MATHEMATICAL MODELS FOR MITIGATING ENERGY HOLES IN CORONA-BASED WIRELESS SENSOR NETWORK

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I dedicate this thesis to my wife. Without her patience, understanding, support, and most of all love, the completion of this work would not have been possible.

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ABSTRACT

Wireless sensor network (WSN) nodes are usually battery-driven devices with limited power supply and the network lifetime has undoubtedly become a crucial issue. Normally, in WSNs, the data are sent to a base station or cluster heads through multi-hop routing. Under the condition of multiple hops, the sensor nodes closer to the base station or cluster heads tend to die faster because of the imbalance traffic among sensor nodes that consequently lead to an energy hole problem. For mitigating the problem, a mathematical formula to calculate the optimal number of coronas in both random uniform and non-uniform deployment nodes is proposed in circular networks also known as corona-based networks. To formulate it, the energy consumption was calculated for each corona. Besides that, a lemma and two propositions have been proven in this research. Based on this lemma, the critical corona can be identified. In addition, the two proposed propositions can determine the situation in which the interior corona is the one with the greatest energy hole. In addition, an energy-balanced method, Intermittent Varied Range (IVR) data transmission method is proposed to prolong the overall network lifetime and simulations showed that the second inner-most corona has the most positive effect. For IVR method, only two transmission ranges could increase the network lifetime. There would be an increase more than doubled for environment with path loss exponent of two. In this research, a new relay nodes deployment technique is also proposed to balance the energy consumption in the coronas. Using the proposed mathematical equations, the number of relay nodes for maximizing the lifetime of corona-based WSNs could be calculated.

ABSTRAK

Nod rangkaian penderia tanpa wayar (WSN) lazimnya merupakan peranti pacuan bateri dengan bekalan kuasa yang terhad dan tempoh hayat rangkaian tanpa diragui menjadi isu kritikal. Biasanya, dalam WSN, data dihantar ke stesyen pangkalan atau kepala kluster melalui penghalaan multi lompatan. Di bawah situasi multi lompatan, nod penderia berdekatan dengan stesyen pangkalan atau kepala kluster cenderung untuk mati lebih awal kerana ketidakseimbangan trafik antara nod penderia yang akhirnya menyebabkan masalah lubang tenaga. Untuk menangani masalah ini, rumus matematik untuk mengira bilangan korona yang optimal dalam kedua-dua letak atur nod seragam rawak dan bukan seragam dicadangkan dalam rangkaian membulat yang dikenali juga sebagai rangkaian berasaskan korona. Untuk merumuskannya, penggunaan tenaga dikira pada setiap korona. Selain itu, satu lema dan dua proposisi telah dibuktikan dalam kajian ini. Berdasarkan lema ini, korona kritikal boleh dikenal pasti. Dua proposisi tersebut boleh menentukan situasi bila mana korona dalaman manghadapi lubang tenaga terbesar. Sebagai tambahan, kaedah tenaga seimbang yang dinamakan sebagai kaedah penghantaran data Julat Berselang Ubah (IVR) dicadangkan untuk memanjangkan keseluruhan tempoh hayat rangkaian dan simulasi menunjukkan korona kedua dalam mendapat kesan terbaik. Dengan kaedah IVR, dua julat penghantaran sahaja mampu meningkatkan tempoh hayat rangkaian. Dalam kajian ini juga, teknik letak atur nod geganti dicadangkan untuk menyeimbangkan penggunaan tenaga dalam korona. Dengan persamaan matematik yang dicadangkan, bilangan nod geganti untuk memaksimumkan tempoh hayat rangkaian WSN berasaskan korona dapat dikira.

