\Xi(i,j)$ as data relay nodes. Through this result, the value of the total amount of data, $D_{(i,j)}$, and the average amountof data, $d_{(i,j)}$, for the nodes in $\Xi(i,j)$ to transmit, can be derived as below.

For the Region $G-1$, these values can be obtained as

$$D_{(G-1,i)} = l(E(m_{(G-1,i)}) + \lambda_n \cdot A_{(G-1,i)}) \tag{5-22}$$

$$d_{(G-1,i)} = l(\frac{E(m_{(G-1,i)})}{\lambda_n A_{(G-1,i)}} + 1) \tag{5-23}$$

For Region i with $(G-2) \leq i \leq 1$, the calculation is given by

$$D_{(i,j)} = \sum_{k=1}^{\Delta_{(i,j)}} d_{(i+1,k)} \cdot E(m_{(i,j,k)}) + l\lambda_n A_{(i,j)} \tag{5-24}$$

$$d_{(i,j)} = \frac{D_{(i,j)}}{\lambda_n A_{(i,j)}} \tag{5-25}$$

5.3.4 Routing Balance Ratio

In this section, a measure is proposed to evaluate the degree of unbalanced energy consumptions of the sub-regions in each region.

The ideally balanced amount of data transmission for each node of Region i in the network, represented by ds_i, can be calculated as

$$ds_i = \frac{D_{all(i)}}{\lambda_n A_i} \tag{5-26}$$

where A_i is the area in Region i and $D_{all(i)}$ represents the total amount of data for the nodes in Region i to transmit. $D_{all(i)}$ can be derived as

$$D_{all(i)} = \sum_{j=1}^{M_i} D_{(i,j)} \tag{5-27}$$

where $D_{(i,j)}$can be evaluated by (5-22) or (5-24) and M_i represents the total number of sub-regions for Region i. The *routing balance ratio* for $\Xi(i,j)$ can then be defined to be the ratio between the average amount of data for the nodes in $\Xi(i,j)$ to transmit and the corresponding ideal amount of data as below

$$\Psi_{(i,j)} = \frac{d_{(i,j)}}{ds_i} \tag{5-28}$$

It is noted that the energy consumption of the sub-region $\Xi(i,j)$ is more balanced, if the value of $\Psi_{(i,j)}$ is closer to 1. The value larger than 1 indicates that certain part of the network is overused, while a value smaller than 1 implies that the workflow for the corresponding sub-region is lower than its capacity.

5.4 Region Constraint Selection Scheme

The numerical results of the analytical model and the simulation results presented in Section 5.6 indicates that the random selection scheme suffers severely from spatially unbalanced energy consumption. In this section, the region constraint scheme is proposed to tackle this problem.

5.4.1 Scheme Description

The proposed region constraint node selection scheme restricts the relay nodes' selection area of certain node. In this restriction method, nodes in a region will have a more balanced chance of being selected, and thus the energy consumption of the network will be balanced. In order to achieve this goal, the parameter S, which is leveraged to control the node selection region, is illustrated in Figure 5-3 and defined as

Definition 1 *S is the length of a sub-segment of the segment determined by the sink node and certain sensor node, starting at the point with the distance of r_t away from this sensor node on the segment, ending at this node.*

With this region constraint parameter, the selection area of a node can be restricted. The sub-regions, in which the sensors can be selected by this node, are

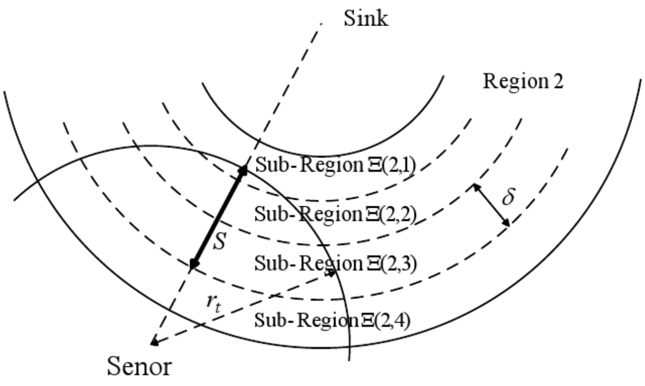

Figure 5-3: The Definition of S

those covered by a sub-segment with the length of S, in the next inner-region of the region the node belongs to. This scheme allows the nodes to select relay nodes randomly among the sensors in this controlled selection area. As a result, through the usage of a proper value of S, the energy usage for nodes in different sub-regions can be balanced.

5.4.2 The Modification of Node Selection Probability

Since limiting the node selection area further leads to a change in the number of sensors that have the potential to be selected by certain node(i.e. the value of $\Phi_{(i,k)}$), the calculation of the node selection probability, $\rho_{(i+1,m,k)}$, needs to be modified to analyse this scheme.

Define $g_{c(i+1,m)}(r'_{(i+1,m)})$ as the function for calculating the value of $\Phi_{(i+1,m)}$ of the region constraint node selection scheme. Also let $A_{outer}(r', r)$ be the function of the area formed by the intersection of the coverage area of the node with distance r' to the sink node, and the circle with radius r centred at sink node. Leveraging the function $A_{outer}(r', r)$, $g_{c(i+1,m)}(r'_{(i+1,m)})$ can be calculated. The node selection probability for the region constraint node selection scheme, $\rho_{c(i+1,m,k)}$, can be calculated as

$$\rho_{c(i+1,m,k)} = \frac{g_{(i+1,m,k)}(E(min(r'_{(i+1,m)})))}{g_{c(i+1,m)}(E(min(r'_{(i+1,m)})))} \tag{5-29}$$

With this result, the probability for m nodes to choose nodes in $\Xi(i, k)$ presented by (5-10) can be modified to the following formula for this scheme.

$$P_r(m_{(i,k,j)} = m) = \begin{pmatrix} \eta_{(i,k,j)} \\ m \end{pmatrix} \rho^m_{c(i+1,j,k)} \cdot \rho_\varsigma \tag{5-30}$$

where $\rho_\varsigma = (1 - \rho_{c(i+1,j,k)})^{\eta_{(i,k,j)}-m}$.

5.4.3 The Modification of Estimated Sub-region Data Amount

Since the selection region constraint parameter limits the node selection area, it is necessary to modify equations (5-21) and (5-24), in order to estimate the expectation of the value of $m_{(i,j)}$ for this scheme.

Denote $\zeta_{(i,j)}$ as the start value of the summation in (5-21) and (5-24). This value is the first sub-region number, in which the sensors can select the nodes in $\Xi(i,j)$ as relay node. Exploiting this notation, the (5-21) and (5-24) can be re-written as

$$E(m_{(i,j)}) = \sum_{k=\zeta_{(i,j)}}^{\Delta_{(i,j)}} E(m_{(i,j,k)}) \tag{5-31}$$

$$D_{(i,j)} = \sum_{k=\zeta_{(i,j)}}^{\Delta_{(i,j)}} d_{(i+1,k)} \cdot E(m_{(i,j,k)}) + l\lambda_n A_{(i,j)} \tag{5-32}$$

The modification of the model can be used to analyse the node selection region constraint scheme. According to (5-30), the equation (5-20) can be modified as

$$E(m_{(i,j,k)}) = \eta_{(i,j,k)} \cdot \rho_{c(i+1,k,j)} \tag{5-33}$$

5.4.4 The Application of the Scheme

Once the network parameters are specified by the application, the optimum value of S can be obtained through the calculation of the mathematical model presented above, as shown in Section 5.6.3, and configured into the operating system of the sensor nodes. Since the position information of the neighbouring nodes is able to be gathered through an initialisation process, a sensor node can simply use the information to determine whether a node is a candidate for the next hop, by checking whether it is in the region constrained by S internally, without the necessity of adjusting the transmission range. The candidate next-hop nodes in the constraint region only need to be determined once. Then each node stores the information of the nodes in the constraint region for the routing process. The storage complexity is $O(n)$, where n is the number of the candidate next-hop nodes.

5.5 Hybrid Scheme

The maximum residual energy node selection strategy is proposed in [67], where the source node selects the node with the maximum residual energy, among all its neighbours, as the data relay node. With this scheme, when multiple candidate nodes have the same energy level, they will be selected randomly, which will cause the spatial unbalance of the energy consumption. A hybrid method is proposed in this section that solves this problem. This scheme is the combination of the maximum residual energy selection strategy and the region constraint mechanism. Nodes using this routing strategy only select the node with the highest energy level of all of the neighbour nodes in the constraint region, formed as described in Section 5.4. As revealed by the experiments in Section 5.6, this scheme will improve the performance of a system that can afford the additional costs of providing the availability of energy information.

5.6 Experimental Results

In this section, both the numerical results and the simulation results are presented. Firstly, using the results of the routing balance ratio, the problem of the spatial unbalanced energy consumption in the random node selection scheme will be demonstrated. Then the results of the routing balance ratio for the region constraint mechanism show the improvement of the region constraint mechanism on this issue. Finally, at the end of this section, the performances of all the node selection strategies mentioned in this chapter will be evaluated through simulations.

Due to the assumption of the scheduled network with constant density of working nodes, the achievement of spatially balanced energy usage among the uniformly distributed working nodes will lead to the spatially balanced energy consumption of the non-uniformly deployed network. Consequently the evaluation of the scheme proposed in this chapter in the scenario of uniform distribution is adequate. Hence the uniform distribution is used in the simulations. The simulation model follows the system model presented in Section 5.2.

5.6.1 Parameter Settings

In order to establish the experiments, proper parameters for both the sensor nodes and the network should be used. This section explains the parameter settings conducted in this chapter.

5.6.1.1 Sensor Node Parameters

As the experiments conducted in this chapter need to evaluate the energy consumption of each node, the proper model for energy consumption for the radio transceiver must be applied. In this chapter the model used is as follows [70]

$$e_{tx} = e_{elec} + e_{amp} d^{\beta} \tag{5-34}$$

In the equation above, the e_{elec} is the energy consumed by activating the circuit of radio transceiver and the e_{amp} is the energy used by the transceiver amplifier for communication. The d is the transmission distance, which is set to r_t in this chapter.

For the experiments, the hardware parameters for each sensor node are selected similar to the Motes [27,28]. Table 5-2 lists the settings for the hardware parameters used in the experiments, in which the e_{ini} is the initial amount of power supply for each sensor node.

Table 5-2: Sensor Node Parameter Settings

Parameter Name	Value
e_{ini}	$2J$
e_{elec}	$5.0 \times 10^{-11} J/bit$
e_{amp}	$1.0 \times 10^{-11} J/bit$
β	2
r_t	$40m$

5.6.1.2 Network Parameters

In addition to the configurations of the nodes, the settings of the network parameters should also be allocated. In Table 5-3 the values of these settings used in this chapter are listed.

Table 5-3: Network Parameter Settings

Parameter Name	Value
r'_t	$30m$
G	7
l	$640bits$
l_i	$32bits$

The parameter l_i is the length of the data that needs to be transmitted, for disseminating the information of nodes' residual energy. The region width, r'_t, is set to $30m$, so that each node in one region can communicate with at least one node in the adjacent inner-region. This value is close enough to the transmission range, so that the number of hops for the data transmission to reach the sink node can be decreased. This configuration can be explained through the router-able probability described in Section 4.5

$$P_\gamma = 1 - e^{-\lambda_n A_{tinf}} \tag{5-35}$$

where A_{tinf} is the area formed by the intersection of the transmission area of the node and the next inner-region. It is clear that the probability increases with the enlargement of the area. Thus if a node at the outer-boundary of a region has a large enough value of P_γ, all the other nodes in the same region will have a larger router-able probability. Define r_Δ as the ratio of the transmission radius and the region width. That is

$$r_\Delta = \frac{r_t}{r'_t} \tag{5-36}$$

As A_{tinf} is a function of r_t and r'_t, it can also be written as a function of r_t and r_Δ. Consequently by adjusting the ratio r_Δ, the appropriate route-able probability can be obtained. It can be shown that given $r_t = 40$, the appropriate route-able probability can be achieved when $r_\Delta = 1.3$.

In order to conduct the experiments, the value of the parameter δ representing the width of a sub-region also needs to be correctly chosen. In this chapter δ is chosen to fulfil the requirement $\lambda_n A_{(1,1)} \geq 1$, so that at least one node will exit in each sub-region. In Table 5-4 the values of δ for the three network densities used in the experiments of this chapter are listed.

Table 5-4: The Value of δ

Network Density (λ_n)	δ
0.5	$2m$
0.1	$2m$
0.04	$6m$

5.6.2 Routing Balance Ratio for Random Scheme

In Figures 5-4, 5-5 and 5-6 the routing balance ratio for each sub-region of three regions is presented, according to the three network density values. These results indicate that with the random node selection mechanism the spatially unbalanced energy consumption is serious. From the curves, it is noted that the sensors in the sub-regions further from the inner-boundary of the region need to consume more energy than those in the inner-sub-regions. Furthermore, the cross-over between Region 3 and 5 shows that the energy consumption of Region 3 is more unbalanced than that of Region 5. The different level of the routing balance ratio for Region 1 is due to the value of the radius, r_t, of Region 1.

