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**Routing protocols for wireless sensor networks: A survey**

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## Abstract

Wireless sensor networks (WSNs) are different to traditional networks and are highly dependent on applications, thus traditional routing protocols cannot be applied efficiently to the networks. As the variability of both the application and the network architecture, the majority of the attention, therefore, has been given to the routing protocols. This work surveys and evaluates state-of-the-art routing protocols based on many factors including energy efficiency, delay and complexity, and presents several classifications for the various approaches pursued. Additionally, more attention is paid to several routing protocols and their advantages and disadvantages and, indeed, this work implements two of selected protocols, LEACH and THVRG, on the OPNET, and compares them in many aspects based on a large amount of experimental data. The survey also provides a valuable framework for comparing new and existing routing protocols. According to the evaluation for the performance of the routing protocols, this thesis provides assistance in relation to further improving the performance in relation to routing protocols. Finally, future research strategies and trends in relation to routing technology in wireless sensor networks are also provided.

**Keywords:** Wireless Sensor Network, Routing Protocol, Classification of Routing Protocols.

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# Terminology

## Abbreviations

WSNs	Wireless Sensor Networks
OSI	Open System Interconnect
SPIN	Sensor Protocols for Open System Interconnect r Information via Negotiation
LEACH	Low-energy Adaptive Clustering Hierarchy
PEGASIS	Power-efficient Gathering in Sensor Information Systems
TEEN	Threshold sensitive Energy Efficient sensor Network protocol
THVRG	Two-Hop Velocity-based Routing for Gradient net- work
CSMA	Carrier Sense Multiple Access
CSMA/CD	Carrier Sense Multiple Access with Collision Detec- tion
CSMA/CA	Carrier Sense Multiple Access with Collision Avoid- ance
CSMA/BA	Carrier Sense Multiple Access with Bitwise Arbitra- tion
CSMA/CP	Carrier Sense Multiple Access with Carrier Preemp- tion
TDMA	Time Division Multiple Access

CDMA	Code Division Multiple Access
QoS	Quality of Service
MAC	Media Access Control
GPS	Global Positioning System
ADV	Advertisement
REQ	Request
FT	Forwarding Table
BS	Base Station
BPSK	Binary Phase Shift Keying
IEEE	Institute of Electrical and Electronics Engineers
PDR	Packet Delivery Ration
FSM	Finite State Machine
STD	State Transition Diagram

# 1 Introduction

## 1.1 Background and problem motivation

With the development of wireless communication, electronic and sensor technology, wireless sensor networks have become a topic of significant interest.[1] WSNs consist of a large number of wireless sensor nodes equipped with sensing capabilities, data processing, and short-distance wireless communication function, and have been widely applied in the field of military surveillance and national defense, environmental monitoring, bio-medical science, rescue and disaster relief, as well as commercial applications, etc, as shown in Table 1.

Table 1: Applications of wireless sensor networks.[23]

Domain	Applications
Industrial control	Detection toxic gas emissions.
Environment	Monitoring forest fire.
Agriculture	Monitoring resources and soil moisture.
Disaster prevention and relief	Detection flood and earthquake.
Health care	Telemonitoring patients' physiological data.
Military defense	Monitoring nuclear and chemical attacks.
Smart home network	Intelligent home. Smart kindergarten.
Space exproation	Interplanetary exploration. Cosmic radiation exploration.
Logistics	Cargo tracking.

WSNs are very different from the traditional fixed networks. The packets in the WSNs are smaller, thus the data transfer overhead is bigger. The node computing, storage and, communication ability are more limited in WSNs.[17] Sensor nodes in the WSNs are battery-powered and easily fail because of limited energy. “The WSN is built of nodes - from a few to several hundreds or even thousands, where each node is connected to one (or sometimes several) sensors.”[2] The WSNs' network traffic has many-to-one and one-to-many characteristics.[17]-[18]

A large number of traditional fixed network protocols cannot be effectively applied to WSNs due to the above features. In order to explore and overcome the constraints of WSNs, many new protocols have been proposed to solve the issues concerning design and application at the same time. [54][55]

Moreover, many localization, tracking protocols and detection, also require the sensor nodes in the networks to route messages. Therefore, routing becomes one of the most important challenges in the design of wireless sensor networks.

## 1.2 Overall aim

Wireless sensor networks make a broad use of routing technologies and they involve many requirements in relation to these aspects such as delay, energy, and lifetime. Thus it has become necessary to extend some existing routing technologies. In addition, routing protocols specifically for wireless sensor networks has been the focus of a great deal of research.

However, there are an insufficient number of acceptable up to date surveys on routing protocols and the analysis regarding routing protocols is incomplete. In [4], the authors presented several routing protocols, but they ignored the advantages and disadvantages of these protocols. Another paper, [16], resembled that of [4] and did not provide some classifications of these protocols. In the paper, [2], it lacked a comparison of the routing protocols.

By learning routing technology and by means of an analysis of state-of-art routing algorithms and protocols, this work reviews the problem in relation to routing and the requirement for routing in WSNs, and presents the characteristics of routing in WSNs in detail. This work also explains some typical routing protocols for wireless sensor networks, and then classifies and evaluates these protocols. In addition, this work analyzes those protocols based on both theory and experimental results, implements LEACH and THVRG on OPNET and compares them in relation to several fields. Finally, this work summarizes routing in relation to the current research status and presents the future development prospects for routing in wireless sensor networks.

## 1.3 Scope

The study has its focus on routing.

Firstly, it presents a survey of routing protocols for wireless sensor networks including SPIN, TEEN, LEACH, THVRG, etc., based on some aspects such as energy efficiency, delay, computational overhead and so on.

Secondly, this work classifies all the presented routing protocols into ten categories from many points of view, which should prove to be of assistance to the readers with regards to choosing the most suitable protocol for their applications.

Thirdly, it has achieved the implementation of two outstanding protocols on the OPNET, LEACH and THVRG, and compared them from many fields in detail based on a large amount of simulation results.

Finally, this study builds a framework for comparing state-of-the-art routing protocols, which should prove to be of assistance in choosing the most suitable routing protocol for an application.

## **1.4 Concrete and verifiable goals**

1. This work analyzes and evaluates some existing routing protocols respectively based on theory and simulation results in energy efficiency, delay and some other aspects.
2. This work classifies routing protocols in WSNs into the following categories:
  - a. Uni-path protocol vs. Multi-path protocol
  - b. Flat protocol vs. Hierarchical protocol
  - c. Data-centric protocol vs. Address-centric protocol
  - d. Data aggregation protocol
  - e. Query-driven protocol
  - f. QoS-aware protocol
3. This work implements LEACH and THVRG on the OPNET and compares them from a considerable number of fields based on a large amount of simulation results.
4. This work surveys, compares and evaluates several state-of-the-art routing protocols based on some aspects including energy efficiency, delay, scalability, lifetime, and computational complexity, etc

## **1.5 Outline**

This thesis is organized as follows.

Chapter 2 introduces the reader to design factors for WSNs and the requirements for routing protocols in WSNs. In chapter 3, the methodology used in this work and the simulation tool are shown. Chapter 4 analyzes several existing routing protocols in wireless sensor networks in detail, such as Flooding and Sensor Protocols for Information via Negotiation (SPIN), Low-energy Adaptive Clustering Hierarchy (LEACH), Gradient-based routing protocol, Power-efficient Gathering in Sensor Information Systems (PEGASIS), Direc-

ted Diffusion protocol, Energy-aware routing protocol, Threshold sensitive Energy Efficient sensor Network protocol (TEEN), Rumor Routing protocol, Gossiping protocol, and Two-Hop Velocity-based Routing for Gradient network (THVRG). This is followed by some classifications and a comparison of these routing protocols in Chapter 5, and an analysis of these protocols is also provided. Chapter 6 introduces the simulations of LEACH and THVRG, and gives some detailed comparison between them and a corresponding explanation, and finally, the conclusions of the survey and the direction of future work with regards to routing protocol are given in Chapter 7.

## **1.6 Contributions**

The paper presents a survey of routing protocols in wireless sensor networks, based on a palette of aspects such as energy efficiency, delay, computation overhead, communication overhead, lifetime and so on. In addition, the study builds a framework for comparing state-of-the-art routing protocols. It should prove to be of assistance in choosing the most suitable routing protocol for an application.

All the survey work, collecting and reading papers, sorting out the classification and criteria, classifying the protocols, surveying and evaluating the state-of-the-art routing protocols, analyzing, implementing and comparing the protocols, has been completed by the author.

## 2 Related Work

Since wireless sensor networks have been developed faster and faster and more and more new routing techniques have been proposed, more and more researchers come to survey the communication protocols, characteristics and applications in this technical area. The features that distinguish this survey are highlighted in this subsection, and the differences in the scope are also highlighted.

In [1], the goal of authors is to make a survey for communication techniques and design issues comprehensively in wireless sensor networks, which describes both some physical constraints on wireless sensors and the algorithms and protocols proposed in all the layers of network stack. Suitable applications of wireless sensor networks are also discussed. This survey provides a good introduction for readers who are interested in the broad area. However, although a number of routing protocols for wireless sensor networks are covered in the paper, it does not provide a classification for those routing protocols, which resembled that of [16].

The goal of [4] is to survey recent routing protocols for wireless sensor networks and present a classification for the various approaches pursued. The authors presented several routing protocols for wireless sensor networks and provides a good classification of the protocols pursued, but they ignored the advantages and disadvantages of these protocols which are important for choosing a suitable application.

In paper [2], the various routing protocol for wireless sensor networks are classified and described. However, the list of protocols discussed in this paper is not complete, and it also lacked any comparison of the routing protocols.

This survey is more focused and can serve those readers who are interested in a deeper insight regarding routing protocols and techniques in wireless sensor networks. The advantages and disadvantages of these protocols are introduced in detail. In addition, several classifications, which are from all aspects, of routing protocols in wireless sensor networks are provided. Possible applications of those routing protocols are also discussed. This work reflects the current state-of-the-art in routing research by providing a comprehensive comparison list of the routing protocols presented. Moreover, this work achieved the simulation of two outstanding protocols, namely LEACH and THVRG, and a comparison based on simulation results, which has not been provided by the majority of survey papers.