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LIST OF ABBREVIATIONS

AI	-	Artificial Intelligence
AVHS	-	Asynchronous Variable Hop Size
BECR	-	Biased Energy Consumption Rate
BS	-	Base Station
CH	-	Cluster Head
EPND	-	Energy Proportional Node Distribution
ESPDA	-	Efficient Secure Pattern based Data Aggregation
FHS	-	Fixed Hop Size
GND	-	Geometric Node Distribution
HEED	-	Hybrid Energy-Efficient Distribution
H-AVHS	-	Heuristic Asynchronous Variable Hop Size
H-SVHS	-	Heuristic Synchronous Variable Hop Size
IVR	-	Intermittent Varied Range
LEACH	-	Low-Energy Adaptive Clustering Hierarchy
MAC	-	Medium Access Control
MISO	-	Multi-Input Single-Output
MOP	-	Multi-Objective Optimization Problem
NLM	-	Network Lifetime Maximization
NP-Hard	-	Non-deterministic Polynomial-time Hard
RN	-	Relay Node
SAPC	-	Secure Aggregation Protocol for Cluster-Based
SN	-	Sensor Node
SVHS	-	Synchronous Variable Hop Size
WSN	-	Wireless Sensor Network

LIST OF SYMBOLS

A_i	-	The energy required to be added to C_i aimed to balancing the energy
C_i	-	Corona i
E_{Ci}	-	Energy consumption in corona i
E_{elec}	-	Electronic energy consumption
E_d	-	Energy of sensing
E_{rx}	-	Reception energy
E_{Tx}	-	Transmission energy
$E_S(i)$	-	Energy consumption of each node in C_i
G_i	-	Energy consumption ratio in C_i
k	-	Number of coronas in the network
K_{opt}	-	Optimal number of coronas
L_{Ci}	-	Life time of the nodes in the corona i
l	-	Packet length
M	-	Number of nodes in the network
N_i	-	Number of nodes in corona i
n	-	Path loss exponent
R	-	Node transmission range
R_{area}	-	Network radius
α	-	Energy dissipated in the op-amp
ε_0	-	Initial energy of each sensor node
ε_R	-	Initial energy of each relay node
P	-	Nodes density

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CHAPTER 1

INTRODUCTION

1.1 Overview

A wireless sensor network (WSN) consists of spatially distributed sensors to monitor environmental or physical conditions. There are various applications on WSNs such as the environmental monitoring, tracing and tracking mobile objects, telemedicine and applications for military domains. A sensor network consists of many inexpensive, sensor nodes that are small-sized and low-powered devices equipped with radio, a micro processor, a power supply, memory, and an actuator. The sensed data is sent from sensor nodes to a sink. Unlike the traditional networks, WSNs are designed based on the applications and the environments within which they are to be used. They suffer from some constraints including limited communication range, limited bandwidth and limited processing and memory resources. Thus, the WSN application is designed to be closely related to the environment to be observed.

When the energy of a node is depleted, it dies and will be disconnected from the sensor network. Thus, the application on the network cannot be fully operational. Network lifetime depends on the active nodes and connectivity. Therefore, the energy should be conserved in an efficient way.

Battery is the main power supply of the sensors. Sensors are usually deployed in unattended area and the batteries cannot be replaced easily, and rechargeable battery might not be practical in some environments. Consequently, energy-efficient methods should be used in the networking protocols to prolong the network lifetime. Thus, the network lifetime is one of the most significant issues to be studied in WSN field.

In some situations, to save the energy and prolong the network lifetime, multi-hop transmissions are employed for transmitting the data from the sensor nodes to the sink (Bhardwaj *et al*., 2001). However, for large-scale sensor networks, a clustering method is more suitable (Bandyopadhyay and Coyle, 2004). In a clustering architecture, each sensor node forwards data to its cluster-head (CH) and after aggregation, the CH sends data to the sink. Also data transmission from the sensors to CH or from CH to the sink can be directly or through multi-hop transmissions mode. It also depends on distance from source to destination or restriction on the radio range of the sensors (Abbasi and Younis, 2007).

In multi-hop transmission traffic pattern (or many-to-one), the energy consumption of the nodes is imbalance among the sensors and the sensor nodes which are closer to the sink/cluster-head dissipate more energy than others. Thus, they die earlier and create the energy holes. Alternatively, if the multi-hops are not employed and all sensors transmit data directly to the sink, the nodes deployed far from the sink die much faster than those deployed closer to the sink due to long distance. The energy holes partition the network and, consequently, the network cannot monitor completely and this problem reduces considerably the network lifetime. Therefore, some techniques are required to avoid the energy holes problems. Among current techniques for mitigating energy holes include transmission range control techniques, using mobile sink, and using non-uniform node deployment strategy (Xiaobing *et al*., 2008).