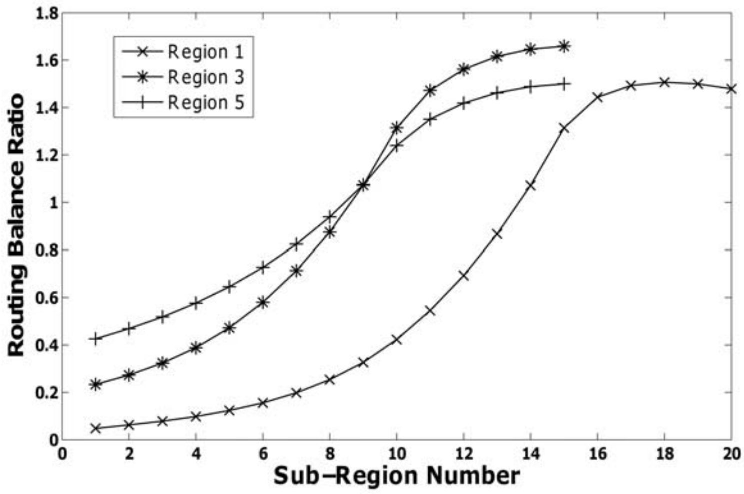

Figure 5-4: Routing Balance Ratio ($\lambda_n = 0.5$)

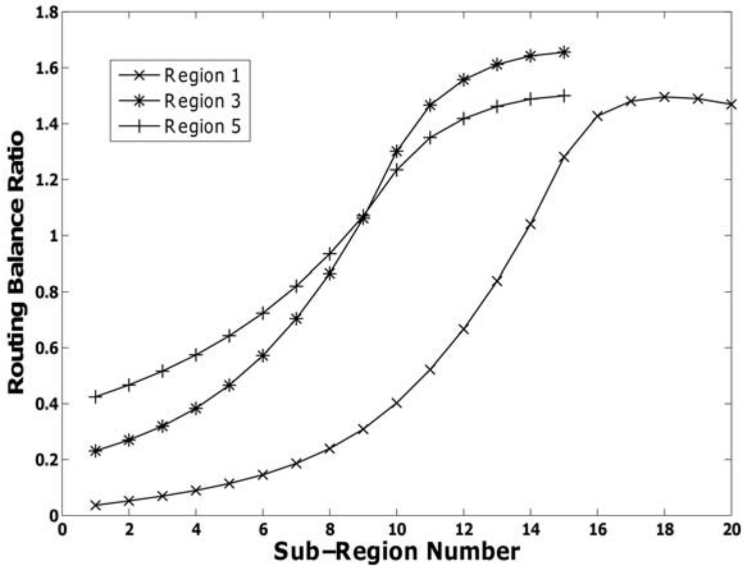

Figure 5-5: Routing Balance Ratio ($\lambda_n = 0.1$)

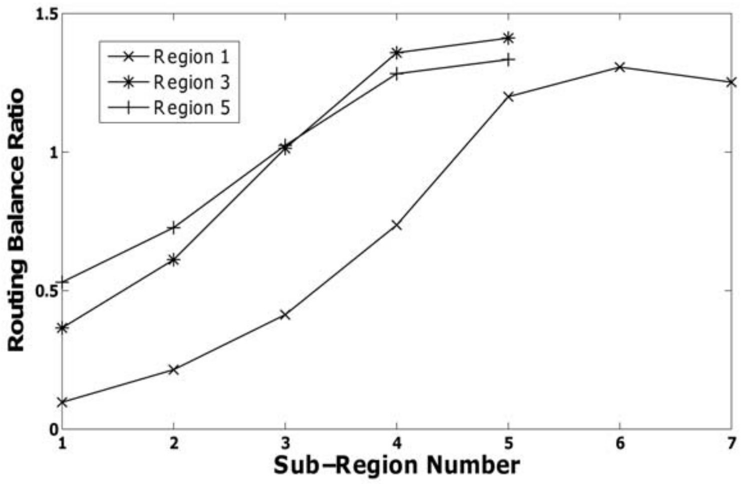

Figure 5-6: Routing Balance Ratio ($\lambda_n = 0.04$)

The corresponding simulation results for the network density values, 0.1 and 0.04 are provided in Figures 5-7 to 5-10. Since the computational capacity required by simulating the network with density value 0.5 is too high, the corresponding experiments on this density value cannot be performed. Each value of the simulation results is the average of the results of 1000 runs. The figures prove that the simulated system performs the same spatially unbalanced energy consumption characteristic as predicted by the mathematical model proposed in previous sections. In addition it is also noted that the distortions between the simulation results and the numerical results are acceptable. This proves the accuracy of the mathematical model for random node selection mechanism presented in this chapter. Since the distribution of nodes among regions will be more random in the sparse network, the differences in results between simulation and analysis will widen in networks with lower λ_n as indicated by the results.

5.6.3 Routing Balance Ratio for the Region Constraint Scheme

In this section the results of routing balance ratio for the region constraint node selection scheme are presented. As mentioned in Section 5.4, the value of the parameter S is crucial for the performance of this mechanism. Thus in the first part of this section, the problem of how to find the proper S is discussed. In the second part, the results of the routing balance ratio are provided based on the chosen values of S. The simulation model used in this section also follows the system model presented in Section 5.2.

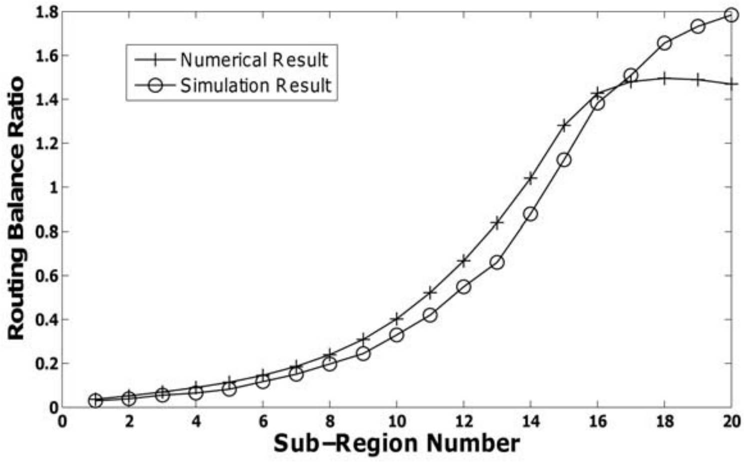

Figure 5-7: Routing Balance Ratio (Region 1, $\lambda_n = 0.1$)

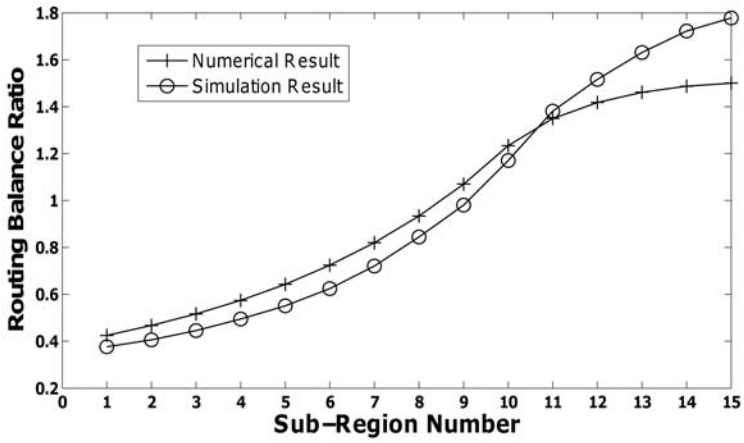

Figure 5-8: Routing Balance Ratio (Region 5, $\lambda_n = 0.1$)

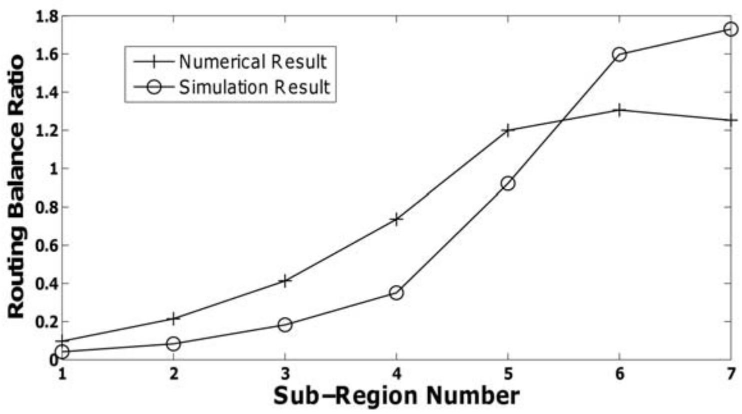

Figure 5-9: Routing Balance Ratio (Region 1, $\lambda_n = 0.04$)

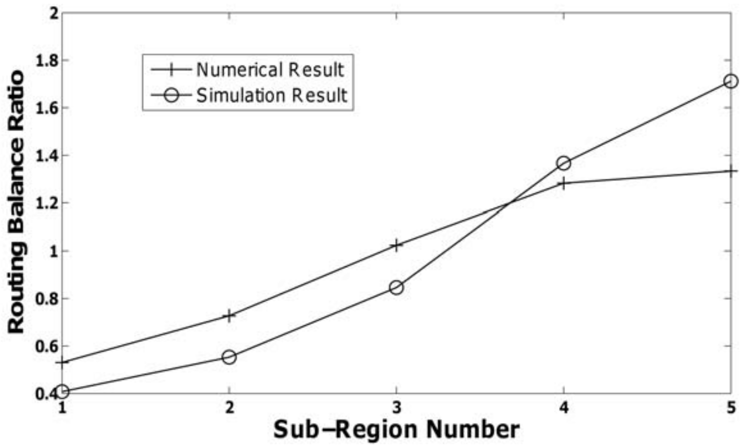

Figure 5-10: Routing Balance Ratio (Region 5, $\lambda_n = 0.04$)

5.6.3.1 The Setting of S

The value of S can be determined by the results of the mathematical model, when different configurations are used for this parameter. Since the maximum number of the routing balance ratio is important for the system, the proper setting of S is selected as the value, which leads to the lowest routing balance ratio.

Figures 5-11, 5-12 and 5-13 show the maximum routing balance ratio of different regions under various values of S for the three values of network density. Through these results the proper values for S can be clearly determined. The values used in this chapter are given in Table 5-5.

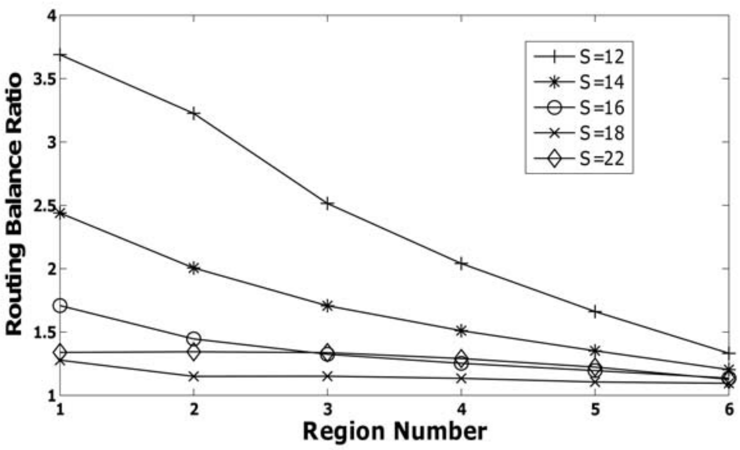

Figure 5-11: Maximum Routing Balance Ratio ($\lambda_n = 0.5$)

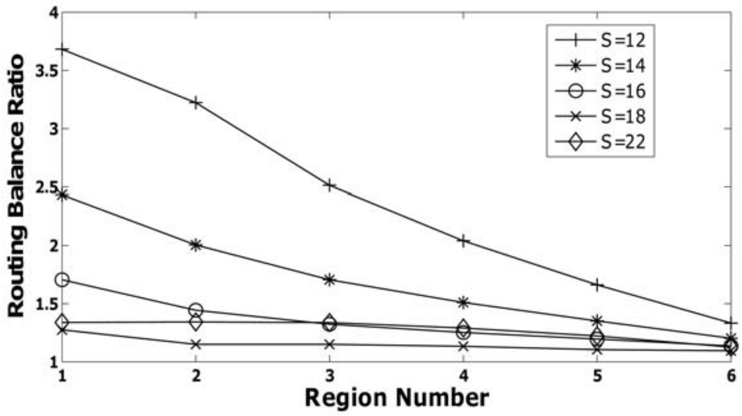

Figure 5-12: Maximum Routing Balance Ratio ($\lambda_n = 0.1$)

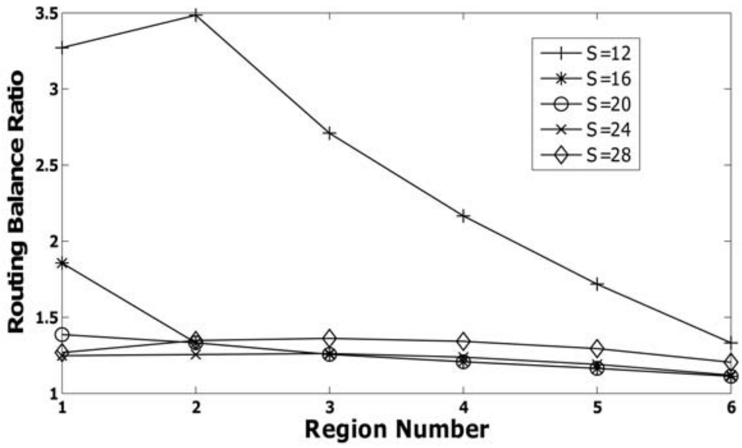

Figure 5-13: Maximum Routing Balance Ratio ($\lambda_n = 0.04$)

Table 5-5: The Value of S

Network Density (λ_n)	S
0.5	$18m$
0.1	$18m$
0.04	$24m$

5.6.3.2 Results of Routing Balance Ratio

Figures 5-14, 5-15 and 5-16 provide the numerical results of the routing balance ratio, for the region constraint node selection scheme, according to the three network densities. These results of the analytical model indicate that through the region constraint scheme, the maximum values of the routing balance ratio decrease for all the conditions examined, compared to the random scheme. This improvement is caused by forcing more data to be transmitted through the inner-sub-regions of a region. From the figures, it can be seen that the curves for the region constraint scheme are much flatter than those for the random scheme. The special characteristic of the routing balance ratio of Region 1 is due to the value of the radius, r_t, of Region 1.