## 2.1 Design Factors for WSNs

Due to the large number of sensor nodes in the network and the dynamic of their operating environment, this offers unique challenges in the design of wireless sensor networks. "Routing design is closely related to the system architecture mode." [7] In general, there are some architectural issues of wireless sensor networks and how they affect the routing process, which are listed as follows [21][37-39]:

1. **Dynamic Network:** Generally, there are three components which constitute a WSN—sensor nodes, sink and event. Sensor nodes and sink can be either fixed or mobile. In most applications, sensor nodes are assumed to be stationary. Thus, the stability of the routing data is an important design factor, the exceptions being for bandwidth utilization and energy consumption. [24][60]
2. **Node Deployment:** The topology of node deployment is dependent on the applications, which will affect the performance of the routing protocol. If the nodes are randomly deployed, they must create an infrastructure in the network and establish paths to route the data by organizing themselves. If nodes are deployed with a fixed location, a pre-determined path could be built to route the data. In addition, the position of the sink is also important in order to optimize the routing paths. [34][62]
3. **Energy Constraint:** Energy consideration greatly affects the process of setting up the routes in the network. [48] Since radio transmission degrades rapidly with distance, it means that energy consumption must be well managed in relation to the communication distance. If all the sensor nodes are close to the sink node, directed transmission would perform in a satisfactory manner. [49] However, in most applications, it is necessary to use multiple hop routing to consume less power than is the case for directed transmission, because the sensor nodes are always randomly deployed in the network. However, this will introduce significant overhead with regards to topology management. [20]
4. **QoS Requirements:** Different applications may have different QoS (Quality of Service) requirements, such as delay, bandwidth and reliability. These various QoS requirements will be described in detail in the following: [34-36]
  - **Delay:** In some applications, WSNs are required to ensure a stringent deadline, for instance, an event must be reported within a certain period of time. Many applications, such as fire monitoring in the forest, medical care and structural health diagnosis, are extremely time critical applications. More importantly, in some

applications, there are several different deadline requirements in the same system. Location monitoring data, for example, for a fast moving target has shorter deadline when compared with a slow moving target.[29]

- **Bandwidth:** In addition to transmission of their own data packets, sensor nodes may work as relay nodes in a network. If a large chunk of video data is sent using a single path, it can very likely exhaust the path and result in some failure. To solve the aforementioned problem, the available bandwidth can be utilized by using multiple paths or multiple channels in an overlapped manner in order to meet the high bandwidth.[24]
- **Reliability:** It can be defined in terms of the ability to transmit a data packet to the destination with the minimum packet loss. For example, some applications, such as forest fire monitoring, may require the packets to reach their destination without any loss. Additionally, according to the content of the sensed data, different reliability constraints are required to be imposed. For instance, in a forest fire monitoring application, the temperature information about the regions with normal temperatures, is required so that a certain percentage of packet losses can be endured. On the other hand, the sensed data containing the information about the regions experiencing abnormally high temperature should be transmitted to the destination with a high packet delivery ratio since it can be a sign of fire. In order to provide assurance regarding such applications, multi-path routing or prioritized forwarding scheme can be adopted. In addition, sending several copies of the same packet data via different paths increases the probability that at least one copy will reach the destination correctly.[29][33]

In addition, fault tolerance, throughput maximization, and energy efficiency are some other parameters often used to measure QoS requirement in WSNs.

5. **MAC Protocol Design:** To operate a routing protocol in a wireless sensor network successfully, the MAC protocol is an important issue, which is required to consider both energy consumption and the complexity of the implementation.[56]
6. **Hole Detection:** Because of the high bandwidth requirements and the bursty property of multimedia streaming data, some paths in wireless sensor networks can become exhausted, which is to say that the residual energy of the nodes falls below a threshold value. Such scenarios are called dynamic holes. These holes may damage the performance of many applications, such as multimedia by encumbering several routing

paths in the network. Therefore, new hole-bypassing routing protocols should be designed to address the aforementioned problem while balancing the energy usage throughout the whole network.[30]

## 2.2 Requirements on Routing Protocol

The following requirements should be met when designing or evaluating routing protocols:

**Energy Efficiency:** Each node in the network has limited energy resources because of the limiting amount of power. Routing protocols should consider this limitation. [48][57][58]

**Scalability:** With sensors becoming ever cheaper, tens of thousands of sensors might be deployed in wireless sensor networks. Thus, routing protocols should work well with any number of nodes in the network.

**Complexity:** The complexity of a routing protocol can make a protocol impractical for many applications because of the limited hardware capabilities and the severe energy constraints in wireless sensor networks.

**Robustness:** Wireless sensor network might be deployed in harsh and lossy environment, in other words, network nodes might die or exit the network. Routing protocols should have the ability to adapt to all kinds of environments and function well in all applications. [22][46]

**Delay:** Many applications, such as detecting temperature, require an immediate response without any significant delay. The total time required to route the sensed data to the sink must be as low as possible in these kinds of applications.

**Data Transmission and Transmission Models:** According to different applications in the wireless sensor networks, the data transmission can be query-driven, event-driven, hybrid and continuous. In a query-driven model and an event-driven model, the node starts to transmit data only when a query is generated by the sink node or an event occurs. While in the continuous transmission model, each node periodically sends data. Of course, some applications combine the continuous model, event-driven and query-driven model. [24][28]

There are some other issues, such as transmission media and network size, which also affect the performance of a routing protocol.

## 2.3 Design Challenges and Issues of Routing for Wireless Sensor Networks

The design of routing protocols for wireless sensor networks is challenging due to several network constraints and requirements. Due to the limitations of network resources such as storage, bandwidth and energy, the main design challenges in wireless sensor network include the following aspects:

- **Limited energy capacity:** Since wireless sensors are battery powered, their energy capacity is limited. Therefore, energy introduces a major challenge for designers in some hostile environments, such as a battlefield, where it is not possible to access the sensors to recharge their batteries. What is more, the sensor will not be able to work normally after the energy of a sensor node falls below a certain threshold, this will seriously affect the performance of the network. Thus, routing protocols designed for wireless sensor networks should be as energy efficient as possible in order to extend their lifetime, and to simultaneously guarantee their good overall performance. [59][60]
- **Sensor location:** Another challenge that is required to be noted is that the locations of the sensor nodes in the network must be managed properly. Most protocols assume that the sensors use some localization technique to acquire knowledge regarding their locations or are equipped with global positioning system(GPS) receivers.
- **Limited hardware resources:** In addition to the limited energy capacity, the processing and storage capacities are also limited in wireless sensors. Therefore, only limited computational functionalities can be performed. Due to these constraints of hardware, the software development and network protocol design for wireless sensor networks have many challenges. Both the energy constraint and the processing and storage capacities of sensors must be considered by the designers.[31]
- **Massive and random sensor deployment:** Sensor deployment in wireless sensor networks is application dependent. The performance of the protocol can be affected since the deployment in wireless sensor networks can be either random or manual. In many situations, wireless sensor nodes are deployed randomly within the required region or dropped massively into an inaccessible area. If the deployment of sensor nodes is not uniform, in order to ensure an energy efficient network operation, optimal clustering will be necessary to connect each node.
- **Network characteristics and unreliable environment:** In most situations, wireless sensor networks work in an unreliable environment. The topology of a network, which is defined by the sensor nodes and the communication links between the sensor nodes, changes frequently because of the sensor addition, damages, deletion, node failures, or energy depletion. Also, the sensor nodes in a wireless sensor network are linked by a wireless medium which is time varying, noisy, and error prone. Therefore, routing protocols should consider the network topology dynamics because of the limited energy and sensor mobility, as well as the increasing network size, in order to maintain the application requirements in terms of connectivity. [31][32]

- **Data Aggregation:** Since sensors may generate the data with significant redundancy, the number of data transmissions can be reduced by aggregating similar packets from multiple sensors. In many routing protocols, energy efficiency can be achieved and data transfer can be optimized when the data aggregation is used.[37-39]
- **Scalability:** Routing protocols should have the ability to scale in relation to different network sizes. Also, the capabilities of sensor nodes such as sensing, energy, and particularly communication may not be the same. Therefore, the communication links between sensor nodes are unable to be symmetric, which is to say, for every two sensor nodes, the communication in both directions may not be available. This should also be considered by designers when designing the routing protocols.[31]

### 2.4 CSMA

Carrier Sense Multiple Access (CSMA) is a probabilistic Media Access Control (MAC) protocol. Before transmitting on a shared transmission medium or a band of electromagnetic spectrum, the situation of other traffic must be verified.

"Carrier Sense" means that a transmitter determines whether or not the traffic is busy before attempting to send by using feedback from a receiver. Thus, it attempts to listen a carrier wave from another node before transmitting. If a carrier is busy, the station will not start its own transmission until the current transmission is finish. "In other words, CSMA is based on the principle "sense before transmit" or "listen before talk"."[26]

"Multiple Access" means that there are multiple stations communicate on the shared transmission medium. If stations are using the same transmission medium, the transmissions from one node will generally be received by all other stations.

Considering the specific conflict resolution strategies, CSMA will be divided into the categories shown below:

1. Carrier Sense Multiple Access with Collision Detection(CSMA/CD), in order to improve the performance of CSMA, once a collision is detected, the transmission will be stopped as soon as possible. Thus, it can reduce the probability of a second collision on retry.
2. Carrier Sense Multiple Access with Collision Avoidance(CSMA/CA), in order to improve the CSMA performance, the node will work less "greedily" on the shared transmission channel. The transmission will be backed off for a random interval if the channel is detected to be busy before starting a transmission. Thus, it reduces the probability of collisions on the shared channel.

In addition, there are other categories: Carrier Sense Multiple Access with Bit-wise Arbitration(CSMA/BA) and Carrier Sense Multiple Access with Carrier Preemption(CSMA/CP).

## **2.5 TDMA**

Time Division Multiple Access (TDMA) is also a MAC protocol for networks with shared transmission medium. It divides the signal into different time slots so that several users are able to share a transmission channel under the same frequency. The users use their own time slot to transmit in rapid succession one by one. Thus, using only a part of its channel capacity, the same transmission channel can be shared by multiple stations. [27]

TDMA characteristics:

1. Multiple users share a single carrier frequency.
2. Non-continuous transmission, which makes handoff more simple.
3. TDMA can be dynamic to allow Time slots to be assigned on demand.
4. Less stringent power control than that of CDMA(Code Division Multiple Access).
5. Higher synchronization overhead than that of CDMA.
6. Cell breathing, it is more complicated than CDMA when borrowing resources from neighbor cells.
7. Frequency/Time slot allocation is complicated.

## 3 Methodology

### 3.1 Survey Methodology

Routing in wireless sensor networks is very challenging because of several characteristics which distinguish them from wireless ad hoc networks and contemporary communications.

Firstly, it is impossible to assign a global identifies scheme for a large number of sensors. Therefore, wireless sensor networks are not able to use classical IP-based protocols.

Secondly, in contrast to typical communication networks, in most of the applications of wireless sensor networks, the flow of sensed data is required from a number of sources to a particular base station.

Thirdly, the generated data traffic has significant redundancy, because multiple sensor nodes may generate the same data when monitoring the same phenomenon. Therefore, in order to improve the utilization of bandwidth and energy, it is necessary to exploit such redundancy by the routing protocols.

Fourthly, wireless sensor nodes are strictly limited in terms of transmission power, capacity, storage of processing and on-board energy, which thus requires a routing protocol which has careful resource management ability.

Due to such differences, a number of new protocols have been proposed to deal with the problems of routing technology in wireless sensor networks. The characteristics of sensor nodes and the requirements with regards to routing protocols in WSNs have been considered in these new routing protocols, which have been mentioned in Chapter 2, together with the requirements of the application and architecture.

#### 3.1.1 Classification Criterion of Routing Protocols

Wireless sensor networks can be applied to a large number of applications, from simple temperature monitoring in the factories to safety critical applications. As the majority of networks are coupled to the application quite closely, the protocols used for routing may differ in some aspects and resemble each other in some other aspects. This work classifies routing protocols into the two categories shown below:

- **Routing issues.**
- **Application-dependent feature.**

### 3.1.1.1 Routing issues

WSNs routing protocols are responsible for the reliable data transmission between the sink node and the remainder of the nodes. To accomplish this function, it is necessary for these nodes to follow certain rules. Various options are described as follow.

#### 1. Uni-path Routing Protocol vs. Multi-path Routing Protocol

According to the number of paths in the transmission process, the routing protocols can be divided into uni-path routing protocol (Figure 1) and multi-path routing protocol (Figure 2).