By mitigating the energy holes, the network lifetime will be increased. In addition, to prolong the network lifetime energy efficient designs for the network layers are needed. The wireless sensor network protocols consist of five layers: physical layer, data-link layer, network layer, transport layer, and application layer that are designed for coverage, localization, synchronization, data aggregation, data compression, security and storage. Designing and implementing efficient algorithm and communication protocol in the sensor network layers protocols could also increase the total network lifetime.

1.2 Background of the Study

In many-to-one pattern, the nodes located around the sink relay the data of other sensor nodes and have heavier traffic loads. Therefore, the nodes nearer to the sink consume more energy than others and their energy depletes faster; this problem is known as an energy hole problem (Xiaobing *et al*., 2008) and the place is named hot spot area (Perillo *et al.*, 2005). When the energy hole appears, data cannot be sent from other sensors to the sink even though most the sensors still have energy. Thus, prematurely the network lifetime ends and considerable amount of energy is wasted. Lian *et al*. (2006) found that up to 90% of energy is left unused when the nodes are uniformly distributed due to the hot spot and energy hole problem.

There are some parameters that have effect on the energy hole problem and the network lifetime. These include the width of each corona, the number of coronas, the node transmission range, the nodes distribution strategy and the network area. Based this parameters, there are many approaches to mitigate the energy hole problem including the node or sink mobility, non-uniform sensor distribution strategy, adjustable transmission range, dynamic energy balancing, using relay nodes and optimization (see figure 1.1) and the most of the strategies are modeled by corona-based model. In the mobility strategy, the mobile sink moves to hot spot places in order to avoid the energy hole problem (Wu and Chen, 2007, Marta and Cardei, 2008).

Some strategies have been proposed to decrease the energy hole problem through non-uniform node deployment strategies (Lian et al., 2006, Liu et al., 2006, Xiaobing et al., 2008). In a non-uniform distribution strategy, additional sensors are located in the area that have energy holes problem in order to prolong the lifetime of the network (Xiaobing et al., 2006, Ferng et al., 2011).

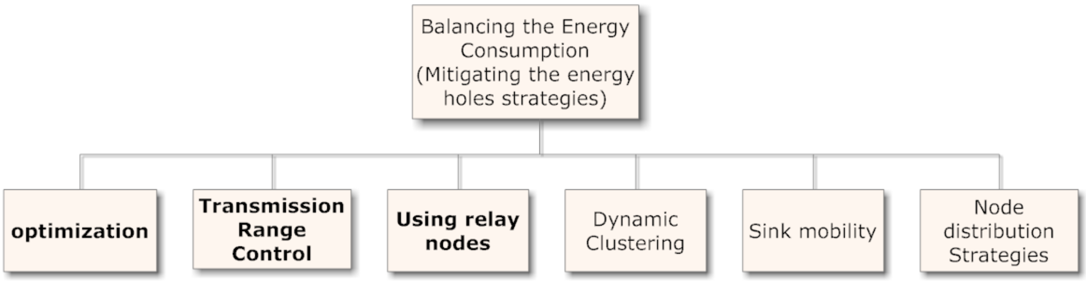

Figure 1-1. Strategies for mitigating the energy holes problem

And in the relay nodes strategy, some relay nodes are located in the hot spot area for mitigating the energy hole problem (Wang *et al*., 2006, Quanhong *et al*., 2007). Perillo *et al*. (2004) showed that the transmission range control could affect on the network lifetime and the strategy of adjusting transmission range is used for balancing the energy and avoiding energy hole (Cardei *et al*., 2005; Olariu and Stojmenovic, 2006; Perillo *et al*., 2004; Song *et al*., 2009; Tang *et al*., 2006). Also, many dynamic algorithms have been designed to balance the energy consumption in the network. The dynamic algorithms usually are used in clustered WSN, e.g. LEACH (Heinzelman *et al*., 2002), MLEACH (Xiangning and Yulin, 2007) and HEED (Ossama Younis, 2004), UCR (Chen *et al*., 2009). In this strategies, the cluster heads are rotated and changed their tasks among the other sensors from time to time, for balancing the energy depletion and mitigating the energy hole problem. In addition, by optimization of the parameters that has effect on the energy holes problem and the network life time, the mitigation of energy holes problem could be achieved (Olariu and Stojmenovic, 2006). This thesis is focused on improvement of the strategies including the optimization strategies, transmission range control strategies and using relay nodes strategies in the corona-based WSN.