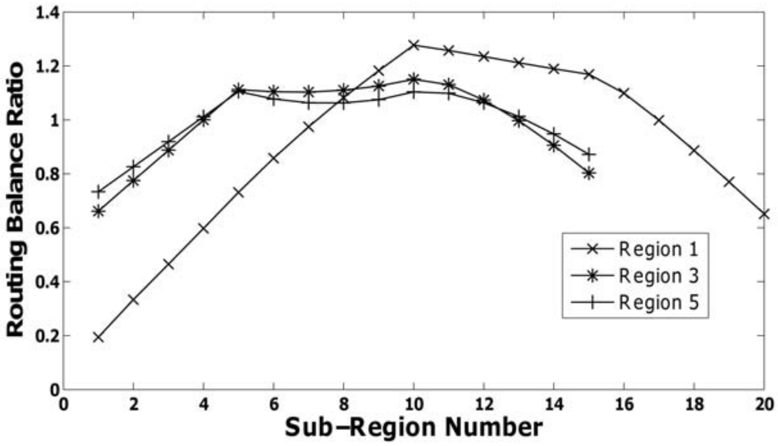

Figure 5-14: Routing Balance Ratio ($\lambda_n = 0.5$)

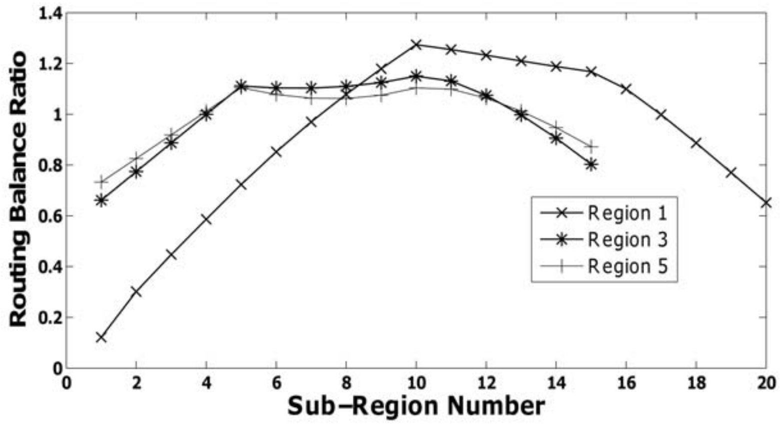

Figure 5-15: Routing Balance Ratio ($\lambda_n = 0.1$)

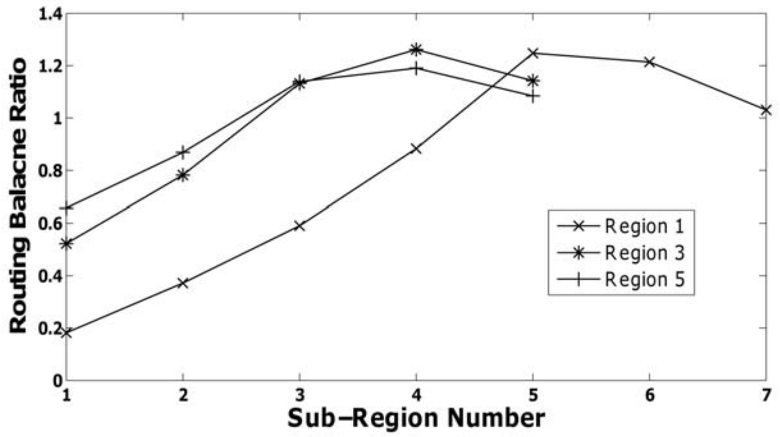

Figure 5-16: Routing Balance Ratio ($\lambda_n = 0.04$)

In Figures 5-17 and 5-18, the simulation results of routing balance ratio for sub-regions of Regions 1 and 5, according to network density 0.1 are provided along with the corresponding numerical results. Figures 5-19 and 5-20 present the results with the network density 0.04. These results prove the accuracy of the analytical model for the region constraint selection scheme. Since the distribution of nodes among regions will be more random in the sparse network, the differences in results between simulation and analysis will widen in networks with a lower value of λ_n as indicated by the results.

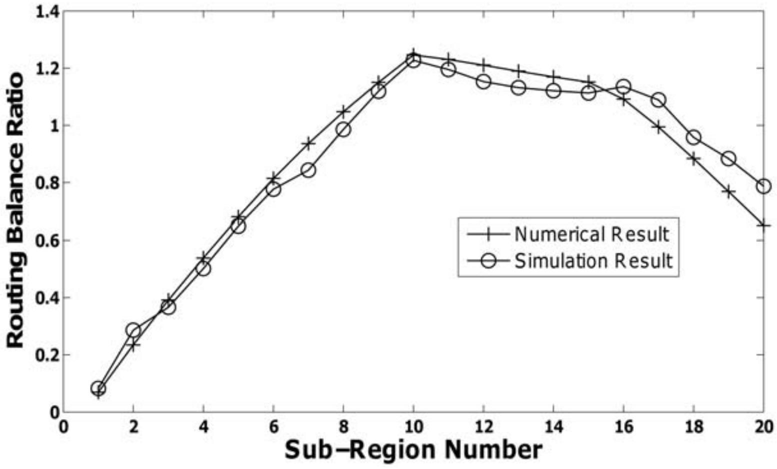

Figure 5-17: Routing Balance Ratio (Region 1, $\lambda_n = 0.1$)

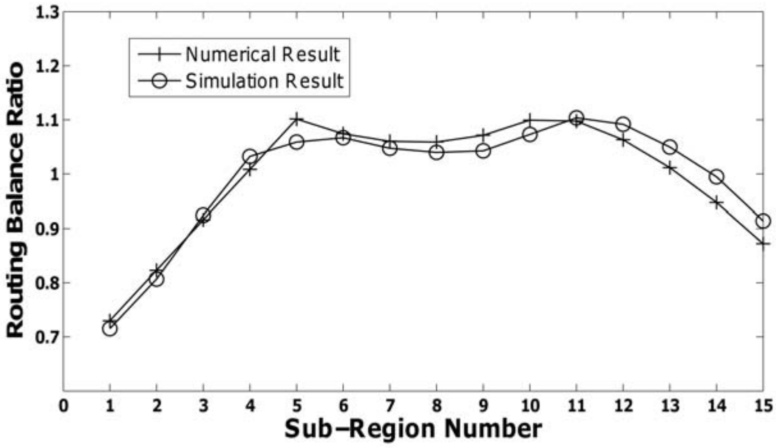

Figure 5-18: Routing Balance Ratio (Region 5, $\lambda_n = 0.1$)

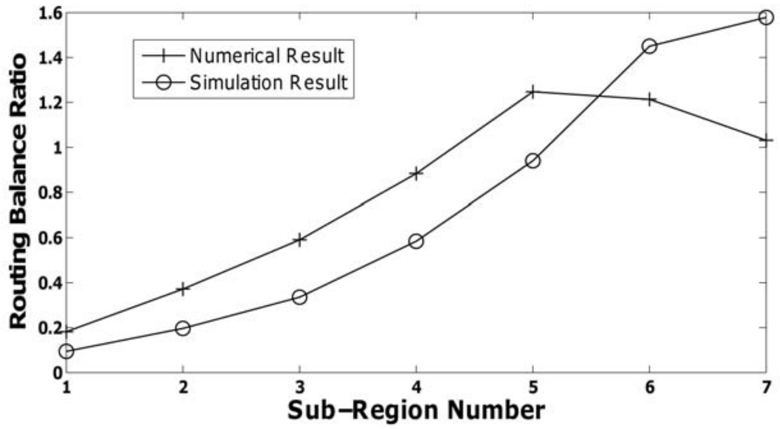

Figure 5-19: Routing Balance Ratio (Region 1, $\lambda_n = 0.04$)

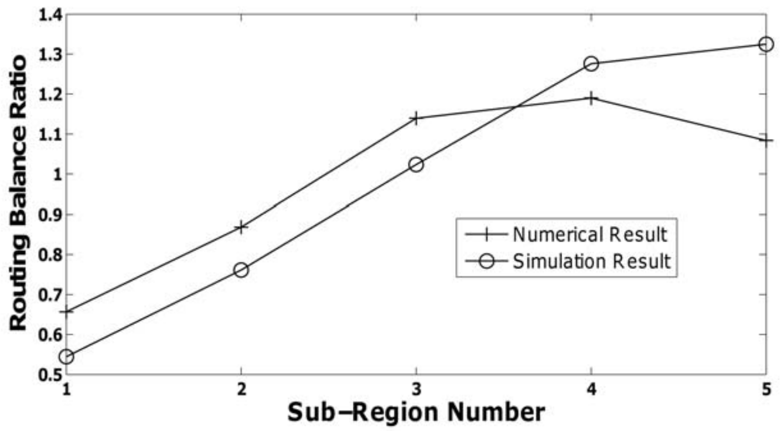

Figure 5-20: Routing Balance Ratio (Region 5, $\lambda_n = 0.04$)

Figures 5-21 and 5-22 present the simulation results for the maximum values of routing balance ratio for each region, obtained by random and region constraint scheme, according to the network density values of 0.1 and 0.04 respectively. These results imply that the energy used for the region constraint scheme is more balanced than the random node selection mechanism. Since the distribution of nodes among regions will be more random in the sparse network, the performance of the region constraint scheme will decrease in networks with lower λ_n as indicated by the results.

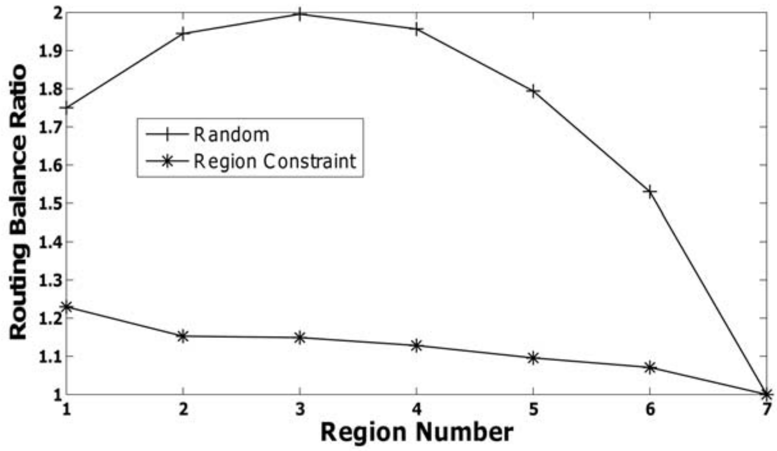

Figure 5-21: Maximum Routing Balance Ratio ($\lambda_n = 0.1$)

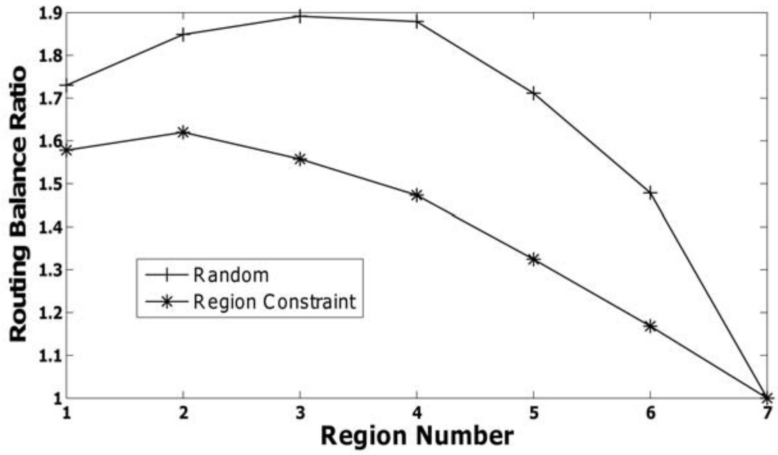

Figure 5-22: Maximum Routing Balance Ratio ($\lambda_n = 0.04$)

5.6.4 Performance

In this section, the simulation results for evaluating the performances of the random selection scheme, region constraint strategy, maximum energy method and hybrid mechanism are presented. The simulation model used in this section also follows the system model presented in Section 5.2. In this section lifetime is defined as the time during which all nodes are alive. This definition is the same as the one used in Chapter 4. This period of time is measured through the number of transmission cycles. Based on the results provided in previous sections, the unbalanced energy consumption levels among sub-regions in Region 1 for both the random scheme and the region constraint scheme are high. Thus Region 1 is the typical region for evaluating the performances of the two mechanisms. Additionally, as the improvement of the hybrid scheme is also due to the reduction of the unbalanced energy consumption level among sub-regions, it is also appropriate to test the performances of the hybrid scheme and the maximum residual energy scheme through the lifetime of Region 1.

Figure 5-23 presents the results of lifetime, according to the energy information update rate, *obtained through simulation experiments*, with the four mechanisms mentioned in this chapter, under the network density of 0.1. The curves indicate that the region constraint node selection scheme significantly prolongs the lifetime of Region 1, when compared to the lifetime of the random mechanism. Both the maximum residual energy node selection scheme and the hybrid scheme perform far better than the other two schemes. However the hybrid scheme with region constraint strategy has a prolonged lifetime when compared to the maximum energy mechanism. When the synchronisation cycle is 0, which is the situation that the system uses real-time energy information, the performance is severely decreased. This is because each node needs to communicate with all its neighbours to gather the residual energy information, and thus each of its neighbour nodes must send this information to it. With a cyclic gathering scheme, each node only needs to synchronise information through broadcasting the information once per cycle. When the system uses a cyclic gathering method to obtain the energy information, which is the case when the synchronisation cycle is at least 1 with the increase of the energy information update cycle, the performances of the maximum energy scheme and the hybrid scheme lowers. The explanation for this is that with the increase in the inaccuracy of the energy information, the two mechanisms will perform more randomly. The hybrid scheme will then behave similarly to the region constraint scheme and the maximum energy mechanism will perform close to the random scheme. The performance outcomes in terms of network density value 0.04 are presented in Figure 5-24. It shows the same trend for all the routing strategies with network density value 0.04 as that for all the routing strategies with the network density 0.1. This figure shows that the schemes with region constraint perform better than the schemes without it. The reason that the improvement is not as dramatic as in the network with the network density 0.1 is that for the sparse network, the spatial distribution of the nodes among regions will be more random. This randomness will affect the performance of the region constraint strategy.