- **Uni-path routing protocol**

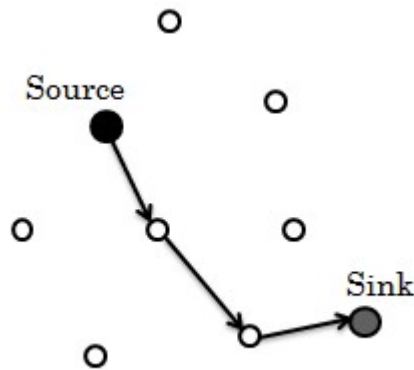


Figure 1: Uni-path routing protocol

Uni-path routing protocol, as shown in Figure 1, saves storage space, and its data communication overhead is less.

- **Multi-path routing protocol**

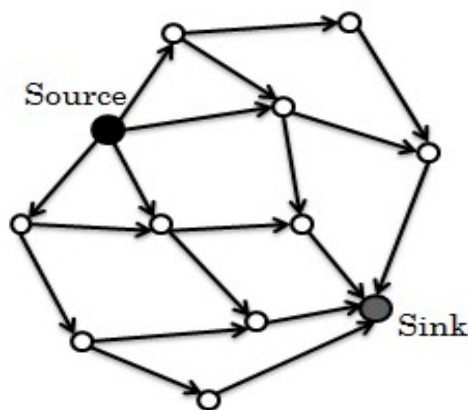


Figure 2: Multi-path routing protocol

In relation to multi-path routing protocol, as shown in Figure 2, its robustness is strong, fault tolerance is better, and it is available to select an optimal route from those multiple-routes.

**2. Flat Routing Protocol vs. Hierarchical Routing Protocol**

According to whether there is a hierarchy of nodes in the routing process, the routing protocols can be divided into flat routing protocol (Figure 3) and hierarchical routing protocol (Figure 4).

- **Flat routing protocol**

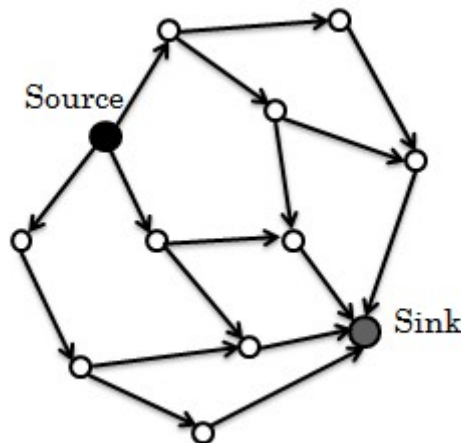


Figure 3: Flat routing protocol

Figure 3 shows a network topology of a flat routing protocol. A flat routing protocol is very simple, its robustness is good, but the overhead of establishment and routing maintenance is large and there are a significant number of data transmission hops. Therefore, it is more suitable for small-scale networks.

Figure 4 shows a typical hierarchical routing protocol. The main goal of the hierarchical routing protocol is to maintain the energy consumption of the sensors in the network efficiently by two steps. Firstly, they will be involved in multi-hop communication within a particular cluster head. Secondly, data aggregation and data fusion will be performed to decrease the number of transmissions to the sink or base station.[50] The formation of cluster heads is typically based on the energy reserve of the wireless sensors and the distance between the sensors and a cluster head.[51][52]

- **Hierarchical routing protocol**

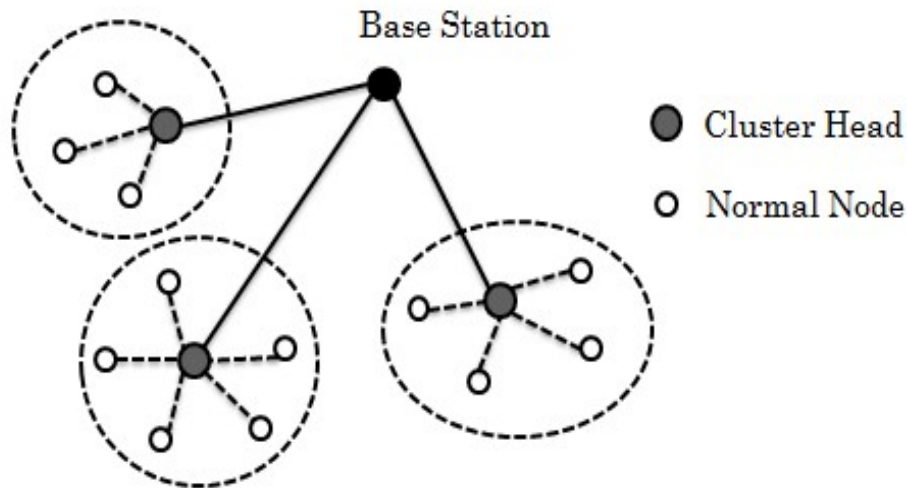


Figure 4: Hierarchical routing protocol

### 3. Data-centric Routing Protocol vs. Address-centric Routing Protocol

According to whether the routes are created among a specific set of sensor nodes or between addressable nodes managed in the network layer of the communication stack, the routing protocols can be divided into data-centric routing protocols and address-centric routing protocols.

- **Data-centric Routing Protocol**

It is not practical to assign global identifiers to every node in many applications in wireless sensor networks because of the huge number of nodes deployed. It is difficult to select a specific set of nodes to be queried due to such a lack of global identification as well as random deployment of nodes. Therefore, significant redundancy is generated since data is always transmitted from each node in the deployment region. Routing protocols which are able to select a set of nodes and utilize data aggregation technology to relay the data have been proposed since it is very inefficient in terms of energy consumption.

- **Address-centric Routing Protocol**

There are many WSNs applications requiring to know the location of unexpected events and, in this case, an address-centric routing protocol can prove to be helpful. Routes are created between addressable nodes managed in the network layer of the communication stack and the position information is utilized to relay the data to the destination in this kind of routing protocols.[45][47]

### **3.1.1.2 Application-dependent feature**

Different applications in wireless sensor networks have their own application requirements. Therefore, many routing protocols are highly relevant to the applications.

#### **1. Data Aggregation Routing Protocol**

According to whether the protocol is utilizing data aggregation or not, routing protocols can be divided into data aggregation routing protocol and non-data aggregation routing protocol.

Data aggregation can reduce the communication overhead, but it requires to be supported by time synchronization technology and increases transmission delay. It is an important consideration for routing protocol in terms of traffic optimization and energy saving.

#### **2. Query-driven Routing Protocol**

According to whether the route establishment timing is related with a query or not, routing protocols can be divided into query-driven routing protocol and non-query-driven routing protocols.

Query-driven routing protocols can save nodes' storage space, but the data latency is large. However, they are not suitable for applications requiring an urgent report such as environmental monitoring.

#### **3. QoS-aware Routing Protocol**

In some protocols, a route setup is modeled and solved as some network flow problems. When a route is to be established, a QoS-aware routing protocol considers delay, packet loss rate and other QoS parameters and then chooses the most suitable route for the QoS applications requirements from a number of possible routes.

**3.1.2 Comparison Criterion of Routing Protocols**

The criteria, which will be used in the next comparison, must be defined in detail before these protocols are evaluated. For the sake of clarity, this work divide the evaluation criteria between quantitative criteria and qualitative criteria. The former include delay, computation overhead, communication overhead and network size. The latter include energy efficiency, scalability, complexity and lifetime. This is shown in Table 2. A detailed descriptions concerning these criteria will be provided in Chapter 5.

Table 2: Comparison criterion

<b>Comparison Criteria</b>	<b>Quantitative Criteria</b>	Delay
		Computation Overhead
		Communication Overhead
		Network Size
	<b>Qualitative Criteria</b>	Energy Efficiency
		Scalability
		Complexity
		Lifetime

In addition to the quantitative comparison and qualitative comparison, the preferred application areas of the presented protocols, which are of assistance to a better understanding and a comparison in relation to the routing protocols will be provided.

The comparison results based on the quantitative criteria and qualitative criteria will provided in Chapter 5, as well as the preferred application areas of each protocol.

## 3.2 Simulation Background

In this work, OPNET is used as a simulator to implement and evaluate two protocols, namely, LEACH and THVRG, which are respectively the representatives of the hierarchical routing protocol and the gradient routing protocol. From many OPNET products, OPNET Modeler has been finally chosen.

OPNET Modeler is a Network Simulation Tool, and in order to analyze and design communication networks, devices, protocols and applications, the R&D process is accelerated. “Users can analyze simulated networks to compare the impact of different technology designs on end-to-end behavior.

Modeler incorporates a broad suite of protocols and technologies, and includes a development environment to enable modeling of all network types and technologies including: VoIP, TCP, OSPFv3, MPLS, Ipv6,etc.”[8]

The OPNET Modeler can be applied in various fields including End-to-end Network Architecture Design, System Level Simulation for Network Devices, Protocol Development and Optimization, and Network Application Optimization and Development Analysis.

It uses hierarchical network modeling. Considering the relationship for the protocols, node module modeling is fully compliant with OSI standards: Application Layer→Presentation Layer→Session Layer→Transport Layer→Network Layer→Data Link Layer→Physical Layer. In addition, it also uses object-oriented modeling. At the beginning, each type of node uses the same node model, then for the different objects, specific parameters are set.

In order to build a network properly, workflow steps should be followed, starting from creating network models, then choosing the statistics and data to be collected and then running the simulation, finally, viewing and analyzing the simulation results. The Figure 5 below illustrates this process:



Figure 5: Simulation design workflow in OPNET Modeler

There are three domains in the OPNET Modeler, which will be introduced in the following sections.

### 3.2.1 Network Domain

In the OPNET Modeler, the Network Domain is the highest level in the hierarchical structure, in which the topology of a network can be created. It can be edited in the main user interface--Project Editor. The OPNET Modeler provides several inherent network models which can be imported directly to a project. Also, according to different projects, users can design specific network topologies.

There are no limitations on the number of nodes or the instances between nodes in a network. A network can contain as many nodes as are required.

The OPNET Modeler also provides several link architectures for wired networks, such as simplex or duplex.

Figure 6 shows the network model of Zigbee. The network topology of the nodes is random, and users can generate different network topologies by changing the locations of the nodes.