1.2.1 Optimization Strategies

Optimizing some parameters such as width of each corona, number of coronas, node transmission range, nodes distribution strategy and the network area, have effect on mitigating the energy hole problem. Optimal number of the coronas for random uniform nodes deployment has been formulated by Olariu and

Stojmenovic (2006). However, for non-uniform node deployment the optimal number of coronas has been obtained from some numerical algorithms and there is no mathematical formulation. Haibo and Hong (2009) computed the optimal number of corona by the Simulated Annealing algorithm for their non-uniform strategy. Xiaobing *et al*. (2008) used the uniform equation of Olariu and Stojmenovic (2006) for finding the optimal number of corona approximately in their proposed strategy. In this thesis, a mathematical formula to calculate the optimal number of coronas in both random uniform and non-uniform deployment nodes is proposed. To formulate it, the energy consumption was calculated for each corona and a lemma and two propositions have been proven.

1.2.2 Transmission Range Control Strategies

Energy-balanced transmission schemes are a type of energy-balanced schemes such that controlling the transmission range helps to mitigating the energy holes problem. Many researchers attempted to find a solution for the energy-balanced transmission schemes in WSNs (Charilaos *et al*., 2006, Jarry *et al*., 2006 Azad and Kamruzzaman, 2011, Thanigaivelu and Murugan, 2012). These strategies are not feasible because they need many different transmission ranges and that is the main drawback of the strategies. In this research, a new strategy is proposed based on only two transmission ranges such that the proposed strategy can be feasible and only two transmission ranges could increase the network lifetime significantly. Accordingly, it has analytically obtained the corona that has the most effect for using transmission range control (second innermost corona is the most effective) and the nodes in the second innermost corona transfer data with a range of *R* or *2R*.

1.2.3 Using Relay Nodes Strategies

Using the relay nodes in the network significantly affect the lifetime and connectivity of WSN systems (Wang *et al.*, 2006, Quanhong *et al.*, 2007, Ammari and Das, 2008, Halder *et al.*, 2011). Moez et. al. (2007) investigated the relationship between the network lifetime and the network density. Ammari (2008) proposed a sensor deployment strategy based on energy heterogeneity with a goal that all the sensors deplete their energy at the same time. In this research, a new relay nodes deployment technique is proposed to balance the energy consumption in the coronas. In the relay node deployment scheme, by adding the extra nodes to relay, the energy balancing will be achieved and relay nodes deployed with priority from interior corona. In addition, relationship between the network lifetime and needed extra energy and relationship between the network lifetime and the number of relay nodes that are required, has been formulated. Using the proposed mathematical equations, the number of relay nodes for maximizing the lifetime of corona-based WSNs could be calculated.

1.3 Statement of the Problem

In the corona-based networks, nodes deployed closer to the sink consume more energy and die sooner than other nodes. This ultimately leads to what is known as energy holes. The energy holes problem significantly reduces the network life time. Many approaches were discussed in the research background for mitigating the energy hole problem. In the optimization strategies, there is no mathematical model to identify the optimum number of coronas to maximize the network lifetime in non-uniform deployment strategy. The questions related to this problem are as follows:

(i) What are the parameters that provide significant effects to the network lifetime in corona-based WSN?

(ii) How to formulate the optimum number of coronas in both the uniform and the non-uniform deployment in corona-based WSN?

(iii) How to find upper bound on the lifetime of corona-based WSN?

In mitigating energy holes problem strategies, the transmission range control strategies are not feasible (Xiaobing *et al.*, 2008), the questions related to this problem are as follows:

(iv) How to develop a feasible method using adjustable transmission range for the mitigation of energy holes problem?

(v) How to mitigate energy hole using only two different transmission ranges?

(vi) How much is the best ratio to transmit data to balance energy in the coronas?

Another approach for mitigating the energy hole problem is using relay nodes. Currently there is no formula for relationship between the network lifetime and the initial energy for extending the network lifetime maximally. The questions related to this problem are as follows:

(vii) What is the relationship between energy (capacity of batteries) and lifetime in a corona-based WSN.