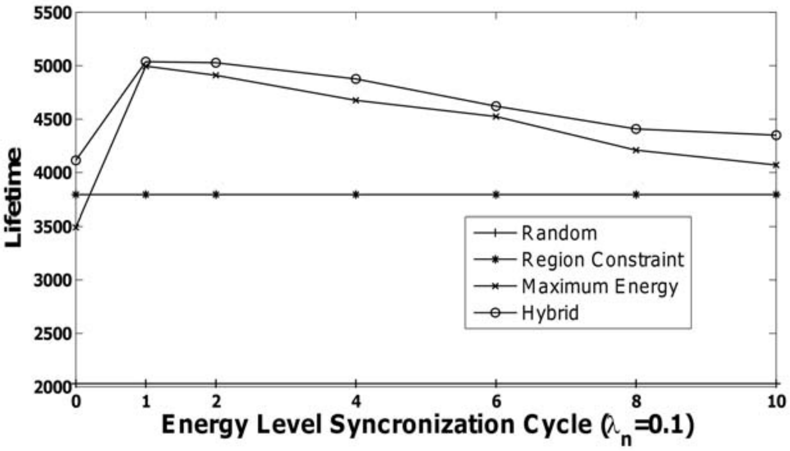

Figure 5-23: Lifetime of Region 1 ($\lambda_n = 0.1$)

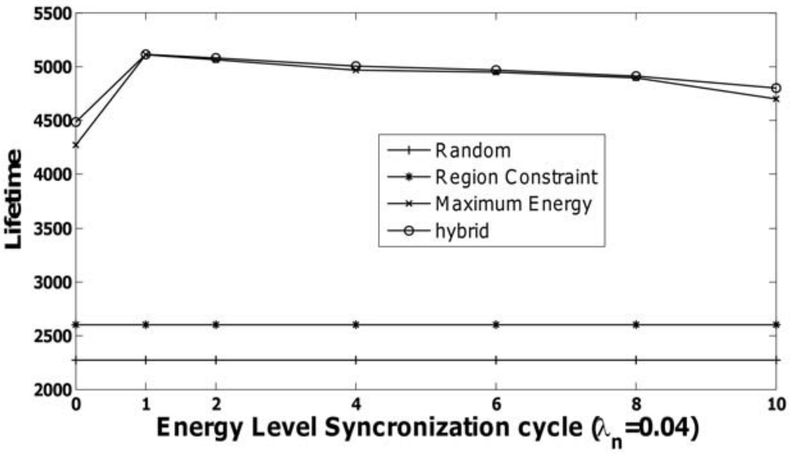

Figure 5-24: Lifetime of Region 1 ($\lambda_n = 0.04$)

5.7 Summary

In this chapter, the problem of the spatially unbalanced energy consumption in the region-by-region routing scheme is examined.

The results of the analytical model and simulation experiments illustrate that this is a serious problem with the pure random node selection scheme. As a resolution for the issue of spatially unbalanced energy consumption, this chapter provides a region constraint scheme which does not need the energy information. Experimental results show that this scheme produces noticeable improvements in lifetime performance, when compared to the random mechanism.

For the mechanisms based on the propagation of the residual energy information of the node, the influence of the information synchronisation frequency on the performance is examined. Experimental results indicate that when real-time information is used, the system suffers seriously from the cost of the residual energy information dissemination. Also, experimental results imply that when the frequency lowers, the maximum energy strategy will perform closer to the random scheme, while the hybrid mechanism will behave more like the region constraint scheme. Under all circumstances considered in the experiments in this chapter, the hybrid scheme's performance is better than that of the maximum energy scheme. This proves that the maximum energy scheme also suffers, although only slightly, from the spatially unbalanced energy consumption problem, and thus can be improved through the hybrid strategy proposed in this chapter.

Chapter 6: Adaptive Duty Cycle Scheduling

6.1 Introduction

The sensor nodes in a mobile sensor network system need to exchange data among each other in order to increase the data delivery rate. However the energy provision constraints of single nodes and the lifetime requirement of applications make it essential for nodes to work in a low duty cycle for energy conservation. Since nodes can only discover each other for data exchange through beacon transmission and reception, the possibility that a node with a fixed duty cycle scheduling strategy will detect other nodes is very low. In this situation, the energy used for beaconing will not be effectively exploited. For increasing the efficiency of energy use, the authors of [113] proposed a scheme for networks with a periodic motion pattern. With this method, on the first day a node will spread its energy use evenly by working at pre-determined fixed intervals. Within this working cycle, the node will record any encounters according to the encounter time. The node will then determine the duty cycle schedule for the second day by calculating a reward function based on the encounter information of the previous day. Each day, the node uses the encounter information from the previous day to update the duty cycle through a learning process. This method will intuitively allocate more energy for the hours when there were more encounters in the previous day. Since nodes in a network with a periodic motion pattern will appear in certain place in the network at approximately the same time every day, this scheme is applicable in this scenario. However this method is not suitable for networks with a non-periodic motion pattern. In networks where nodes move non-periodically, the encounters of the nodes each day will be different from the previous day. As a consequence, the peak time for the encounter cannot be predicted from the information gathered previously. Even using the learning process, it is not possible to predict the encounter time of the nodes.

It is useful to look at an example in the context of both networks with a non-period motion pattern and without a non-period motion pattern. If the peak time for node encounters in a certain day occurs at 1 o'clock, the learning process will use this information along with the data concerning the number of encounters from previous days to make the decision about when the node will work the following day. If the decision is to arrange more energy at 2 o'clock in the following day, the node will decrease its energy exploitation for node discovery at other times during the day. However, in a non-periodic network, the peak encounter time might happen any time. If the peak time is at 5 o'clock but the node is in a low duty cycle, this encounter peak will not be detected, leveraging this decision-making strategy. Consequently, in this circumstance the energy efficiency for this scheme cannot be effectively increased and the problem of duty cycle scheduling for a network with non-periodic motion pattern still requires investigation.

It is noted that the most effective strategy for the duty cycle scheduling is to adjust the duty cycle of a node according to a change in the number of the neighbouring nodes. However it is impossible for a node to sensitively detect changes in the number of neighbour nodes in real-time, so it is necessary for another motion pattern to be leveraged for the design of a duty cycle scheduling scheme. Research on the motion patterns of animals reveals that the animals' movement follows the pattern of forming flocks [131–133]. During the flocking period, the number of the neighbouring nodes of a certain node is relatively stable, thus it will be possible for a node to detect the occurrences of flocks and modify its duty cycle accordingly. In this chapter a duty cycle scheduling scheme based on flock detection will be presented that can be used with mobile nodes, following the pattern of forming flocks.

The chapter is organised as follows. In Section 6.2, the system model used in this chapter is presented. The scheduling problem for this chapter is rigorously described in Section 6.3. The following section provides the arrangement of the basic work cycle and an analysis of the neighbour node number evaluation method. A duty cycle scheduling scheme that exploits the analytic results from Section 6.4 is proposed in Section 6.5. In order to increase the sensibility of the flock detection, the configuration of the listening period of the basic working cycle is studied in Section 6.6. The experimental results are provided in Section 6.7 and Section 6.8 concludes the chapter.

The main contributions of this chapter are: the neighbour node number evaluation method is proposed based on analytical result; the flock detection scheme is provided by using the neighbour node number evaluation method; the adaptive duty cycle scheduling scheme is presented according to the flock detection scheme; and experimental results are presented that show that the proposed scheme is capable of significantly increasing the performance of the efficiency of the energy use of the sensor node.

6.2 System Model

The network considered in this chapter is composed of sensor nodes attached to mobile objects. Each node needs to gather information from the object that it is attached to. The sensed data needs to be transmitted to base stations in the network field. In order to perform data transmission, each sensor is equipped with a radio transceiver with the static transmission range of r_t. Within the transmission range, nodes can communicate with each other. As nodes will not be in the transmission range of the base stations with high probability, each node needs to use beaconing to search for other sensors to transmit its data in order to increase the chance of data delivery. The scheduling is configured to be a Poisson process determined by the intensity parameter λ, by generating random numbers following exponential distribution. Each beacon contains the information of its sender node, including the current duty cycle of the sender node. The energy of nodes is assumed to be provided by batteries and limited. All the nodes have the same amount of initial energy provision. The longevity requirement of the application is T_L and a node does not have enough energy to keep active during the whole lifetime.

The motions of nodes are assumed to be in the pattern where the nodes will gather together and form the stable structure of a flock for a certain period of time. Nodes in the flock will patrol together towards a certain direction. During the flocking period, the number of the nodes within one node's transmission range will remain relatively unchanged. They will then depart from each other and distribute sparsely in the network field. It is further assumed that occurrences of flocks are in a non-periodic pattern.

6.3 Problem Description

Due to a conflict between the constrained energy provision of a node and the network lifetime requirement of an application, the duty cycle of each node needs to be properly adjusted so that it can effectively discover neighbouring nodes while still keeping energy consumption as low as possible in order to fulfil the application's lifetime requirement. The design goal of the duty cycle scheduling scheme is to maximise the nodes' detection efficiency while operating under energy restrictions, which can be evaluated in terms of the number of nodes detected by a certain sensor using the unit energy. Hence it can be obtained through determining the ratio of the total number of nodes detected by a certain node and the total energy used by the node for beaconing during the whole lifetime of the sensor. Divide the required lifetime of the network into T_l small number of time slots and let N_{dect_i} be the number of nodes detected by a certain node in time slot t_i. The optimisation problem can be described as follows

$$\begin{aligned} &max\ r_{dec} = \frac{\sum_{t_i=1}^{T_l} N_{dect_i}}{\sum_{t_i=1}^{T_l} e_{t_i}} \\ &s.t.\ \sum_{t_i=1}^{T_l} e_{t_i} \leq e_{ini} \end{aligned} \tag{6-1}$$

where e_{t_i} is the energy consumption of a node in time slot t_i and e_{ini} is the total energy available for the node detection. Thus the ratio r_{dec} stands for the number of nodes detected by the use of a unit energy. It can be noted from (6-1) that two approaches can be used to increase the value of r_{dec}. The first one is to raise the value of N_{dect_i}, which is the amount of detected neighbours. The other is to decrease the energy use of the node, which is represented by e_{t_i}. When the neighbour node number of a node is large, the amount of the detected nodes will increase accordingly with the rise of the power consumption. On the contrary, the increase of e_{t_i} will not lead to significant improvement in N_{dect_i} if the neighbour node number is low. Hence the most efficient scheme for maximising r_{dec} is to adjust the energy use of the node proportional to its neighbour node number. In simple terms, this strategy is to use more energy for node detection, when there are more nodes within the communication range.

In order to use this strategy, a change in the density of neighbouring nodes needs to be detected. With a low duty cycle and low network density, it is impossible for a node to detect a change in the number of neighbouring nodes. However, when the network density is high, the number of neighbouring nodes can be estimated using a low duty cycle. Normally animals, including humans, occasionally gather together to form flocks with a relatively stable structure. During this flocking period, the network density will be much higher than usual. Thus if the flock is properly detected by a node, the duty cycle schedule can be adjusted accordingly for increasing r_{dec}.

6.4 Neighbour Node Number Evaluation

In order to detect a change in the density of neighbouring nodes, it is essential for a node to be capable of estimating the number of neighbouring nodes. Since the only information about the neighbouring nodes available to a sensor node is the beacons received from other nodes, any method for the estimation of the number of the neighbouring nodes needs to be based on this information. If the number of the neighbouring nodes is small, the interval time between the two consecutive beacons will be long. On the contrary, if the average beacon arrival interval time is short, the network density can be considered high. Consequently, the beacon inter-arrival rate is an important factor for the design of the neighbour node number estimation method. For stably evaluating the beacon inter-arrival rate, the establishment of the work cycle of a node is necessary. Hence this section firstly addresses the arrangement of the work cycle, including the design of the basic working unit for a node to perform beacon transmission and listening operation. The design also deals with the fundamental scheduling of a node. The scheduling is configured to be a Poisson process determined by the intensity parameter λ, by generating random numbers following exponential distribution. By changing this parameter, the duty cycle of a certain node can be adjusted.

Since the value of the parameter λ can also be encapsulated into beacon messages, the receiver of the beacon can also exploit the information obtained from the beacon to estimate the number of neighbouring nodes. According to the property of the Poisson process, the combination of the several Poisson processes is also a Poisson process; thus the beacon inter-arrival rate for a node can be regarded as a Poisson process. As the number of the listening operations for a node also follows a Poisson distribution, the cumulative distribution function of the inter-arrival time of the beacons according to the duty cycle parameters of the neighbouring nodes for a node can be derived. As a consequence the expected value of the beacon inter-arrival time can be obtained. The second part of this section will investigate the calculation of this expected value.

The method for estimating the number of the neighbouring nodes according to the expectation of the beacon inter-arrival time can be obtained with this expectation value, and is demonstrated in Section 6.4.3. Since the expected beacon inter-arrival time can also be evaluated by a node through the received beacons, this method can be leveraged by a node to estimate the number of the neighbouring nodes.

6.4.1 Work Cycle Arrangement

Energy constrained sensor devices like Motes [27, 28] need to stay in inactive mode to save energy. In an inactive state, the sensor node turns off all the onboard units and is unable to send and receive beacons for node detection. Thus in active cycle, the node needs to arrange its tasks to perform listening and beacon transmission. In this chapter an active cycle is a combination of one or more basic working units. Each basic working unit includes one beacon transmission and a listening period of τ seconds.

When the basic working unit starts, the node tries to send a beacon first then switches into a listening period as shown in Figure 6-1. The time between two successive beacons is set to follow a Poisson process with the intensity λ. If there is no more beaconing after a listening period, the node turns to inactive mode until the beginning of the next beacon transmission. In this arrangement, the value of the intensity λ is the parameter controlling the duty cycle of the node.

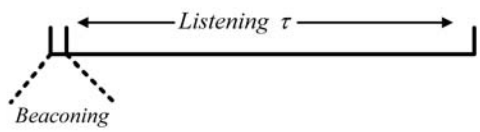

Figure 6-1: Basic Working Unit

6.4.2 Beacon Arrival Rate

With the change of the number of neighbouring nodes, the arrival rate of beacons detected by one node using certain duty cycle will vary. When the flock occurs, the beacon arrival rate for one node will be relatively stable. Hence the analytical result for the beacon arrival rate can be used for detecting of the occurrence of a flock.