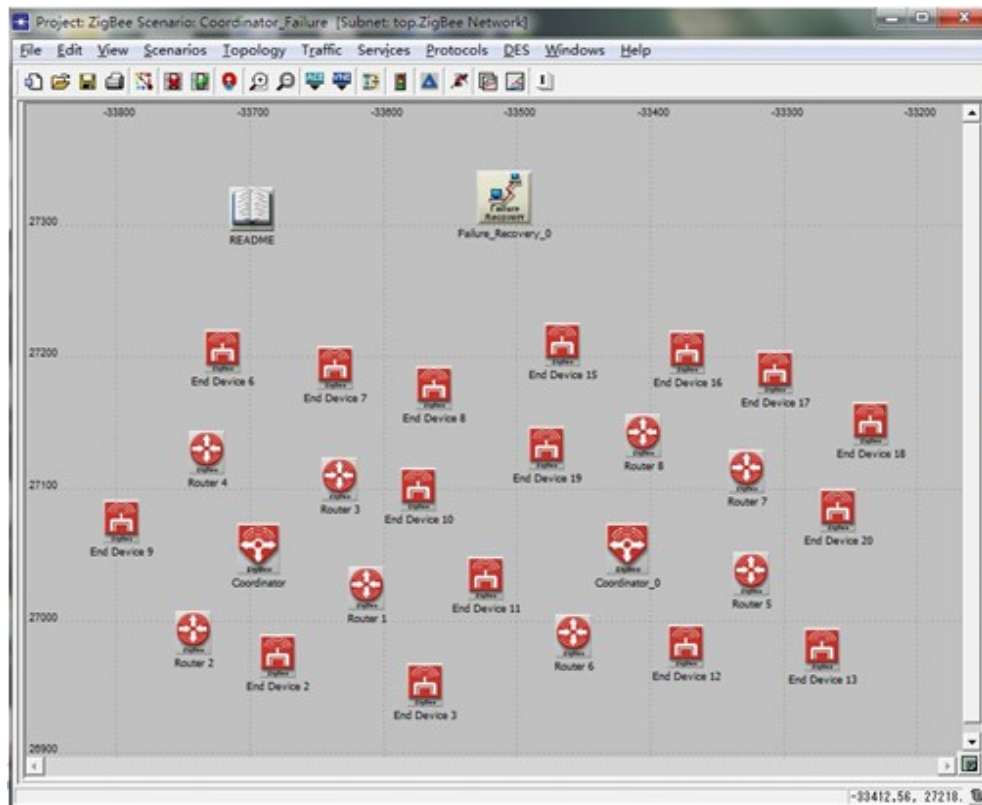


Figure 6: The network model of Zigbee

### 3.2.2 Node Domain

Within a network model, there could be a large number of nodes with the same node model. As is the case for the network model, in addition to the several inherent node models, a node model can also be built by users according to specific requirements. The nodes in the OPNET Modeler correspond to routers, switches, bridges, etc, in the real world.

Each node model is composed of many small building blocks which are called modules. There are two groups of modules in a node model. One is substantially predefined and can only be configured through a set of built-in parameters, such as a transmitter and a receiver. The other is similar to a processor which can be developed in the Process Editor. Figure 7 shows the node model of Zigbee.

The connections between modules can be divided into three different types: packet streams, statistic wires and logical associations. Packet streams allow packets, which are formatted messages, to be transmitted from one module to another. Statistic wires transmit simple numeric signals or control information between modules, which are typically used in the case for which one module is required to monitor the performance or state of another. “Logical associations identify a binding between modules.”[25]

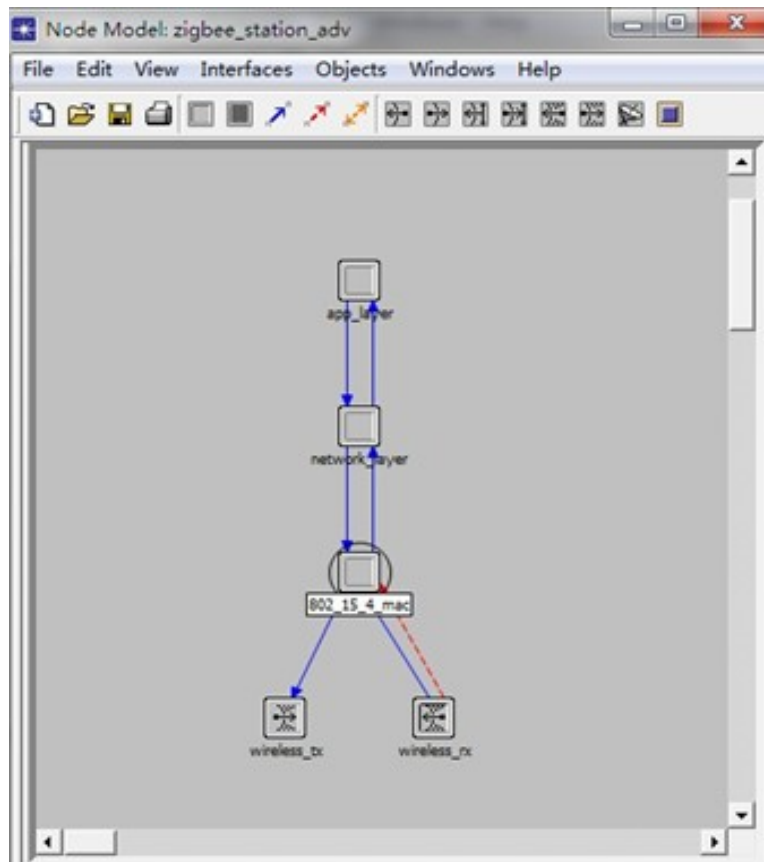


Figure 7: The node model of Zigbee.

### 3.2.3 Process Domain

The finite state machines (FSM) are used to describe the process model. Proto-C is used as the programming language in the OPNET Modeler to develop the protocols and algorithms. It is based on a combination of state transition diagrams (STD), a library of high-level commands such as Kernel Procedures and the general facilities of the C or C++ programming languages.

There are four main parts in the finite state machine: Transition Conditions, determining whether a transition should be executed; Transition Executives, running the specific functions when the transition condition is met; State Variables, defining private static variables, whose range is in one process; State Executives, running the specific functions when the state condition is met. It is noteworthy that only one process is allowed to be executed in a network at the same time.

Figure 8 shows the MAC layer(802.15.4) in Zigbee.

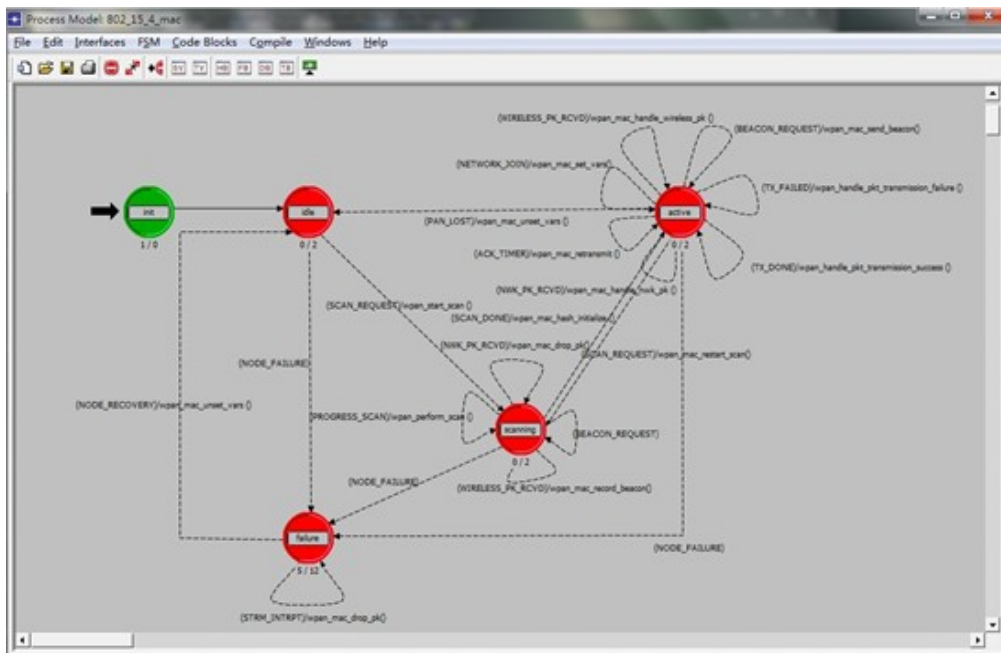


Figure 8: The MAC layer(802.15.4) in Zigbee.

## 4 Routing in Wireless Sensor Networks

### 4.1 Routing Protocols in WSNs

#### 4.1.1 Flooding and Gossiping Protocol

Flooding and gossiping[3] are two classical protocols used to transmit data in sensor networks. And no routing algorithm and topology maintenance are required.

In the flooding protocol, when a sensor node receives a data packet, it will broadcast it to all of its neighbours. The broadcast will continue until one of the following two conditions is reached: when the packet arrives at the destination node, or when the packet's maximum number of hops is reached. [19]

Although flooding is a simple protocol and very easy to implement, it has several drawbacks, including implosion, overlap and resource blindness. The implosion, as shown in Figure 9[4][5], is caused by duplicated messages being sent to the same sensor node. The overlap, as shown in Figure 10[4][5], is caused when two nodes sensing the same region both the send same packets to the same neighbours, and resource blindness[5] is caused by consuming a great deal of energy without giving consideration to the energy constraints.

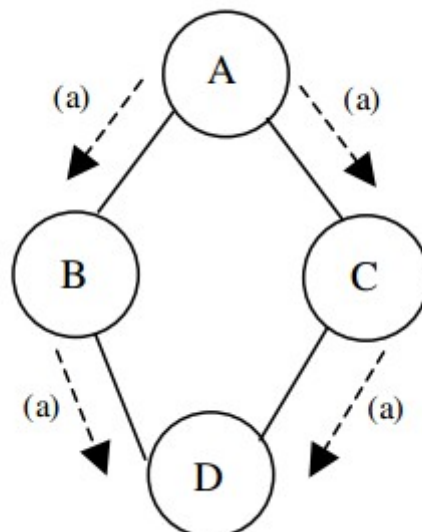


Figure 9: The implosion problem. Node A broadcasts its data to all of its neighbours. D receives two same copies of the data, eventually, which is not necessary.

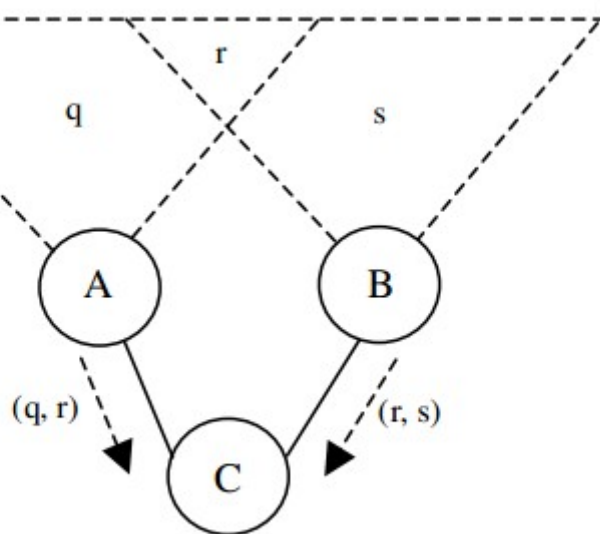


Figure 10: The overlap problem. A and B cover an overlapping geographic region and C receives the same copy of the data from these sensors.

The gossiping protocol[3][44] is a slightly enhanced version of the flooding protocol. In the gossiping protocol, the sensor node receiving a packet sends it to a randomly selected neighbour, which then picks another neighbour randomly to forward the packet to and so on. Thus, the implosion problem can be avoided in gossiping since it selects a random node to send the packet to rather than broadcast the packet. However, the delay will increase in the propagation progress of data via the nodes.