(viii) What is the best deployment strategy for relay nodes to maximize the network lifetime in corona-based WSN?

1.4 Purpose of the Study

This research aims to mitigate energy holes problem by proposing several methods in a corona-based WSN. This study is conducted to analytically formulate the optimum number of coronas generally in both random uniform and non-uniform node deployment, propose a feasible method based on the transmission range control, and propose a relay node deployment strategy in order to mitigate the energy holes problem.

1.5 Objectives of the Study

The main aim of this research is to mitigate energy hole in corona-based WSNs. Accordingly, the research objectives are as follow:

I) To analytically formulate the optimum number of coronas in a corona-based wireless sensor network in both random uniform and non-uniform node deployments.

II) To design and implement a feasible method for mitigating the energy holes problem based on the transmission range control (using adjustable transmission range) in the corona-based WSN.

III) To design and implement a relay node deployment strategy to mitigate energy holes problem in corona-based WSN such that by adding a relay node, the network life time could be extended maximally.

1.6 Contributions of Research

The first part of this research contributions is formulas to obtain the optimum number of coronas in the corona-based WSN. One lemma, two propositions, two theorems, an exponential non-uniform node deployment and a formula to acquire lower bound of energy consumption of the first corona for obtaining the upper bound of the network lifetime have been proposed (see Table 1.1).

Another contribution of this research is a novel feasible method to mitigate energy holes problem based on transmission range control. The contribution is named Intermittent Varied Range (IVR) method to balance the energy consumption in the interior corona (corona 1) and second interior corona (corona 2). In addition, finding the ratio of intermittent data transmission in the method is the second part of these contributions.

Table 1.1: Research contributions

Chapter Number		Contribution
Chapter 4	Optimum number of coronas	A lemma and two propositions to formulate optimum number of corona.
		An exponential non-uniform deployment of nodes.
		A formula for identifying the optimum number of corona generally in random uniform and non-uniform node deployment (theorem 1)
		The upper bound of the lifetime in the first corona has been calculated.
		A formula for identifying the optimum number of corona in uniform corona-based WSN with adjustable transmission range (theorem 2)
Chapter 5	IVR Method	The ratio of the intermittent data sending for energy balancing in the coronas has been found.
		The IVR method to mitigate energy holes feasibly.
	Non-uniform Relay Nodes deployment method	A new solution for finding the initial energy (battery capacity) required for a node in each corona to maximize the network lifetime
		An equation to relay node deployment by adding a number of relay node and maximum prolonging the network lifetime

Finally, a non-uniform relay node strategy to mitigate the energy holes problem has been proposed. The strategy suggests a method to deploy relay nodes such that by adding a relay node, the network lifetime could be prolonged maximally. In this strategy relay nodes deployed with a priority from interior corona to outer coronas. In addition, the initial energy required for a node in each corona have been obtained with new solution for maximizing the network lifetime (see Table 1.1).

1.7 Scope of the Study

In this research, The network is the corona-based WSN (Sink/Cluster-head located at the center of the circle) with a radius of R_{area}. The circular area is divided into k adjacent coronas with a fixed heterogeneous sink and the sink is assumed to be located at the center of the circle and the width of each corona is R. Nodes in corona C_i ($\mathrm{C_i}$ denotes for ith corona) generates and sends l bits data per unit of time to corona $(C_{i-1}|i \geq 2)$ however in the IVR method, nodes in C_2 can send data with transmission range of R and $2R$. Other research scopes are as follow:

(i) The transmission range of each node is R; however, in IVR method, two adjustable transmission range (R and $2R$) are assumed for each node.

(ii) Connectivity requirement on the network is assumed and data aggregation has not assumed.

(iii) The area is in environment with the path lost exponent n and the communication environment is contention-and error-free.

(iv) Each node has ε_0 initial energy, and the sink/cluster-head has no energy limitation.