Suppose that there are k neighbouring nodes for a node with duty cycle λ. The neighbouring node i ($i = 1, 2, \cdots, k$) is working at duty cycle λ_i. Since the beaconing for each node follows a Poisson process with density λ_i independent of other nodes, the arrival of the beacons from neighbouring nodes for the node can be regarded as a Poisson process with intensity, λ_A, which is derived as

$$\lambda_A = \sum_{i=1}^{k} \lambda_i \tag{6-2}$$

Thus the cumulative distribution function for the inter-occurrence time, z, of the beacons can be calculated as

$$Pr(z \leq t) = 1 - e^{-t\lambda_A} \tag{6-3}$$

Under the condition that the detecting node triggers N_t basic working units in time period t, the probability for the beacon inter-arrival time, z_d, larger than t is

$$Pr(z_d \geq t \mid N_t) = Pr(z \geq N_t\tau) = e^{-N_t\tau\lambda_A} \tag{6-4}$$

Because of the Poisson distribution of the occurrences of beacons, the probability for $z_d \geq t$ can be derived as

$$\begin{aligned} Pr(z_d \geq t) &= \sum_{N_t=0}^{\infty} Pr(z_d \geq t \mid N_t) Pr(N_t) \\ &= \sum_{N_t=0}^{\infty} e^{-N_t\tau\lambda_A} \cdot \frac{(\lambda t)^{N_t} e^{-\lambda t}}{N_t!} \end{aligned} \tag{6-5}$$

Hence the cumulative distribution function of z_d can be obtained as

$$Pr(z_d \leq t) = 1 - e^{-\lambda \cdot t(1 - e^{-\tau\lambda_A})} \tag{6-6}$$

The expected value of z_d is

$$E(z_d) = \frac{1}{\lambda(1 - e^{-\tau\lambda_A})} \tag{6-7}$$

6.4.3 Neighbour Node Number Estimation

If the average duty cycle of k neighbours is $\overline{\lambda_k}$, λ_A can be rewritten as

$$\lambda_A = k \cdot \overline{\lambda_k} \tag{6-8}$$

Denote $\overline{T}$ as the expected value of z_d. The equation (6-7) can be expressed as

$$\overline{T} = \frac{1}{\lambda(1 - e^{-\tau k \cdot \overline{\lambda_k}})} \tag{6-9}$$

Thus the number of the neighbours, k, is able to be derived by

$$k = \frac{1}{\tau \overline{\lambda_k}} ln \left(\frac{\overline{T}\lambda}{\overline{T}\lambda - 1} \right) \tag{6-10}$$

6.5 Adaptive Scheduling Scheme

Exploiting the method for estimating the number of the neighbouring nodes, the flock-based adaptive duty cycle scheduling scheme will be presented in this section. Since at the beginning of the system a node does not know what the network density is, an initial duty cycle needs to be assigned to the node. The setting of the initial duty cycle must ensure the fulfilment of the lifetime requirement of the application. Firstly, the calculation of the value of intensity parameter for the initial duty cycle will be addressed. This calculation is determined through spreading the energy of a node evenly across the whole required lifetime of the application.

Although under a very low duty cycle, a node is not able to effectively detect a change in the number of neighbouring nodes when the network density is low, if the network density becomes high enough, the node can exploit the estimation method proposed in the previous section to discover this density change. When nodes gather together and form the relatively stable structure of the flock, the network density will become high. Hence the occurrence of a flock can be detected by a node using the neighbour node number estimation method.

In the second part of this section, the flock detection strategy will be presented. By recording the arrivals of beacons, the average beacon inter-arrival time can be evaluated. Furthermore the average value of the duty cycle of the beacons can also be calculated by leveraging the duty cycle information obtained from the beacons. Through these evaluated results, the number of neighbouring nodes can be estimated. In order to decrease the distortion of estimation, the average value of several estimated results will be used as the final result for each evaluation of the number of the neighbouring nodes. For the further reduction of the distortion of the estimation, the filter on the beacon inter-arrival time is defined through standard deviation. Another similar filter is defined on the estimated number of the neighbouring nodes. Only when each filter is within the corresponding threshold can the estimation be regarded as valid. If the valid estimation of the number of the neighbouring nodes is over the pre-determined threshold, a node can be considered to be in the flock and will adjust the duty cycle accordingly. Since the network might normally be in a certain density level, a node does not need to respond to the detected network density change if the change is not significant. This is the reason for the exploitation of the flock threshold.

When a flock is detected, a node needs to adjust the duty cycle accordingly. The adjustment is issued in terms of the detected flock size. As a node should not consume all of its energy during one flock period, a restriction on the node's energy consumption is deployed. This constraint is defined through the pre-defined minimum inter-flock time determined by an application. A node can only consume the energy equivalent to the amount for it to use during the minimum inter-flock time under the initial duty cycle. The fundamental purpose of the adjustment rule is to distribute the energy evenly across the flock period. If the flock is much larger than the flock threshold, the energy distribution period should be small so that the node can fully leverage the flock period. When the flock size is close to the flock threshold, the distribution period needs to be longer due to the possibility of the formation of a larger flock. In the proposed duty cycle adjustment rule, the energy distribution period is between the pre-defined average flock period and the maximum flock period determined by the application. The energy distribution period is calculated proportional to the decrease of flock size relative to the flock threshold. Through a similar rule a node can also change the duty cycle according to the change of the estimated flock size. These rules will be demonstrated in Section 6.5.3 and Section 6.5.4 respectively. After the discussion of the adjustment rule, the whole duty cycle scheduling scheme will be described at the end of this section.

6.5.1 Initial Duty Cycle

In order to fulfil the network lifetime requirement with the energy constraints of the nodes, initially the energy of each node needs to be distributed equally overtime. Hence the initial duty cycle of each node, $\overline{\lambda}$, is

$$\overline{\lambda} = \frac{\kappa}{T_L} \tag{6-11}$$

where κ is the number of the basic working unit that is able to be supported by the initial energy of the node e_{ini}. The value of κ is

$$\kappa = \frac{e_{ini}}{e_{cycle}} \tag{6-12}$$

where e_{cycle} is the energy consumption of each basic working unit, which can be derived as

$$e_{cycle} = \tau \cdot e_l + l \cdot e_t \tag{6-13}$$

where e_l is the energy cost for listening, e_t is the power consumption for transmitting one bit of data and l is the size of a beacon.

6.5.2 Flock Detection

Leveraging the result provided in Section 6.4, the occurrence of a flock can be discovered through checking the change of the number of neighbouring nodes. When the detected number of neighbouring nodes reaches a stable state, it is considered that a flock has occurred. In order to perform flock detection, the system needs to continuously estimate the number of the neighbouring nodes.

To detect the number of neighbouring nodes, the average beacon inter-arrival time should be obtained through a certain number of successive beacons. Suppose each node uses parameter D to determine the number of beacons. Denote b_i as the i_{th} beacon received by a certain node since the start of the system and let d_i stand for the time between two consecutive beacons, b_i and b_{i+1}. The i_{th} statistics of the expected beacon inter-arrival time, $\overline{d_i}$, can be obtained as

$$\overline{d_i} = \frac{\sum_{j=i}^{i+D-2} d_j}{D-1} \tag{6-14}$$

The corresponding average duty cycle for the D beacons, $\overline{\lambda_{Di}}$, can be estimated as

$$\overline{\lambda_{Di}} = \frac{\sum_{j=i}^{i+D-1} \lambda_{b_j}}{D} \tag{6-15}$$

where λ_{b_j} is the duty cycle information contained in beacon b_j. Thus based on (6-10) the i_{th} estimation of the number of the neighbouring nodes, k_i, is derived as

$$k_i = \frac{1}{\overline{\lambda_{b_i}}\tau} ln\left(\frac{\overline{d_i}\lambda}{\overline{d_i}\lambda - 1}\right) \tag{6-16}$$

Through n^{th} consecutive samples of the number of neighbouring nodes, $k_i \cdots k_{i+n-1}$, the sample mean of the estimations, $\overline{k}$, is

$$\overline{k} = \frac{\sum_{j=i}^{i+n-1} k_j}{n} \tag{6-17}$$

The occurrence of a flock can be determined through the system design parameter K_f. If condition $\overline{k} \geq \delta \cdot K_f$ holds, it is considered that a flock occurs. The purpose of the introduction of the parameter $\delta(0 \leq \delta \leq 1)$ is to tackle the distortion of estimation. If the occurrence of a flock is caused by an estimation $\overline{k}$ with the value smaller than K_f, the value of $\overline{k}$ will be assigned to be K_f.

In order to obtain the stable statistics, a filter on the value of $\overline{d_i}$ is necessary. This filter can be defined through the ratio, $\overline{s_i}$, as

$$\overline{s_i} = \frac{|SD_i - \overline{d_i}|}{d_i} \cdot 100 \tag{6-18}$$

where SD_i can be calculated as

$$SD_i = \sqrt{\frac{\sum_{j=i}^{i+D-2} \left(d_j - \overline{d_i}\right)^2}{D-2}}$$

The stability of the estimated value can be determined through a threshold S. If condition $\overline{s_i} \leq S$ holds, the estimated value of $\overline{d_i}$ is considered stable and can be used for obtaining the corresponding statistics. Similar to the filter $\overline{s_i}$, another filter, $\overline{s_k}$ can be further defined for $\overline{k}$ as

$$\overline{s_k} = \frac{SD_k}{\overline{k}} \cdot 100 \tag{6-19}$$

where SD_k is derived as

$$SD_k = \sqrt{\frac{\sum_{j=i}^{i+n-1} \left(k_j - \overline{k}\right)^2}{n-1}}$$

The stability of $\overline{k}$ can be determined through another threshold S'. If condition $\overline{s_k} \leq S'$ holds, the value of $\overline{k}$ is considered stable and can be used for adjusting the duty cycle.

If a node does not receive any beacons for a long time, it indicates that the number of neighbouring nodes has changed dramatically. In this scenario the node needs to invalidate all the previously stored statistics. This period of time can be defined by a timeout T_X through the expected beacon inter-arrival time derived by (6-9) as

$$T_X = \frac{\gamma}{\overline{\lambda}(1 - e^{-\tau \cdot K_f \cdot \overline{\lambda}})} \tag{6-20}$$

where γ is a system defined scaling parameter.

6.5.3 Duty Cycle Adjustment Rule

When the system detects a flock, the duty cycle needs to be increased accordingly. The fundamental idea of the proposed duty cycle adjustment strategy is to use more energy for beaconing when the node is in a flock, so that the efficiency of the energy consumption can be increased. However, since flocks will also occur in the future, there needs to be a limitation on the total amount of energy that is available for the node to use in the current flock. In the presented duty cycle alternation rule, this limitation is determined by the minimum flock inter-occurrence time $\overline{T_{FI}}$. The total energy available for the node includes the energy that can support the node to work with $\overline{\lambda}$ for the duration $\overline{T_{FI}}$ and the energy that can support the node to work with duty cycle $\overline{\lambda}$ during the flock period. According to the estimated flock size, the following method will arrange the new duty cycle in the flock under the constraint of the available energy. The objective of the duty cycle adjustment rule is to distribute the extra energy determined by $\overline{T_{FI}}$ evenly throughout the period $\overline{T_F}$. Since small flock has the potential of becoming a larger flock in the future, the upper-bound of the energy distribution will be extended towards T_{Fmax} proportional to the decrease of the estimated flock size. The value of the new duty cycle is calculated as

$$\overline{\lambda'} = \overline{\lambda} \cdot \left(1 + \rho(\overline{k}) \cdot \frac{\overline{T_{FI}}}{\overline{T_F}}\right) \tag{6-21}$$

where $\overline{T_{FI}}$ is the system parameter for the minimum flock inter-occurrence time and $\overline{T_F}$ stands for the expected flock duration. The coefficient function $\rho(\overline{k})$ for scaling the distribution range of the extra energy is designed as a function of the estimated flock size $\overline{k}$, which ensures that the distance from the upper-bound of the energy distribution to $\overline{T_F}$ will be proportional to the decrease of the estimated flock size. In order to fulfil this requirement, the function $\rho(\overline{k})$ is defined as

$$\rho(\overline{k}) = \frac{(\overline{k} - K_f)(\rho_{max} - \rho_{min})}{K_{max} - K_f} + \rho_{min} \tag{6-22}$$

where K_{max} is the maximum flock size determined by the application. The terms ρ_{max} and ρ_{min} are

$$\rho_{max} = 1 \tag{6-23}$$

and

$$\rho_{min} = \frac{\overline{T_F}}{T_{Fmax}} \tag{6-24}$$

where the T_{Fmax} represents the maximum flock duration.

6.5.4 Feedback Process

In order to adjust the duty cycle to the change of network structure, it is necessary to process the feedback after the increase of the duty cycle. Let $\overline{k}$ be the new estimation of average neighbour node number. If this new estimation still fulfils the flock condition, the duty cycle needs to be further adjusted according to the value of $\overline{k}$.

The adjustment can be issued similar to (6-21) when the node is still in a flock. However as the node has been in the flock for certain period of time, the calculation of $\overline{\lambda'}$ needs to be based on the expected residual time for the node to stay in the flock. Suppose that t_s is the time that the node spends in the flock. When $t_s < \overline{T_F}$ holds, the expected residual time for it in the flock, t_r, can be obtained as

$$t_r = \overline{T_F} - t_s \tag{6-25}$$

The new value of $\overline{\lambda'}$ can be calculated as

$$\overline{\lambda'} = \overline{\lambda} + \rho'(\overline{k}) \cdot \frac{\overline{T_{FI}} \cdot \overline{\lambda} - n'_{used}}{t_r} \tag{6-26}$$

where n'_{used} is the number of extra basic working units used by the node in the flock during period t_s. Let n_{used} stand for the total number of working units used by the node in time t_s. The value of n'_{used} can be calculated as

$$n'_{used} = n_{used} - \overline{\lambda} \cdot t_s \tag{6-27}$$

The function $\rho'(\overline{k})$ is derived as

$$\rho'(\overline{k}) = \frac{(\overline{k} - K_f)(\rho_{max} - \rho'_{min})}{K_{max} - K_f} + \rho'_{min} \tag{6-28}$$

where

$$\rho'_{min} = \frac{t_r}{T_{Fmax} - t_s} \tag{6-29}$$

If t_s exceeds the $\overline{T_F}$, the new duty cycle can be calculated as

$$\overline{\lambda'} = \overline{\lambda} + \frac{\overline{T_{FI}} \cdot \overline{\lambda} - n'_{used}}{T_{Fmax} - t_s} \tag{6-30}$$

Denote n_{avail} as the total number of the extra basic working units available for the node to use in the flock. It can be derived as

$$n_{avail} = \overline{T_{FI}} \cdot \overline{\lambda} \tag{6-31}$$

Since the occurrence of condition $n'_{used} \geq n_{avail}$ indicates that the node has used up all the extra energy available for the flock period, the duty cycle of the node will be configured as $\overline{\lambda}$ until the end of the flock.