**Advantages:**

1. No need to maintain routing information.
2. No algorithm.
3. Simple.

**Disadvantage:**

1. Poor scalability.

**4.1.2 Sensor Protocols for Information via Negotiation (SPIN)**

SPIN[5] is one of early data-centric routing mechanisms. A data advertisement mechanism is the key feature of SPIN. Before transmission, meta-data are transmitted among the sensor nodes by this mechanism. Each node, on receipt

of new data advertises it to all its neighbours and interested neighbours, not processing that data, retrieve it by sending a request message back. SPIN's meta-data negotiation mechanism solves the classic problems of the flooding protocol such as redundant information passing by, overlapping of sensing the same areas and resource blindness, which can achieve a significant amount of energy efficiency. There is no standard meta-data format in the SPIN, and it uses an application level framing. In order to exchange data among nodes, SPIN defines three kinds of messages: ADV message, REQ message and DATA message. A sensor node is allowed to advertise a meta-data in ADV message, the specific data is requested in REQ message and the actual data is carried in DATA message. This is shown in Figure 11.[4][5]

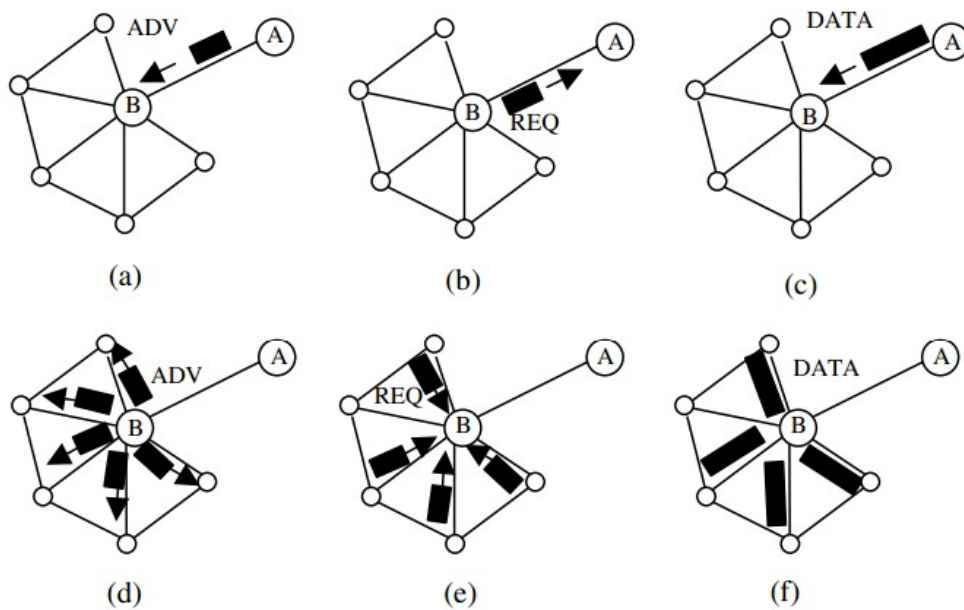


Figure 11: SPIN protocol. (a) Node A advertises its data to node B. (b) Node B responds a request to node A. (c) Node A sends data message to node B. (d) node B then advertisements its data to its neighbours. (e) node who in turn responds a request to node B. (f) Node B sends data message..

**Advantages:**

1. Mitigates implosion.
2. Solves overlap.
3. Avoids resource blindness.

**Disadvantage:**

1. Cannot guarantee the delivery of data.
2. Energy easily runs out.

### 4.1.3 Directed Diffusion

The Directed Diffusion protocol[9][63] can be regarded as an important milestone in the data-centric routing research of wireless sensor networks. The protocol uses a scheme of naming data for all communications to diffuse data through sensor nodes. “It uses attribute-value pairs for the data and queries the sensors on demand.”[7] The protocol defines an interest through a list of attribute-value pairs—such as geographical area, duration, interval, name of objects etc., after which it can then create a query. Interests are propagated by unicast, multicast or broadcast through its neighbours by a sink. When a node receive the interest, it is able to perform caching for later use, such as aggregation and loop prevention. The pre-stored data and the data in the interests are compared by using the interests in the caches. The local gradient is set by propagating interest messages from the sink to the source, where a path reinforcement between a source and a sink can be realized by resending interests frequently. The data which is sent back to a sink consists of data rate, duration and expiration time stamped from the received interest. In addition, several paths can be built so that one of them can be selected by reinforcement. The original interest message is sent again via the selected path by the sink node with a smaller interval, which hence, reinforces the source on that path, decrease the interval of the data packets. Figure 12 [4][9] shows the Directed Diffusion protocol.[64]

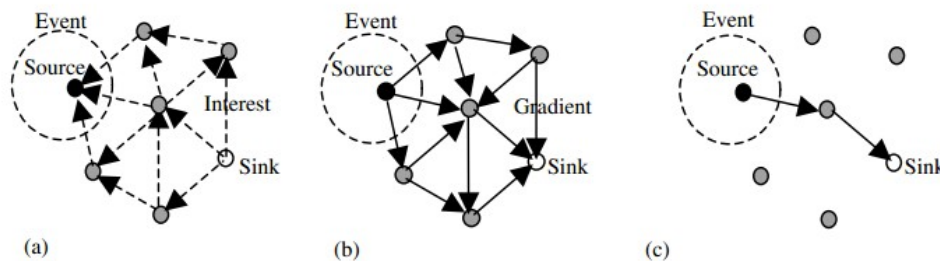


Figure 12: Directed Diffusion protocol. (a) Interest propagation phase. (b) Initial gradients establishment phase. (c) Data delivery phase.

Because there is less traffic, the Directed Diffusion protocol consumes much less energy compared with the flooding protocol. It is highly energy efficient because it is on demand with no requirement to maintain all the network topology. It uses the best path based on the local gradient and thus offers less low delay. The retransmission of interest message makes the protocol robust. Since it is a data-centric protocol, all the communication in the network is neighbour-to-neighbour and there is no need for a node addressing mechanism. Each node in the network can perform data aggregation and data caching, the exception being sensing. “Caching is a big advantage in terms of energy efficiency and delay.”[4]

However, the Directed Diffusion protocol is based on a query-driven data delivery model which makes it application dependent. The application, as is the case for environment monitoring, will not be effective with a query-driven on demand data model since it requires continuous data delivery to the sink.

**Advantages:**

1. Energy efficient.
2. Good robustness.
3. Data caching.

**Disadvantage:**

1. Cannot be applied to all sensor network applications.
2. Overhead of gradient establishment is great.

**4.1.4 Rumor Routing**

“Rumor routing is a logical compromise between query flooding and event flooding app schemes.”[10][11] Rumor routing is between query flooding and event flooding. If nodes have detected a specific event, in order to retrieve information about the events which are occurring, Rumor routing will route the queries to these nodes rather than flooding the whole network.

The Rumor routing protocol employs long-lived packets which are agents in order to flood events via the network. A node will add the event to its local table once it observes an event, and then an agent will be generated. Agents go through the network to propagate the information about local events to those distant nodes. After a query is generated for an event, the nodes which know the route synchronize their event lists with that of the met sensor and can respond to the query by means of their event tables. Figure 13, redrawn from [11], summarizes the Rumor routing protocol .[40-42]

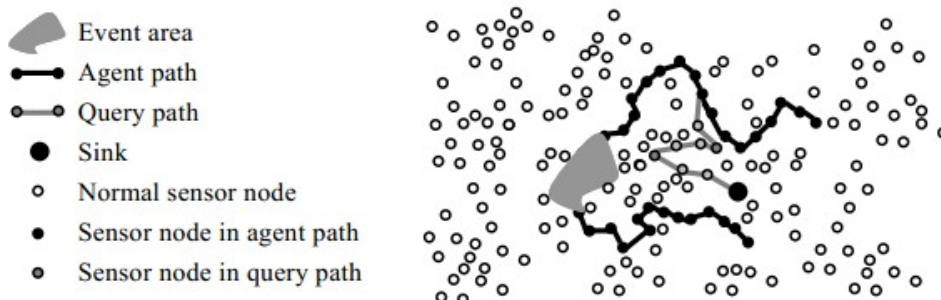


Figure 13: Agent propagation, cross of Agent path and Query path in Rumor routing protocol

Thus, the cost of flooding the entire network can be avoided. In addition, the Rumor routing protocol has only one path between the source and the destination. However, the Rumor routing protocol performs well only in the situation for which the number of events in the network is small. For large number of events in the network, the cost of maintaining agents and event tables is large.[42][43]

**Advantages:**

1. Energy efficient.

**Disadvantage:**

1. Performs well only when the number of events in the network is small.

**4.1.5 Energy- aware routing**

An Energy-aware routing protocol[12] is proposed to increase the lifetime of the network by using a set of sub-optimal paths occasionally in the network. A probability function based on the energy consumption of each path in the network is used to choose the paths. The main metric that the protocol is concerned with is network survivability. The protocol thinks that it will use up the energy of the nodes on one path so as to use the minimum energy path all the time. Instead of that, the Energy-aware routing protocol uses one of the multiple paths with a particular probability in order to increase the whole network lifetime. There are three phases in this approach[4][12]:

1. Set-up phase: In order to find the routing routes and create the routing tables, localized flooding occurs in the network. While this process is continuing, the total energy cost is being calculated in each node. For example, if node  $N_i$  sends the request to node  $N_j$ ,  $N_j$  will calculate the energy cost of the path as follows[12]:

$$C_{N_j, N_i} = \text{Cost}(N_i) + \text{Metric}(N_j, N_i).$$

The energy metric captures both sending and receiving costs together with the nodes' residual energy here. If the paths have a very high cost, they will be discarded. The node selection is according to the distance to the destination. A probability is assigned by each node to each of its neighbours in the routing forwarding table (FT) which corresponds to the formed paths in the network. The probability is as follow[12]:

$$P_{N_j, N_i} = \frac{1/C_{N_j, N_i}}{\sum_{k \in \text{FT}_j} 1/C_{N_j, N_k}};$$

As seen from the formula, the probability is inversely proportional to the energy cost.

Following on from this node  $N_j$  calculates the average energy cost to reach the destination through the neighbours in the forwarding table (FT) by using the formula below[12]:

$$\text{Cost}(N_j) = \sum_{i \in \text{FT}_j} P_{N_j, N_i} C_{N_j, N_i}.$$

2. Data transmission phase: Every node uses the probability formula to choose a node from its forwarding table randomly, and then forwards the packet.
3. Maintenance phase: Localized flooding occurs infrequently in order to keep all the paths alive.

Compared with the Directed Diffusion protocol, the Energy-aware routing protocol save more energy because that it selects a single path from the multiple paths randomly. “Therefore, when compared to Directed Diffusion, it provides an overall improvement of 21.5% energy saving and a 44% increase in network lifetime.”[4] However, in the set-up phase, the protocol needs to gather the location information and set up the addressing mechanism, which is complicated.

**Advantages:**

1. Energy saving.
2. Increase the lifetime of the network.

**Disadvantage:**

1. Processing overhead is large.
2. Calculation is a little complicated.

**4.1.6 Gradient-based routing**

In gradient-based routing, the number of hops will be retained when diffusing the interest through the network. The minimum hops to the sink can be found by every node, which is the height of the node. The gradient on one link is the difference between two nodes' heights. A message packet will be forwarded on the link with the largest gradient. [65]

In order to uniformly balance the traffic all over the network, this protocol plans to use some auxiliary techniques, including data aggregation and traffic spreading. In order to achieve data aggregation, a node, which is a relay for multiple paths can create a data combining entity. Additionally, there are three data spreading techniques:

1. Energy-based scheme: If a node's energy drops below a certain energy threshold, the node will increase its height to reduce the data transmission through this node.
2. Stochastic scheme: The node will randomly choose one node as next hop when there are several next hops with the same gradient.
3. Stream-based scheme: When nodes are currently part of the path of streams, the new streams are diverted away from these nodes.

The data spreading scheme achieves a distribution of the traffic via the entire network, which is helpful with regards to balancing the load on the nodes and thus increases the lifetime of the network.