1.8 Significance of the Study

This research is conducted to find a way for mitigating the energy hole in corona-based WSN. There are many ideas to mitigate the energy hole but none of them formulates optimum number of coronas in non-uniform nodes deployment. In addition, there is no any feasible method based on energy-balanced transmission scheme (using adjustable transmission range), due to the fact that usually the real node has not many different transmission ranges. The IVR method in this research is a new feasible energy-balanced transmission method for mitigating the energy holes problem using only two levels of adjustable transmission range. Since there are real sensor nodes with two different transmission range, IVR method could be a feasible method. IVR can also be applied to multi-hop routing. In addition, in this research, a new real node deployment strategy by maximum increasing the network life time has been proposed.

1.9 Thesis Organization

Chapter 1 is an introduction to the thesis and the research problem. Chapter 2 reviews the literature about the energy holes and related works conducted to solve this problem. In Chapter 3, the research methodology is presented. In Chapter 4 the optimum number of coronas is formulated in both uniform and non-uniform sensor deployments. Chapter 5 proposes and evaluates two new methods to mitigate the energy holes problem. Finally, Chapter 6 concludes the research including contributions and many suggestions for future works. The thesis organization is shown in Figure 1.2.

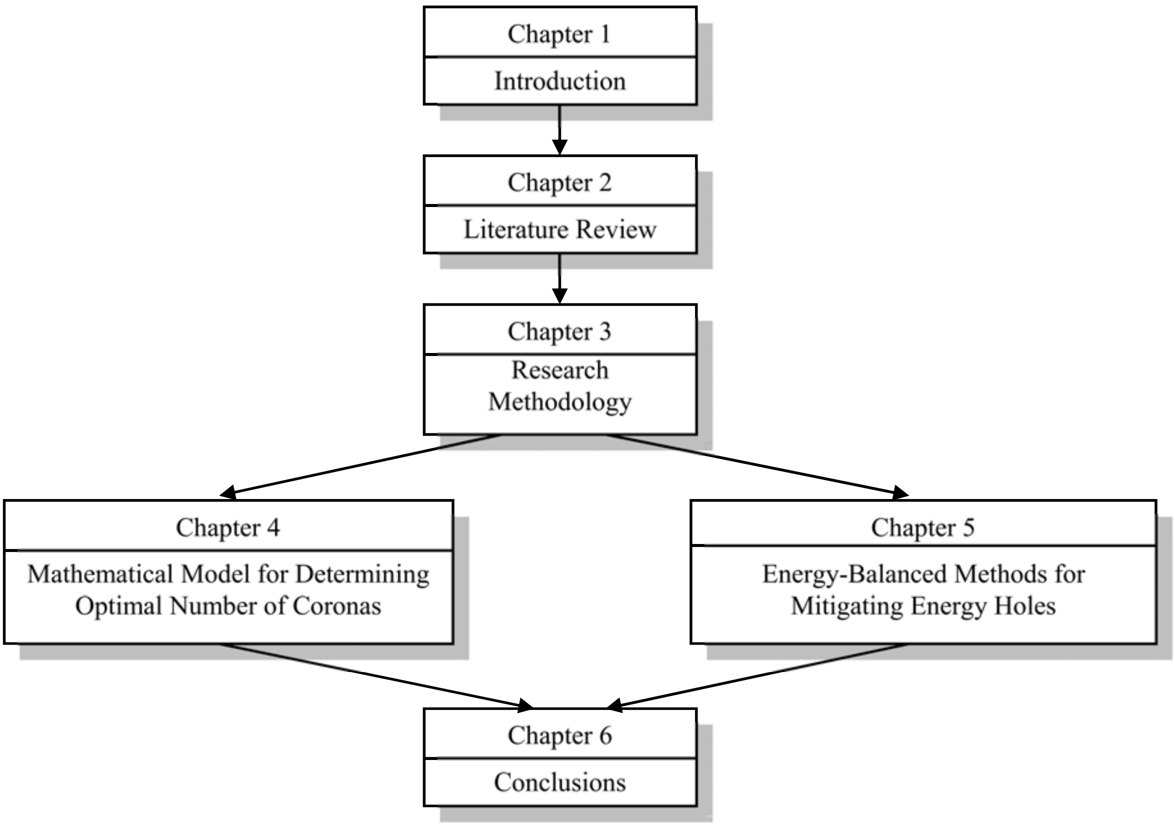

Figure 1.2: Organization of the thesis

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