After time period $\alpha \cdot T_X (\alpha \geq 1)$ has passed without receiving a beacon, the node is considered to be out of the flock. The node is also regarded as being out of the flock if the condition $\overline{k} < \delta \cdot K_f$ occurs for consecutive η times. When the node is out of the flock, it needs to shift into sleep mode to compensate for the over-consumption of energy during the flock period. Suppose the average duty cycle for a node in the flock is $\overline{\lambda_f}$ and the node's total working time in the flock is T_{wf}, the sleep period for a node in this occasion, T_{os}, can be calculated as

$$T_{os} = \frac{\left(\overline{\lambda_f} - \overline{\lambda}\right) \cdot T_{wf}}{\overline{\lambda}} \tag{6-32}$$

The node will return to work with the duty cycle $\overline{\lambda}$ after the sleep.

6.5.5 Scheme Description

Each node in a network starts with duty cycle $\overline{\lambda}$. When the occurrence of a flock is detected, it adjusts its duty cycle according to (6-21). Corresponding to the change of the flock size, the duty cycle of the node will be further adjusted, in consideration of the expected residual time for it in the flock, t_r. If the node has used up all the extra energy available for the flock, it will work with duty cycle $\overline{\lambda}$ until the end of the flock. After leaving the flock, the node goes into sleep mode for T_{os} and then returns to the duty cycle $\overline{\lambda}$. The description of the whole process of the scheme is shown in Figure 6-2. In the flow chart, if one of the conditions occurs, the scheme will enter the corresponding procedure. Hence no concurrent execution will occur.

6.6 Configuration of τ

The configuration of τ in the basic working unit is crucial for the sensitivity of flock detection. A small value of τ will lead to short listening duration. As a consequence, the probability that the node will detect beacons will be low. However the duty cycle of the node will decrease with large value of τ, which will also lower the chance of beacon detection. Since the sensitivity of flock detection is proportional to the

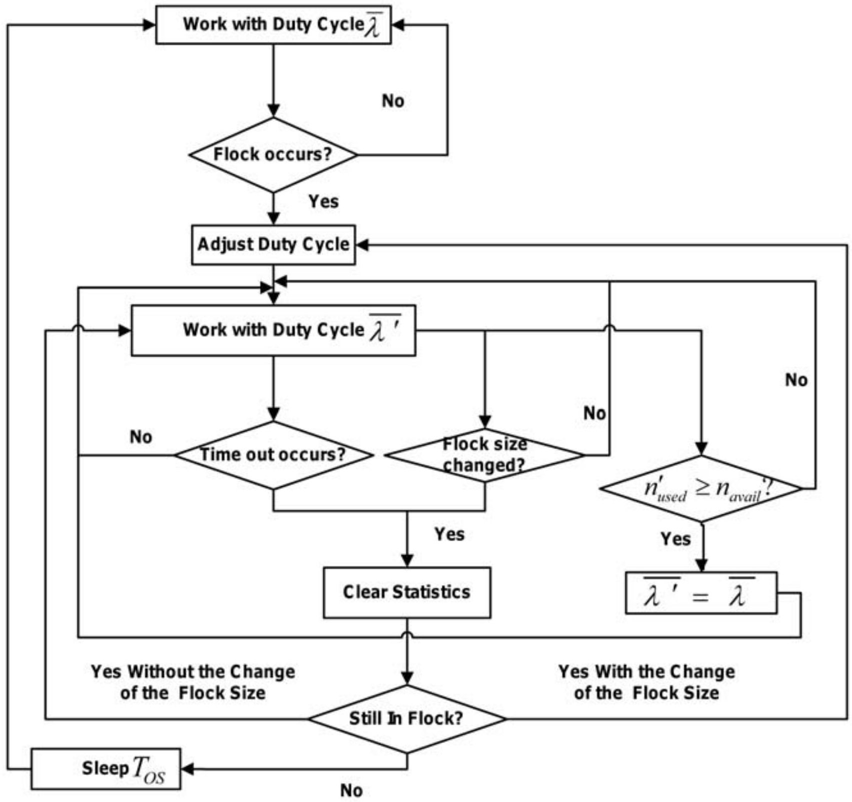

Figure 6-2: The Process of the Scheme

chance of beacon detection, the value of τ for the highest chance of beacon detection will optimise the sensitivity of flock detection.

The measure for the sensitivity of flock detection is the number of the neighbouring nodes, $k(\tau)$, that is needed for a node to detect the existence of another node within an application-specified detection period T, when all the nodes in the flock work on the duty cycle $\overline{\lambda}$. The smaller value of $k(\tau)$ will lead to the higher sensitivity of flock detection. Exploiting (6-10) and (6-11) it can be derived as a function of τ as below

$$k(\tau) = \frac{(\tau \cdot e_l + l \cdot e_t) \cdot T_L}{\tau \cdot e_{ini}} ln\left(\frac{T \cdot e_{ini}}{\Psi(\tau)}\right) \tag{6-33}$$

where

$$\Psi(\tau) = T \cdot e_{ini} - T_L \cdot l \cdot e_t - T \cdot \tau \cdot e_l \tag{6-34}$$

It can be proved that there exists a value of τ that leads to the minimum value of function $k(\tau)$. This optimum value of τ can be obtained through solving the equation $k'(\tau) = 0$, which is a transcendental equation. Using numerical method, this value is able to be found.

6.7 Experimental Results

In this section the performance of the duty cycle scheduling scheme will be evaluated through simulation experiments issued by J-SIM. The configurations of the parameters for the scheme are obtained from analytical results and the simulation experiments. The simulation model follows the system model presented in Section 6.2.

6.7.1 Parameter Settings

The parameter settings for a single node are listed in Table 6-1. The energy consumption model for radio transmission is assumed to be the first-order radio model as follows [70]

$$e_t = e_{elec} + e_{amp} r_t^{\beta} \tag{6-35}$$

This model shows the energy consumption for transmitting one bit. The parameter e_{elec} is the energy consumed for activating the circuit of radio transceiver and the e_{amp} is for the transceiver amplifier to communicate. The energy for listening for one second is only the energy consumed by the transceiver circuit. Thus the e_l is calculated as

$$e_l = e_{elec} \cdot \gamma_t \tag{6-36}$$

where γ_t is the data transmission rate of the node. The parameters related to the data transmission properties are selected similar to the Motes [27, 28]. In the experiments for the performance evaluation, the network lifetime T_L is set to be 9 days. The value of $\overline{\lambda}$ is calculated in accordance with T_L through (6-11). By (6-33) described in the previous section, the configuration of τ is issued by the condition $T = 200s$. In this scenario, the condition $\tau = 0.005s$ will lead to the sensitivity of $k(\tau) \approx 1$. Hence the parameter τ is set as $0.005s$.

The selection of the scaling parameter γ for determining the statistics timeout T_X needs to be examined. This parameter must be large enough so that it will not have serious impact on the generation of statistics when the node is in the flock. However the parameter should also be as small as possible to ensure that the node can react quickly to the change of the amount of neighbouring nodes. In order to obtain this value the probability, $P_{timeout}$, for the occurrence of the timeout when the node is in the flock with stable number of neighbouring nodes needs to be examined.

Table 6-1: Parameter Settings for Single Node

Parameter Name	Value
e_{ini}	$2J$
e_{elec}	$5.0 \times 10^{-11} J/bit$
e_{amp}	$1.0 \times 10^{-11} J/bit$
β	2
r_t	$40m$
l	$160bits$
τ	$0.005s$
γ_t	$250kbit/s$
T_L	$9days$
$\overline{\lambda}$	1

Through the definition of T_X in (6-20) and the cumulative distribution function of z_d provided by (6-6), the $P_{timeout}$ can be obtained as

$$\begin{aligned} P_{timeout} &= Pr(z_d \geq T_X) \\ &= e^{-\lambda \cdot T_X (1-e^{-\tau\lambda_A})} \\ &= e^{-\gamma} \end{aligned} \tag{6-37}$$

For verifying the above analytical result, several simulation experiments are issued. In each experiment, nodes are deployed in the transmission range with each other. Thus each node has exactly the same number of neighbours during the whole process of the simulation. The duration of each experiment is configured to one day. After each experiment, the average value of the estimated probability of the occurrence of the timeout is obtained through the statistics gathered during the simulation. Figure 6-3 shows the results according to the total number of nodes used in each experiment. These results reveal that the simulation results fit the numerical results achieved through (6-37).

Based on the analysis above, the value of γ is able to be determined through the condition $P_{timeout} \leq p_{timeout}$. The ceiling of the largest value that fulfils the condition will be chosen as the configuration of γ. This value can be calculated as

$$\gamma = \lceil -\log p_{timeout} \rceil \tag{6-38}$$

In the following simulation experiments, the value of γ is set as 6 in accordance with the condition $p_{timeout} = 0.3\%$, which is considered small enough for the simulation to generate stable statistics. In real applications the value can be selected by the application according to some specific requirements.

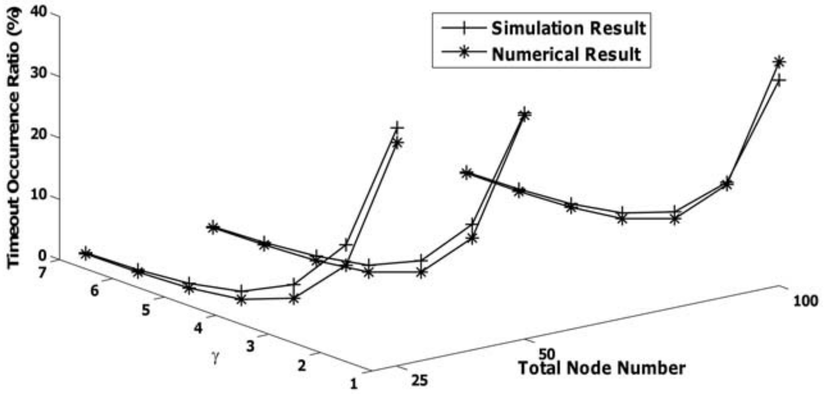

Figure 6-3: Timeout Occurrence Ratio

In order to obtain a stable estimation of the number of neighbouring nodes, the settings of parameters D and n also need to be determined. Since parameter D is the beacon number for forming one sample of the neighbour node number, the parameter D should be large enough to ensure the accuracy of the statistics. Furthermore, as parameter n is the number of samples for generating the estimation of the neighbour node number, it should also be large enough to ensure the accuracy of the statistics. However, if the values are too large, the delay in generating a statistical result will be long. Thus a limitation is necessary for constraining the delay. In the simulation experiment in this chapter, this constraint is determined through the expected value of $\overline{T_{sta}}$, the interval time between the two consecutive statistics, when a node is in a flock with 25 nodes. The value of $\overline{T_{sta}}$ can be calculated in accordance with (6-9). Under the condition of $\overline{T_{sta}} < 15min$, totally 100 beacons can be received averagely. Hence the two parameters can be determined as $D = 10$ and $n = 10$.

In addition to the settings of D and n, the configurations of S' and S also need to be examined. For obtaining the proper values of the two parameters, some simulation experiments are issued to evaluate the impact of S, under the condition of $S' = 30$ with the node in the flock of k_{real} nodes. The evaluations are based on the estimation in-flock ratio defined as

$$r_{ei} = \frac{N(\epsilon \leq \xi) + N(\epsilon > \xi, \overline{k} \geq k_{real})}{N_{etotal}} \tag{6-39}$$

where N_{etotal} is the total number of the neighbour node number estimations formed by the node, $N(\epsilon > \xi, \overline{k} \geq k_{real})$ is the number of estimations that are larger than k_{real} as well as following the condition $\epsilon > \xi$ and $N(\epsilon \leq \xi)$ is the number of estimations that fulfil the condition $\epsilon \leq \xi$. The estimation in-flock ratio measures the proportion of estimations that can correctly indicate if a node is in a flock. The measure of ϵ is defined as

$$\epsilon = \frac{|\overline{k} - k_{real}|}{k_{real}} \cdot 100 \tag{6-40}$$

In Figure 6-4 the results of the simulation experiments for a flock with 25 nodes for different values of ξ, according to threshold S are shown. Similar results for a flock containing 100 nodes are provided in Figure 6-5. These results indicate that when ξ is set to 40, the proper value of r_{ei} can be achieved under the condition of $S = 10$ and $S' = 30$. Since conditions $\epsilon > 1 - \delta = \xi/100$ and $\overline{k} < k_{real}$ lead to the situation of a node to be outside a flock, the parameter δ can be determined from the value of ξ as $\delta = 1 - \xi/100$ and the parameter δ can be set as 0.6. Through the results of r_{ei}, the setting of the parameter η, which controls the decision of whether the node is still in the flock, can also be achieved. As implied by the results in Figure 6-4, the probability for the occurrences of the estimations that lead to condition $\overline{k} < \delta \cdot k_{real}$ is lower than 0.5% with the corresponding configurations of other parameters. Hence the probability for condition $\overline{k} < \delta \cdot k_{real}$ to occur consecutively five times will be $(0.5\%)^5$, which is low enough to be ignored. Consequently if the parameter η, the number of the consecutive occurrence of condition $\overline{k} < \delta \cdot k_{real}$ for the node to make the decision of being out of the flock, is set to 5, the probability that the system will incorrectly regard the node as being out of the flock will be low enough that the value is acceptable for the simulation. Thus the setting $\eta = 5$ is used in all the experiments for the performance evaluation.