### **Advantages:**

1. Energy efficiency.
2. Balance the traffic uniformly over the network.
3. Increases the network lifetime.

### **Disadvantage:**

1. Network maintenance overhead is large.

#### **4.1.7 Low-energy Adaptive Clustering Hierarchy (LEACH)**

Low-energy adaptive clustering hierarchy (LEACH)[6] is one of the most popular hierarchical routing protocols in wireless sensor networks. In the LEACH, local cluster heads are used as routers to the sink, and clusters of sensors are formed according to the strength of received signal. [51]

It will save a significant amount of energy because the transmission process will only be performed by those cluster heads rather than by all the sensor nodes.

All the data processing, such as data fusion and data aggregation, are local to the cluster heads. Cluster heads change randomly in every time period in order to balance the energy in the network. This decision is made as follows: every node in the network chooses a random number between 0 and 1. If one node's number is below the following threshold, this node will become a cluster head for the current round[4][6]:

$$T(n) = \begin{cases} \frac{p}{1 - p * (r \bmod 1/p)} & \text{if } n \in G, \\ 0 & \text{otherwise} \end{cases}$$

where  $r$  is the current round,  $p$  is the desired percentage of the cluster heads in the network, and  $G$  is the set includes all nodes that have not been cluster heads in the last  $1/p$  rounds.

LEACH increases the lifetime of the network by using dynamic cluster electing. This protocol does not require global knowledge of the network and is completely distributed. Because of data aggregation, the communication overhead is reduced. However, LEACH uses single-hop transmission. The data can be directly transmitted to the cluster head or the sink in the network by every node. Thus, it is not applicable to those networks in a large region and, additionally, the method of dynamic cluster selecting introduces extra overhead, which also costs a great deal of energy.

**Advantages:**

1. Energy saving.
2. Increases lifetime of system.
3. Reduce communication overhead.

**Disadvantage:**

1. Bad scalability.
2. Dynamic clustering introduces extra communication overhead.

**4.1.8 Power-efficient Gathering in Sensor Information Systems (PEGASIS)**

To improve the LEACH protocol, Power-efficient Gathering in Sensor Information Systems[13] has been proposed. Instead of forming multiple cluster heads, this protocol forms the chains from sensor nodes. Thus, every node only sends and receives message from its neighbour. And only one node in that chain

is selected to communicate with the sink or the base station. The data is gathered when travels in the network. And also, the data is aggregated and is then sent to the sink or the base station. The chain construction is shown in Figure 14[13].

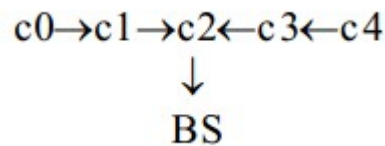


Figure 14: Chain in PEGASIS

Node c1 aggregates node c0's data with its own and transmits the aggregated data to node c2. Node c3 aggregates node c4's data with its own and transmits the aggregated data to node c2. After node c2 receives data from both neighbours, it aggregates its neighbours' data with its own. Finally, the aggregated message is transmitted to the base station by node c2.

This protocol uses multi-hop route by forming chains and selects only one node to directly transmit to the base station rather than using multiple nodes in the LEACH protocol. "PEGASIS has been shown to outperform LEACH by about 100–300% for different network sizes and topologies."[4]

Although the PEGASIS protocol avoids the overhead of selecting cluster heads in LEACH, it still requires a dynamic topology adjustment because the node's energy is unable to be tracked. For example, each node must be aware of its neighbour's status so that it knows where to transmit its data. Thus, this kind of topology adjustment significantly increases the overhead.

**Advantages:**

1. Energy efficient.
2. Reduces the number of transmission.
3. Increases the lifetime of the system.

**Disadvantage:**

1. Bad scalability.
2. Every node must have the ability to communicate with the sink.
3. Not in real-time.
4. Topology adjustment increases extra overhead.

**4.1.9 Threshold sensitive Energy Efficient sensor Network protocol (TEEN)**

Threshold sensitive Energy Efficient sensor Network protocol[14] is a hierarchical protocol. It is proposed in order to respond to sudden changes, such as temperature and luminance, in the sensed attributes. Responsiveness is important for real-time applications. The network architecture is based on a hierarchical grouping in which closer nodes form the cluster heads and this process continues on the second level until the base station is reached. The process is depicted in Figure 15[4][14]:

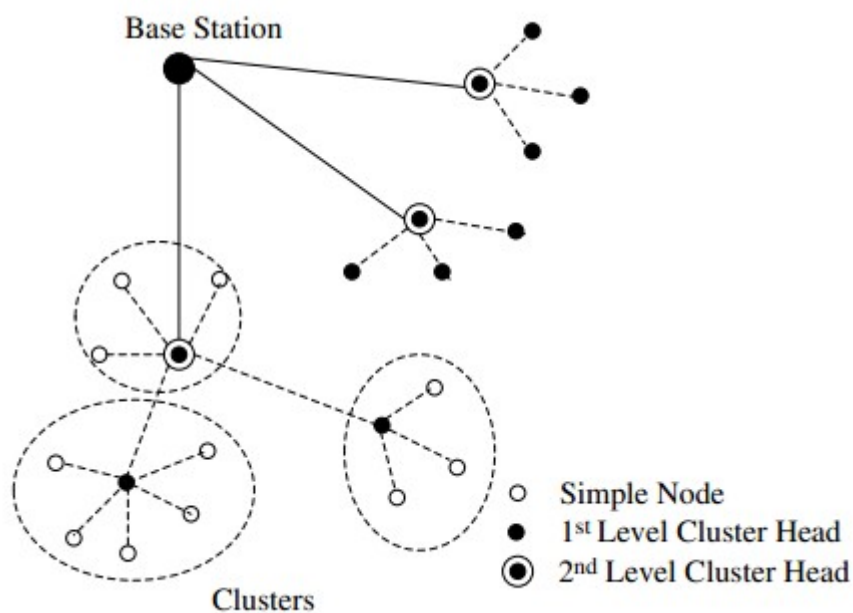


Figure 15: Hierarchical clustering in TEEN

The cluster head broadcasts two thresholds to the nodes when the clusters are formed, which are hard and soft thresholds for sensed attributes. A hard threshold is the minimum possible value of a sensed attribute, which will make a sensor node to switch on its transmitter and transmit attributes to the cluster head. Thus, only when the sensed attribute is in the range of interest, the hard threshold allows the nodes to transmit to the cluster head. The number of transmissions is significantly reduced. Once a value is sensed to be equal to or beyond the hard threshold, the sensed data will be transmitted only when the sensed value changes by an amount which is equal to or larger than the soft threshold. Therefore, if there is little or no changes in the sensed value, the soft threshold further reduces the number of transmissions in the network. Both the hard and soft threshold values can be adjusted in order to control the number of transmissions in the network. However, if periodic reports are required in the application, TEEN will not be suitable since the user is not able to obtain any sensed data at all until the thresholds are reached.

**Advantages:**

1. Reduces the number of transmission.
2. No need to have high-power communications capability.

**Disadvantage:**

1. Not suitable for applications where periodic reports are required.

**4.1.10 Two-Hop Velocity-based Routing for Gradient network (THVRG)**

THVRG[15] is based on the gradient network. In order to adapt a gradient network, this protocol uses the schemes which are composed of three sections below:

1. Gradient set-up phase: In this phase, the sink node broadcasts a packet containing a counter set as 1. Once receiving the packet from the sink, a node sets its height to the same value as the counter in the packet, increases the counter in the packet by 1, then forwards the packet to its neighbour.
2. Height calculation phase: The sink node sets its height equal to 0. The heights of other nodes in the network are equal to the smallest number of hops to the sink node.
3. Forwarding techniques phase: Every node calculates the joint parameters. A node compares all the received joint parameters of its neighbouring nodes and selects a neighbour to forward its packets to the sink.

After that, the protocol calculates some parameters according to several formulas. The threshold velocity that guarantees the end-to-end delay is given by the formula below[15]:

$$S_{th} = \frac{h_s}{t_{set}}$$

where  $t_{set}$  is the required deadline delivery, and  $h_s$  is the height of the source. Therefore, the two-hop velocity is calculated by the formula below:

$$S = \frac{2}{t_i + t_j}$$

where  $t_i$  is the delay from node  $i$  to node  $j$ , and  $t_j$  is the delay from node  $j$  to its optimal forwarder. If node  $j$  satisfies  $S \geq S_{th}$ , it is added into set  $P$  which is the potential forwarder set.

Considering both velocity and energy, the joint metric  $VE$  is defined as follows:

$$VE = f(\Delta t) \times \frac{S}{\sum_P S} + (1 - f(\Delta t)) \times \frac{E/E_0}{\sum_j E/E_0}$$

where  $\Delta t = t_{set} - t_0$  is the residual time to meet the deadline of the packet,  $t_0$  is the required time to forward the packet to node  $i$ ,  $f(\Delta t)$  is the function of  $\Delta t$ . The function  $f(\Delta t)$  must also satisfy the three requirements as follows:

1. It is an inverse function.
2. The value of the function belongs to  $[0, 1]$ .
3. When  $\Delta t \geq (t_{set} * h_i) / h_s$ ,  $f(\Delta t) < 0.5$ . Vice versa.

In addition, the larger  $f(\Delta t)$  means that the end-to-end delay is more interesting, and the smaller  $f(\Delta t)$  means distribute traffic to nodes with higher residual energy.

The optimal forwarder is selected according to analysing the value of the joint metric,  $VE$ . When a node wants to send a packet, it searches for the set of potential forwarders  $P$ . If  $P$  is empty, the initiative drop scheme is used. In order to find the set of potential forwarders, the source calculates the joint metric of its all one-hop neighbours.

A node decides whether to forward its packets based on the forwarding probability of a node, as below[15]:

$$u_i = 1 - K(\beta) \frac{\sum_{j=1}^N e_j}{N}$$

where  $e_j$  is the packet loss ratio and can be achieved by reading the link quality indicator.  $K(\beta)$  is the coefficient according to the gradient of node  $i$ , and  $\beta = h_i / h_s$ . In this protocol,  $K(\beta)$  is defined as follows[15]:

$$K(\beta) = \begin{cases} K_1, & \beta > \frac{1}{2} \\ K_2, & \beta \leq \frac{1}{2} \end{cases}$$

where both  $K_1$  and  $K_2$  are the positive coefficients.

The routing decision is according to the number of hops from the source node to the sink node and the two-hop information. The control scheme used in this protocol, additionally, reduces the computational complexity and enhances the energy efficiency of the sensor nodes. However, if one or more new nodes are added into the network, the whole gradient-based network must be set-up again. This may cost a great deal of energy. In a mobile network, each node has to periodically send additional messages in order to maintain two-hop information.

**Advantages:**

1. Improves the end-to-end delay.
2. Reduces the computational complexity.
3. Enhances the energy efficiency.

**Disadvantages:**

1. Poor scalability.
2. Overhead of update message is large.

## 5 Results

### 5.1 Classification of Routing Protocols

Routing in wireless sensor networks has attracted much attention in recent years and has introduced unique challenges as compared to traditional data routing in wired networks.[2]

This paper has summarized some state-of-the-art routing protocols in wireless sensor networks and has classified the approaches into two main categories mentioned in Chapter 2 in this paper. In order to provide a better understanding with regard to this comparison, the table list is used. Tables 3 and 4 summarize the classification of the routing protocols covered in this survey respectively based on routing issues and application-dependent feature.