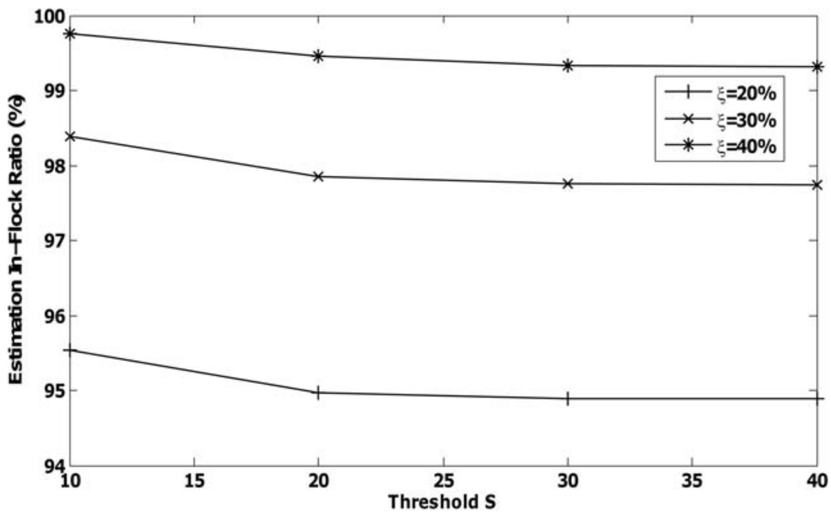

Figure 6-4: Estimation In-Flock Ratio ($k_{real} = 25$)

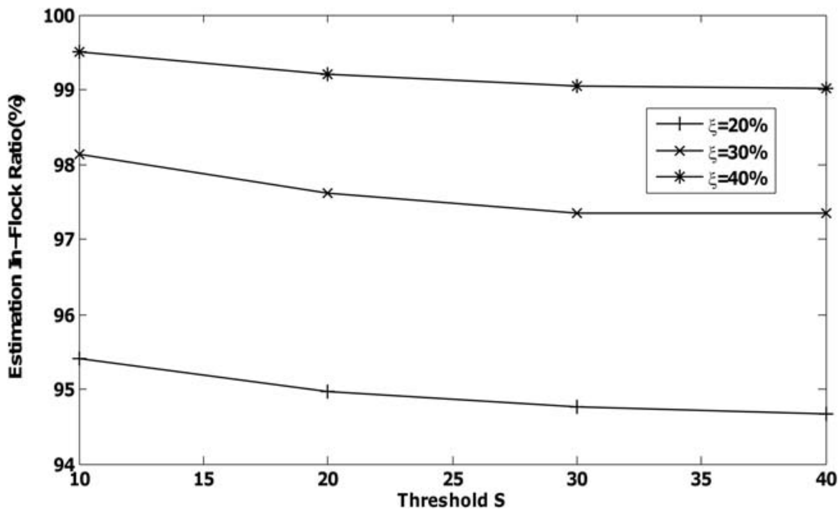

Figure 6-5: Estimation In-Flock Ratio ($k_{real} = 100$)

6.7.2 Performance Evaluation

For evaluating the performance of the proposed scheme, simulation experiments are issued with the total network scales of 25 nodes, 50 nodes and 100 nodes respectively. The network field used in the simulations is a square of $3000m$ by $3000m$. Since the performance of the presented scheme is only affected by the density change of the network, the network size of 100 nodes is large enough for the scenario of a sparse network that is the focus of this chapter. The inter-occurrence time of flocks is uniformly distributed with a minimum value of $5400s$ and a mean value of $10800s$. Similarly the flock period is also uniformly distributed with a minimum value of $1800s$ and an average value of $3600s$. The size of the flock also follows a uniform distribution with the network size as the maximum value and three-quarters of the maximum value as the mean. Since the theoretical metric for the efficiency of energy use, r_{dec}, defined by (6-1) in Section 6.3 is difficult to evaluate in the experiments, an equivalent and practical measure for the experiments is defined as

$$r'_{dec} = \frac{N_{ba}}{N_{bt}} \tag{6-41}$$

where N_{bt} is the total number of beacons transmitted by a certain node and N_{ba} is the total number of sensors that receive the beacons from the node. This ratio measures the average number of nodes that can be reached by a single beacon. Since the probabilities for nodes to receive data from each other can be regarded as the same, statistically the number of nodes detected by a sensor is able to be evaluated by the number of beacons from the sensor detected by other nodes. Additionally, the energy consumption, which is more difficult to measure, can be replaced by the number of beacons transmitted by a node. Hence the measures r_{dec} and r'_{dec} are equivalent. In all the experiments in this chapter the average value of r'_{dec} of all the nodes in the network is exploited for the performance comparison. Each comparison is issued between the system with the duty cycle scheduling scheme and the system with the fixed duty cycle under the same network settings.

In Figure 6-6 the results for the performance comparison are shown according to the network size. It can be seen that with an increase in the network size, the performances for both the duty cycle scheduling scheme and the fixed duty cycle scheme will rise. This is due to the improvement of the chance that nodes will encounter each other. Furthermore the curves also reveal that the duty cycle scheduling scheme can achieve significant increase in the system performance compared to the fixed duty cycle scheme in accordance with all the network size tested in the experiments.

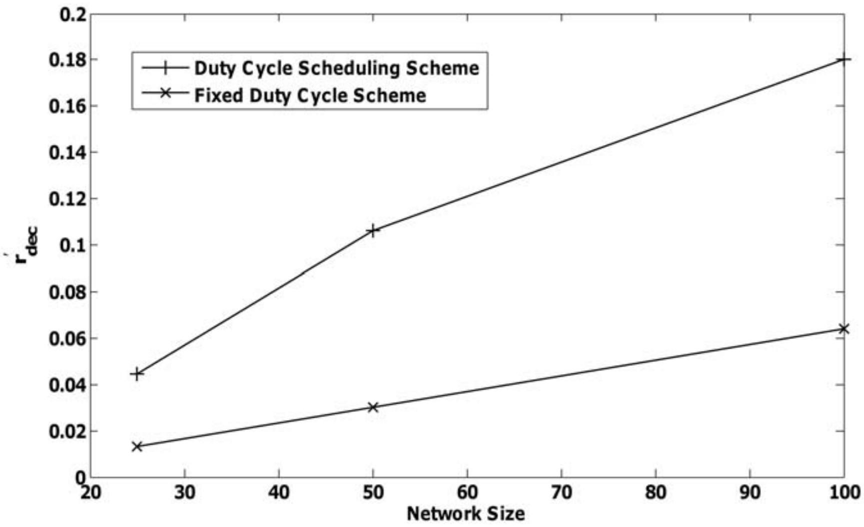

Figure 6-6: Performance According to Network Size

Since the changes of other patterns of the flock will also influence the performance of the presented scheme, experiments are issued to investigate the affections. The effect of the change of the flock inter-occurrence time is studied firstly through several experiments on the network with 25 nodes, 50 nodes and 100 nodes. In these tests the settings of the parameters are the same as the previous experiments, except that the average value of the flock inter-occurrence time changes in each experiment. Figure 6-7 provides the results for the network with 25 nodes. It can be seen that with the increase of the flock inter-occurrence time, the performances of both the duty cycle scheduling scheme and the fixed duty cycle scheme decrease. This effect is due to the decreased frequency of the occurrence of the flock, which leads to the lower chance that nodes will encounter each other. A similar influence of the change of the flock inter-occurrence is also shown by the results in Figure 6-8 and Figure 6-9, which are obtained by doing the same experiments on the networks with 50 nodes and 100 nodes respectively.

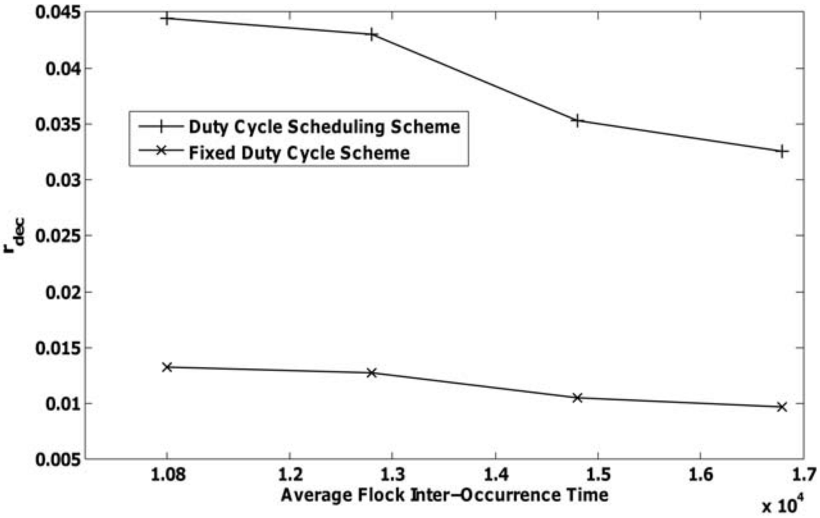

Figure 6-7: Performance According to Flock Inter-Occurrence Time (25 nodes)

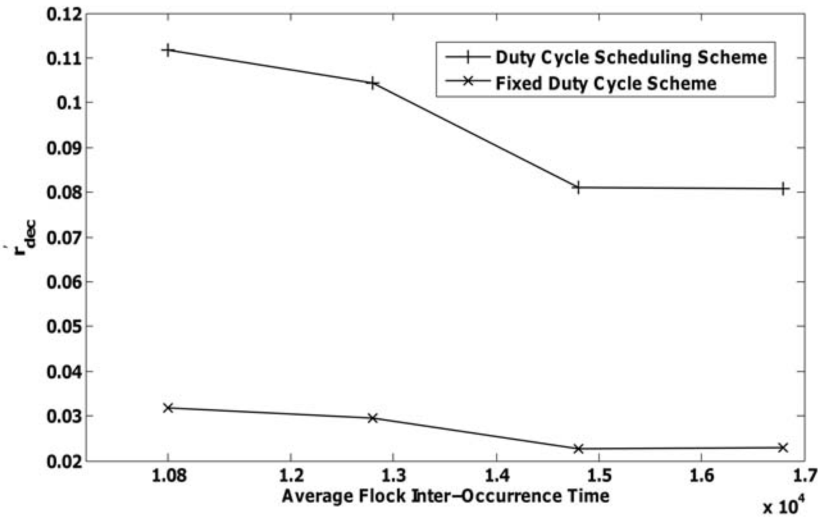

Figure 6-8: Performance According to Flock Inter-Occurrence Time (50 nodes)

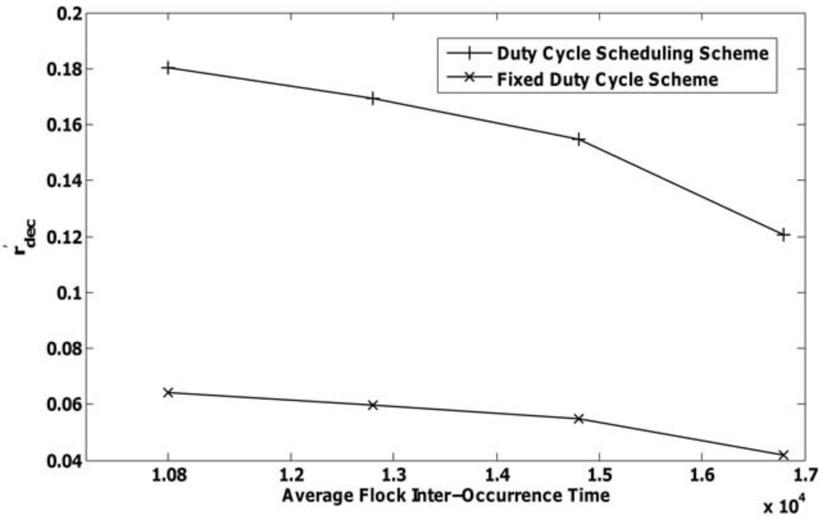

Figure 6-9: Performance According to Flock Inter-Occurrence Time (100 nodes)

Further experiments are also performed by alternating the average flock period of the network. In Figures 6-10, refch6performance5 and 6-12, the results of the networks with 25 nodes, 50 nodes and 100 nodes are provided. These results show that the rise of the flock period will lead to the increase of the performances of both the two schemes. The performance increase is also due to the increase of the encounters of nodes.

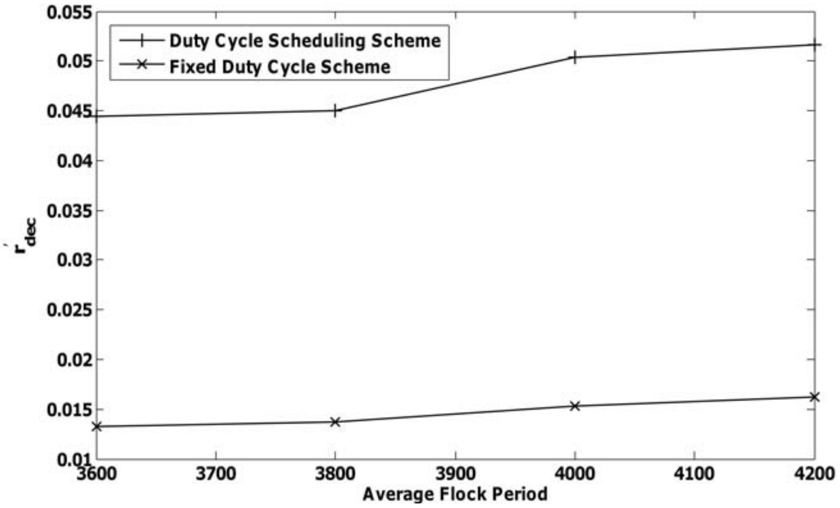

Figure 6-10: Performance According to Flock Period (25 nodes)

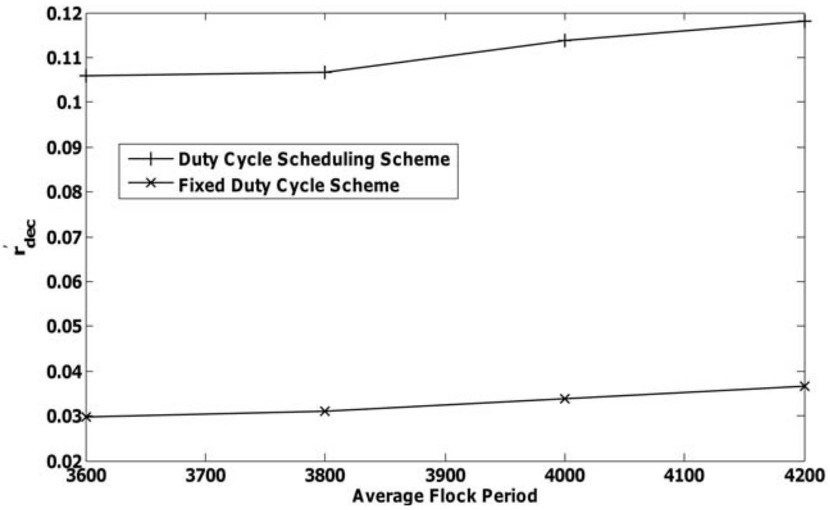

Figure 6-11: Performance According to Flock Period (50 nodes)

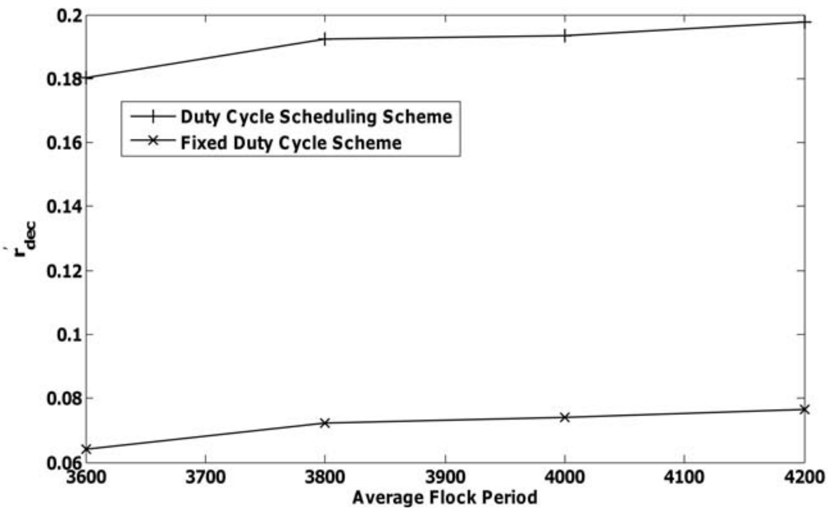

Figure 6-12: Performance According to Flock Period (100 nodes)

The experimental results indicate that the performance of the duty cycle scheme varies in terms of the pattern of the flock. When the flock size or the flock period becomes larger, the increase in the chances for the nodes to encounter will lead to rise of the performance of the scheme. Additionally, a decreased frequency for the occurrence of a flock will lower the chances that the nodes will encounter each other and thus decrease the performance of the scheme. In all the cases studied in the experiments the duty cycle scheduling scheme proposed in this chapter significantly outperforms the fixed duty-cycle scheme.

6.8 Summary

In this chapter, a flock detection based duty cycle scheduling scheme for mobile wireless sensor networks with non-periodic motion patterns is proposed. Aiming at increasing the energy efficiency for node discovery as well as conserving the energy required for the fulfilment of the network lifetime requirement of applications, this scheme adjusts the duty cycle of a node in terms of the change of the number of the neighbouring nodes. Through this method, the duty cycle adjustment can be issued adaptively without the requirement of the periodic node encounter pattern. In order to achieve an estimation of the number of neighbouring nodes, an analytical model is designed based on the Poisson configuration of the fundamental work cycle. Although when working in low duty cycle, a node cannot detect the real-time change in the number of neighbouring nodes, the occurrence of a high network density when nodes form flocks can be discovered through the neighbour node number estimation method proposed in this chapter. Hence a flock detection mechanism is presented based on the neighbour node number estimation method. Exploiting the flock detection, an adaptive duty cycle scheduling scheme is designed in this chapter. The results of the experiments issued by simulations show that the presented adaptive duty cycle scheduling scheme is capable of significantly increasing the efficiency of the energy use of each node when detecting other nodes in network systems with non-periodic motion pattern comparing to the fixed duty cycle scheme. The performance of the scheme is closely related to the frequency of the occurrence of the flocks. With a rise in flock occurrence frequency, the performance of the scheme will increase. The performance of the scheme is also proportional to an increase in flock size, due to the increase of node encounters in the network. All the experimental results indicate that the presented duty cycle scheduling scheme has the ability to improve the energy efficiency of the node discovery for mobile wireless sensor network systems with non-periodic motion pattern.

Chapter 7: Conclusions and Future Works

7.1 Conclusions

The limited energy provision of each node places considerable constraints on the sensor network system. Due to this restriction, it is essential for the proper mechanisms to be developed, so that the energy of the nodes can be conserved and the longevity of the network will be such that the requirement of the application is fulfilled. In this thesis, the issue of conserving the energy of each node and thus prolonging the lifetime of the sensor network system is addressed. Specifically, the energy hole problem and the spatially unbalanced routing problem of the static sensor network system are discussed. The issue of designing an energy-effective duty cycle scheduling strategy for a mobile sensor network system is also examined. As a result of the research undertaken in this thesis, three energy conservation and lifetime prolongation schemes are proposed to tackle the three specific problems.

➢ A non-uniform node deployment scheme was proposed for tackling the energy hole problem of the static sensor network system;

➢ A spatially balanced routing scheme for solving the problem of spatially unbalanced energy consumption in the routing phase of the static sensor network system with non-uniform node deployment; and

➢ An energy-efficient duty cycle scheduling scheme for dealing with the non-efficient energy exploitation of the mobile sensor network system.

Through a literature review of the existing work on the mechanisms of the energy constraint problem of sensor network systems, it has been shown that a practical solution for the energy hole problem is the non-uniform node deployment strategy.

However, no work has taken the energy consumption of the node in the active mode without data transmission and reception into consideration in the establishment of the scheme. The energy use of the working mode cannot be ignored in this situation as many applications require nodes to perform continuous sensing. In this thesis, a novel non-uniform node deployment scheme has been presented that concerns this part of the nodes' energy consumption. By analysing the impact of the spatial density of events on the network, a mathematical model of the amount of data transmission of the system is constructed. Through analysis of the influence of the temporal density of the events to the network system, a theoretical model for the estimation of the network lifetime is established exploiting the model of the amount of data transmission. Leveraging this result the node deployment density of each region in terms of the lifetime requirement of applications can be derived and thus the node deployment strategy is proposed. The numerical results of the analytical model and the simulation results obtained from the network simulation experiments prove the eligibility of the presented scheme.

A sensor network system that uses a non-uniform node deployment scheme needs to transmit data region-by-region to the sink node. In order to ensure the fulfilment of the lifetime requirement of applications for the whole network, the energy consumption during the routing phase needs to be spatially balanced among nodes. If the next hop data relay node is selected randomly, nodes covered by the transmission region of more nodes have a higher probability of being chosen and thus will die faster. Among all of the schemes that have been proposed for balancing the energy consumption of routing, only the maximum residual energy strategy is capable of achieving balanced energy consumption with the region-by-region routing. However, it is essential that special be used equipment for accessing the accurate residual energy information, which increases the cost and complexity of the system. Therefore it is necessary that a spatially energy balanced routing scheme without energy information be constructed. For a system that has access to accurate energy information, nodes with the same energy level will still suffer slightly from the unbalanced energy consumption problem. Furthermore, since the practical method for disseminating the residual energy information of the node is through periodical broadcasting, the accuracy of the energy information will vary according to the variable broadcast period. Thus, a proper method is needed that compensates for the disadvantages of the maximum residual energy scheme. In this thesis the spatially unbalanced energy consumption of the random node selection strategy is analysed and a theoretical model is presented. Through modification of the analytical model, a mathematical model on the balance of the energy consumption for the region constraint node selection strategy is provided and hence the region constraint node selection scheme that does not depend on the energy information of the node is proposed. Through the combination of the region constraint strategy and the maximum residual energy method, a hybrid scheme is proposed that compensates for the disadvantages of the maximum residual energy scheme. The numerical results and the simulation results show that the region constraint scheme is capable of increasing the performance of the system significantly when compared to the random selection scheme and the hybrid scheme can achieve better performance in comparison with the maximum residual energy scheme. With the decrease of the accuracy of the energy information, the performance improvement of the hybrid strategy to the maximum residual energy method will increase.

In a mobile sensor network system, nodes need to exchange information among each other so that the data delivery rate can be increased. Due to the limited energy provision of each single node, it is also necessary for a node to reduce its power usage by working in low duty cycle in order for the lifetime requirement of applications to be fulfilled. Since nodes working in the inactive mode cannot transmit or receive beacons, it is impossible for them to detect each other in this scenario. Hence if the duty cycle of the system is fixed, the possibility for node discovery within the network will be very low and as a consequence the effectiveness of the energy use for the node discovery will also be low. In order to increase the efficiency of the power consumption of the node detection, it is necessary to utilise the proper duty cycle scheduling strategy. Throughout the works reviewed in this thesis, only the duty cycle scheduling mechanism for the network with periodic motion pattern is designed for tackling this problem. However, no work has been done on networks with a non-periodic motion pattern. In this thesis, the duty cycle scheduling scheme for a mobile sensor network system with non-periodic motion pattern is proposed that exploits the flock motion pattern of the network. Through configuring the duty cycle of the node as a Poisson process, an analytical model for the beacon inter-arrival rate according to the number of neighbouring nodes is derived. Based this result, the neighbour node number estimation method is proposed. Leveraging the neighbour node number estimation method, the flock detection mechanism is presented. According to the scale of the flock, the duty cycle adjustment scheme is presented. The simulation results indicate the significant improvement in the performance of the proposed duty cycle scheduling scheme to the fixed duty cycle scheduling strategy.

7.2 Future Works

For the resolution of the energy hole problem, there are still some issues that need to be examined. In this thesis the distributions of events are considered as Poisson processes. However, in a real sensing field the events might have different distributions. Thus the non-uniform node deployment scheme needs to be examined according to different event distributions in future work. Additionally when the scale of the static sensor network system is large, the essential node density for some regions of the network will be so high that it will be very difficult to perform the deployment. Hence, it is necessary to examine this issue in the future. The direct solution for this problem is to divide the whole network into several smaller sub-networks each with a separate sink node. Since using multiple sink nodes will increase the cost of the system, optimising the network division for maximum efficiency is a necessity for reducing the number of the sub-networks.

Another possible method for solving the energy hole problem is combining the cluster routing mechanism and the non-uniform node deployment scheme. Though the cluster routing method cannot effectively solve the energy hole problem, it is effective in decreasing the contention of the network. Thus through the combination of the cluster routing mechanism and the non-uniform node deployment scheme, the performance of the network will be significantly increased. However, the design of the node deployment strategy will need to be reconsidered when used with the cluster routing scheme. Since the cluster scheme will perform data aggregation or compression, the impact of this operation on the amount of data transmission needs to be generalised and taken into consideration when designing the node deployment scheme. Additionally, the cluster formation mechanism also requires reconstruction to fit the node deployment strategy.

According to a certain method for solving the energy hole problem, the corresponding issues with the energy balance of the routing phase also need to be considered further. For networks with multi-sinks, the routing strategy that dynamically arranges the data flow among the multiple sinks can also be taken into consideration for balancing the energy consumption of the network. If the cluster routing is used, it is essential that the energy consumption be balanced spatially among the clusters. The size of the clusters needs to be even so that the energy consumption of cluster heads can be balanced. This requirement demands an energy balanced cluster formation scheme and that the data routing among cluster heads be balanced spatially. Hence the spatially energy balanced routing scheme outlined here also needs to be investigated in the future.

This thesis proposed a duty cycle scheduling scheme for the mobile sensor network system. One aspect of this scheme that needs to be investigated further is the joint optimisation method of the system parameters. The design of alternative filters for achieving the statistics is also a potential direction for improving the performance of the presented scheme. In addition further modification of the duty cycle adjusting method that considers balancing the transmission chance for each packet also needs to be examined.

Since it is also important to control the packet replication during the data exchange stage, the design of a data transmission control scheme suitable for a system with an adaptive duty cycle scheduling scheme also needs to be considered. With the flock-based duty cycle scheduling scheme, it is possible to leverage the inter-occurrence time of the flocks for the design of the data transmission control scheme. In order to establish such a mechanism, the analytical model for the impacts of the data replication control factors on the performance of the system through the inter-occurrence time of the flocks should be analysed. Additionally, a method that estimates the data delivery probability using the same parameter also needs to be established. Based on these analytical results the corresponding data transmission control scheme can be designed.

Due to the strong research interests into creatures' behaviours when they form flocks, the flocking pattern the motions of the nodes can be employed to design a data aggregation scheme for the mobile wireless sensor networks. This scheme needs to perform the data aggregation operation through application-defined statistical functions during the flocking period. In this process nodes will retrieve information from other nodes and aggregate the data obtained to form a set of values. This procedure will decrease the size of the stored data. The aggregated value formed can then be redistributed for the nodes to form new values with a wider view of the flock.

In a mobile wireless sensor network, the static base station will lead to a high latency of data delivery. By exploiting the mobile sink nodes, the severity of this issue can be reduced. In order to design an effective strategy for the movement of the mobile sinks, the motion pattern of the sensor nodes needs to be taken into consideration. Using the motion pattern of the nodes, the motion strategy of the mobile base stations can be generalised into an optimisation problem. The solution of the optimisation problem will provide a scheme for the movement control of the sink nodes that decreases the data delivery delay and increases the data delivery rate.

Appendix A: Derivation of Equation (4-30)

In this chapter the derivation of (4-30) will be explained. Substituting the T_{req} into (4-27) leads to

$$T_{req} = (k_j + 1)\frac{1}{\lambda_t} \tag{A-1}$$

Thus the k_j can be calculated as

$$k_j = T_{req}\lambda_t - 1 \tag{A-2}$$

Through (4-26) the (A-2) can be further derived as

$$e_{all} = (T_{req}\lambda_t - 1)\xi + e_{w1} \tag{A-3}$$

where ξ is

$$\xi = e_{trans} + e_{active} \tag{A-4}$$

Exploiting (4-25) the equation above can be written as

$$\nu_j A_j e_{ini} = (T_{req}\lambda_t - 1)\xi + e_{w1} \tag{A-5}$$

Hence the deployment density ν_j can be derived as

$$\nu_j = \frac{(T_{req}\lambda_t - 1)\xi + e_{w1}}{A_j e_{ini}} \tag{A-6}$$

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