Table 3: Classification of the routing protocols based on routing issues

Protocol	Uni-path	Multi-path	Flat	Hierarchical	data-centric	address-centric
Flooding		√	√			√
Gossiping	√		√			√
SPIN		√	√		√	
Directed Diffusion		√	√		√	√
Rumor routing	√		√		√	
Energy-aware	√		√		√	√
Gradient-based		√		√		√
LEACH	√			√	√	√
PEGASIS	√			√		√
TEEN	√			√	√	√
THVRG		√		√		√

Table 4: Classification of the routing protocols based on application-dependent feature

<b>Protocol</b>	<b>Data-aggregation</b>	<b>Query-driven</b>	<b>QoS-aware</b>
Flooding			
Gossiping			
SPIN	√	√	
Directed Diffusion	√	√	
Rumor routing	√	√	
Energy-aware		√	√
Gradient-based	√	√	
LEACH	√		
PEGASIS	√		
TEEN	√		
THVRG			√

## 5.2 Comparison of Routing Protocols

This work compares and evaluates the various state-of-the-art routing protocols in wireless sensor networks. The criteria, which will be used in the next comparison, must be defined in detail before these protocols are evaluated. For the sake of clarity, this work divides the evaluation criteria between quantitative criteria and qualitative criteria. The former include delay, computation overhead, communication overhead and network size. The latter include energy efficiency, scalability, complexity and lifetime. Additionally, this work evaluates the application areas of routing protocols and makes a table list in order to provide a better understanding.

### 5.2.1 Quantitative evaluation

Actually, routing protocols differ broadly in their computational requirements, communication requirements, energy consumption and delay. In addition, there is no protocol which clearly outperforms the others in all possible applications of wireless sensor networks. For instance, a low energy cost, high delay routing protocol could be appropriate for many applications with a slow update rate. However, many safety-critical applications, such as intrusion detection or aircraft navigation in military systems, require low delay protocols in order for nodes to correctly identify events occurring in the network. Table 5 compares the routing protocols studied in this survey in terms of the following quantitative criteria.

#### **Delay.**

Traditional wired networks are fully connected networks where the variability in the propagation and data queuing delay is relatively small. In addition, any node in the net can send a message directly to another one at any point in time. The delay in wireless sensor networks implies a constant end-to-end delay throughout the network. It also provides a close approximation for the actual latency. Wireless sensor networks may be large in size and have to transmit over a shared wireless medium.

#### **Overhead.**

In the whole routing process, in addition to the useful data, there is a great deal of control information, which is used for ensuring the completion of the communication. This control information is called the overhead. The information controlling computation is the computation overhead, and those for controlling data communication is the communication overhead.

**Network Size.**

Each routing protocol for WSNs is suitable for a kind of network, such as large-scale network or a small-scale network. Certainly, some are able to perform well in both large-scale and small-scale network. When evaluating this aspect, this work chooses the most suitable network for each protocol studied in this survey.

Table 5: Quantitative performance comparison of routing protocols.

<b>Protocol</b>	<b>Delay</b>	<b>Computation Overhead</b>	<b>Communication Overhead</b>	<b>Network Size</b>
Flooding	Average	Low	High	small-scale
Gossiping	High	Low	Low	small-scale
SPIN	High	High	Low	small-scale(with several sinks)
Directed Diffusion	Low	High	Low	small-scale
Rumor routing	High	Very high	Very high	small-scale
Energy-aware	Average	High	Low	small or medium-scale
Gradient-based	Average	High	Low	small-scale
LEACH	High	Very high	Low	small-scale
PEGASIS	Average	Low	Low	small-scale
TEEN	Average	High	Low	small-scale
THVRG	Low	High	Very low	medium or large-scale

**5.2.2 Qualitative evaluation**

This work evaluates the protocols based on overall quality criteria. While a quantitative evaluation, which deals with parameters, assists the reader to fine-tune a routing protocol by providing a telescopic view, a qualitative evaluation provides the readers with a broader and more general perspective. Table 6 compares the routing protocols studied in this survey in terms of the following qualitative criteria.

**Energy Efficiency.**

Energy efficiency is an implicit requirement in most wireless sensor networks and it varies depending on the application. For instance, in some cases, the requirement for the energy efficiency in sensor networks is quite strict, which limits the energy for routing and some other tasks. The main reason behind the energy constraint is the size of the batteries in the sensor nodes, which greatly limits the amount of energy which can be used and stored. An important trade off for wireless sensor networks between using the available energy for computing or for communicating must be considered.

**Scalability.**

The scope of a sensor network is the geographic span of the sensor nodes which are routed. In general, the scope of a sensor network can be expanded by increasing the number of nodes in the networks. As the sensors are becoming ever more cheap, wireless sensor networks are becoming larger, up to tens of thousands of nodes. Therefore, routing protocols must have sufficient scalability with respect to the network size.

**Computational Complexity.**

Since wireless sensor networks always have limited hardware capabilities and severe energy constraints, the complexity of a routing protocol can make a protocol impractical for many applications. The complexity, here, is viewed as a combination of protocol complexity, computation overhead and communication overhead.

Table 6: Qualitative performance comparison of routing protocols.

<b>Protocol</b>	<b>Energy Efficiency</b>	<b>Scalability</b>	<b>Computational Complexity</b>
Flooding	Low	Poor	Low
Gossiping	Low	Good	Low
SPIN	Average	Good	Low
Directed Diffusion	High	Poor	Low
Rumor routing	High	Good	Low
Energy-aware	High	Poor	High
Gradient-based	High	Poor	High
LEACH	Low	Good	High
PEGASIS	High	Poor	Low
TEEN	High	Poor	High
THVRG	Very high	Poor	Low

According to Tables 5 and 6, readers are able to choose the most suitable protocol for their different conditions.

### 5.2.3 Application areas evaluation

Application areas refer to the preferred application area of the protocol, but this is not absolute. It should depend on the specific application.

Table 7 compares the routing protocols studied in this survey in terms of application areas.

Table 7: Comparison of application areas of routing protocols

<b>Protocol</b>	<b>Application areas</b>
Flooding	Multiple sinks; high transmission reliability; node moving frequently; low scalability; reporting emergent event.
Gossiping	Multiple sinks; delay not aware; data loss tolerance; low scalability; node moving frequently.
SPIN	Multiple sinks; low scalability.
Directed Diffusion	Few sinks; query-driven application; each query with periodical responses.
Rumor routing	Multiple sinks and few event; delay not aware; query-driven application; each query with one response.
Energy-aware routing	query-driven application; node knows neighbor's energy cost; high network survivability.
Gradient-based routing	Few sinks; high transmission reliability.
LEACH	Delay aware; low scalability; node with high power.
PEGASIS	Delay aware; low scalability; node with high power.
TEEN	Delay aware; node with high power; reporting data with threshold.
THVRG	Few sinks; delay aware; low scalability.

## 6 Simulations of LEACH and THVRG

This work compares the low-energy adaptive clustering hierarchy (LEACH) with the two-hop information velocity-based routing for a gradient network (THVRG). These two algorithms are verified by means of the OPNET modeler 17.5.

### 6.1 Simulation Model

The IEEE 802.15.4-2006 standard is adopted in the wireless medium access control and the physical layer. The frequency band is 30 MHz, the data rate is 1024bps, and the modulation is BPSK. The parameters for the two protocols are consistent. The lossy wireless link model is adopted in the simulations.

### 6.2 Simulation Scenario

In fact, WSNs are used widely in agriculture, industry, civil, military applications, such as environmental monitoring, military surveillance, rescue and disaster relief, etc. In these applications, wireless sensor nodes update information to the sink through wireless sensor networks with short packets. In addition, the distribution of the sensor nodes is uniform or random within a wide area and every sensor node has a limited internal power.

In this simulation, two kinds of network topologies are used.

1. Square network: Figure 16 shows the topology of the network in the investigated simulation.



Figure 16: Square network topology used in the simulation

2. Straight network: Figure 17 shows the topology of the network in the investigated simulation.

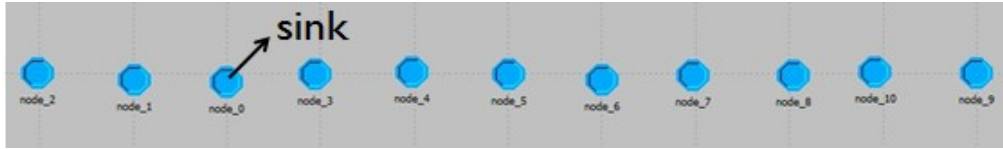


Figure 17: Straight network topology used in the simulation

### 6.3 Simulation Results

When comparing these two protocols, all the simulation results are based on the same conditions, such as the topology, the number of nodes, link model, etc. The simulation results are mainly compared in relation to these aspects: energy consumption, delay, packet delivery ratio(PDR), lifetime, complexity and priority.

#### 6.3.1 Energy Consumption

In this section, energy is all the energy consumed by all the sensor nodes in the network. Figure 18 shows the comparison of the two routing protocols in terms of the energy consumption.

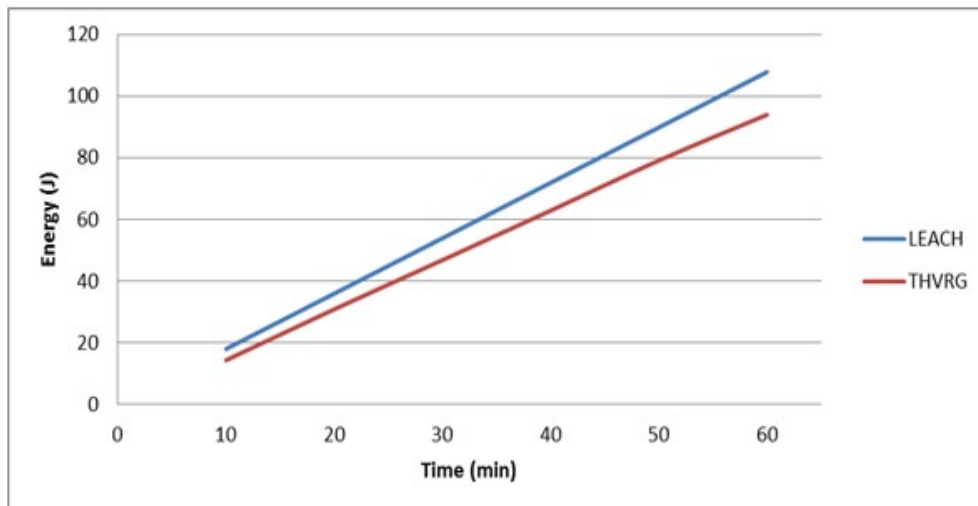


Figure 18: Comparison of energy consumption in the same period

Both of the protocols are simulated on the topology with 20 nodes(for LEACH, with 2% of the nodes being cluster heads) with the random network shown in Figure 16.

Figure 18 shows the amount of energy dissipated using LEACH versus using THVRG. This figure shows that the LEACH protocol dissipates more energy in the whole routing process. In a short period, the difference between LEACH and THVRG is not great. With the passage of time, LEACH protocol will dissipate much more energy than is the case for THVRG. Thus, THVRG is more energy efficient.

This is because THVRG is better able to forward data packets in a small number of hops with less message exchange overhead than the other protocols. Additionally, LEACH must select cluster heads at the beginning of each round and every cluster head in the LEACH must transmit data to the base station directly, regardless of the distance, which will cost a significant amount of energy.

**6.3.2 Packet Delivery Ratio(PDR)**

The packet delivery ratio is the ratio of the number of data packets actually delivered to the destination over the number of data packets which are supposed to be received. For a more comprehensive comparison of PDR, this work also uses two different network topologies to simulate LEACH and THVRG.

**Square network:**

The network topology is as shown in Figure 16. Figure 19 shows the comparison of the PDR for LEACH and THVRG in a square network.

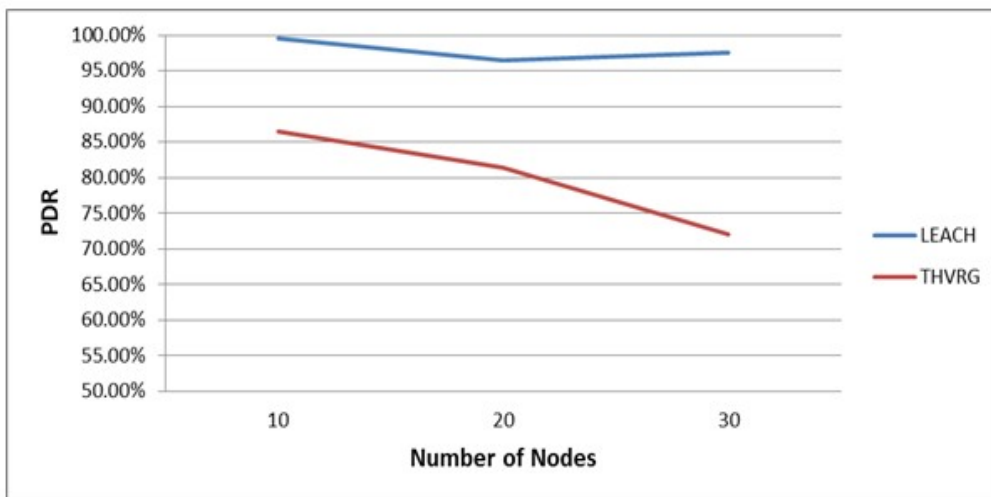


Figure 19: Comparison of PDR under the varied number of nodes in a straight network

As shown in Figure 19, the performance in PDR of LEACH is much better than that of THVRG. This is because, with the the number of nodes increasing, the packet collision in the THVRG is more severe, which leads to a decrease in the PDR. While in LEACH, there are only a few cluster heads in a round so the effect of its packet collision can be ignored.

**Straight topology:**

Then the straight network is used, as shown in Figure 17. Figure 20 shows the comparison of the PDR of LEACH and THVRG in a straight network.

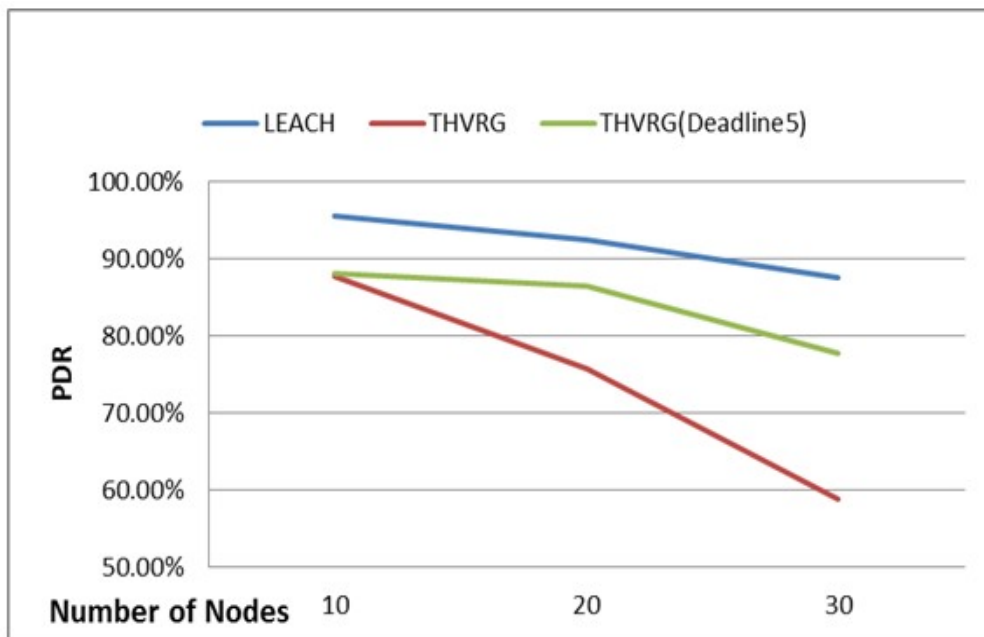


Figure 20: Comparison of PDR under the varied number of nodes in a straight network

As shown in the figure, the PDR of LEACH decreases as the number of nodes increase, but is still higher than that of THVRG. Due to the TDMA schedule in the LEACH, the straight network topology affect its PDR slightly. For THVRG, in the case with a 2s deadline, the PDR decreases very rapidly. There are two reasons for this, namely, many nodes are too far from the sink to transmit the packets successfully and if there are many nodes transmitting packets to the sink, the collisions will be very severe. These two points could affect the performance to a significant degree in relation to its PDR. While in the case with a 5s deadline, its performance in relation to the PDR improves a little. The packet collision in the THVRG being the main reason for this improvement.

All in all, the performance in the PDR of LEACH is much better than that of THVRG no matter which network topology is used.

**6.3.3 Delay**

The number of nodes affects both the energy consumption and end-to-end delay especially for CSMA-based routing protocols. Therefore, in this section, this work considers end-to-end delay under a variety of numbers of nodes in the network. For a more in-depth comparison, this work uses two different network topologies to simulate LEACH and THVRG.

**Square network:**

First, the random square network is used, as shown in Figure 16. Figure 21 shows the comparison of the two routing protocols in an end-to-end delay in a square network.

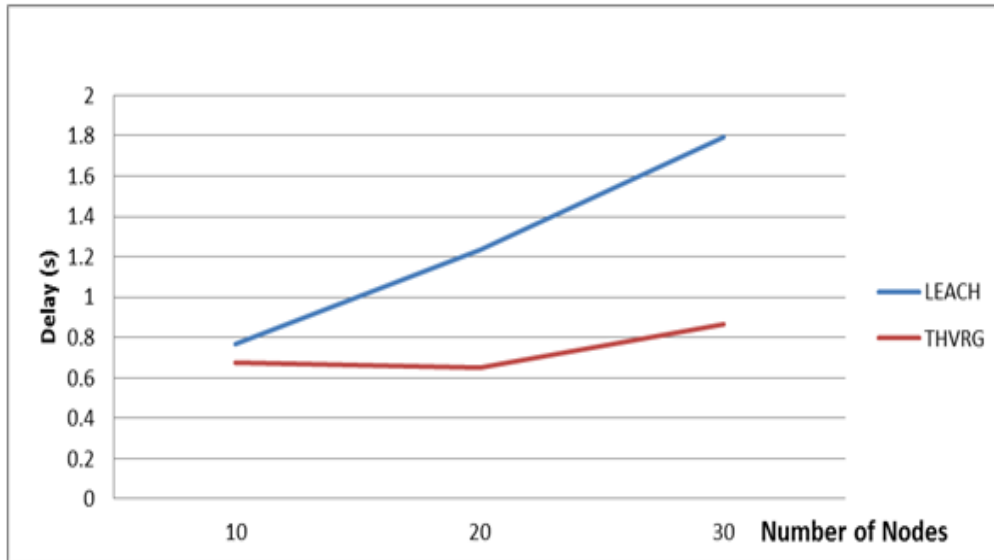


Figure 21 : Comparison of end-to-end delay under the varied number of nodes in a square network

As shown in Figure 21, the end-to-end delay of LEACH is much higher than that of THVRG. Additionally, the delay of LEACH increases significantly. When the number of nodes is less than 20, the delay of THVRG is almost the same, being about 0.65s. With the number of nodes increasing from 20, the delay for the THVRG starts to increase, but the margin is relatively small as compared to that for LEACH.

The reasons can be summarized into three points: 1. In LEACH, before data transmission, cluster heads must be selected in each round. 2. When normal nodes send data to cluster heads, a TDMA schedule is used. Each node only transmit data in its own time slot. 3. THVRG uses the CSMA MAC protocol. Only when the number of nodes is large, will its delay become high.

**Straight topology:**

Secondly, the straight network is used, as shown in Figure 17. This kind of network topology is often used in some factories. Figure 22 shows the comparison of the two routing protocols in an end-to-end delay in a straight network.

From the figure, it can be seen that the delay of LEACH in a straight is almost the same as for a straight network. But the change of topology significantly affects THVRG. In the THVRG with a 2s deadline, its delay decreases with the number of nodes increase. While in the THVRG with a 5s deadline, its delay increases significantly. Its maximum delay in the straight network with 30 nodes, is about 4s and this is almost twice as long as the maximum delay of LEACH in a square network with 30 nodes.

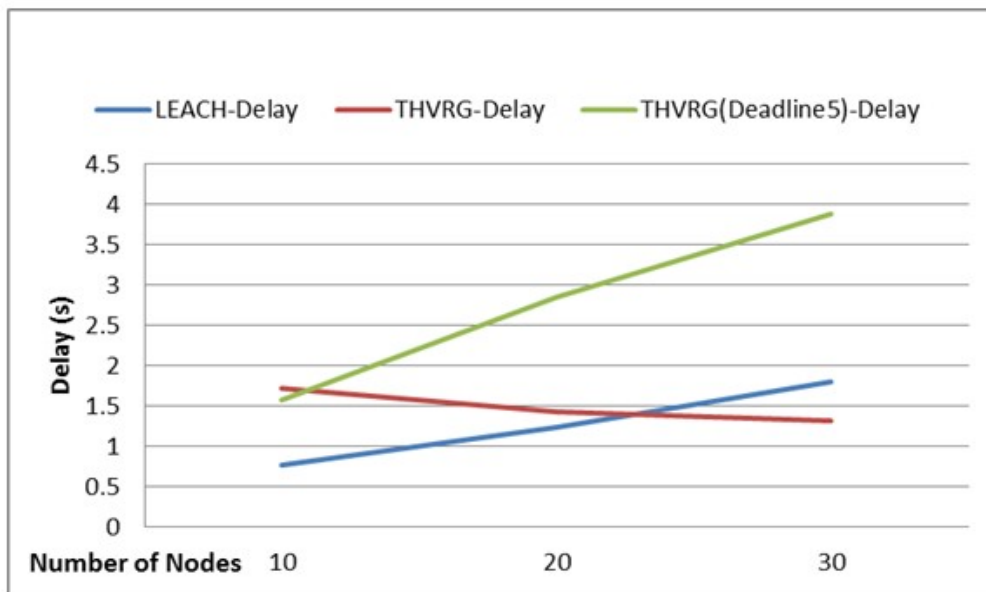


Figure 22: Comparison of end-to-end delay under the varied number of nodes in a straight network

For LEACH, the delay does not change a great deal since it uses a TDMA schedule to set the time for each normal node to be able to transmit. While for THVRG, in the situation with the 2s deadline, not all the data packets can be transmitted to the sink because of the straight network topology, only those nodes near to the sink transmit data packets to the sink successfully, which can be seen from Figure 23. In addition, THVRG uses the CSMA MAC protocol, the more nodes there are, the more collisions occur. Thus, its delay decreases as the number of nodes increase. In another situation with the 5s deadline, most of the nodes could transmit data packets to the sink successfully through multiple hops and the maximum hops could be 28 hops. Thus, its delay obviously increases as the the number of nodes increase.

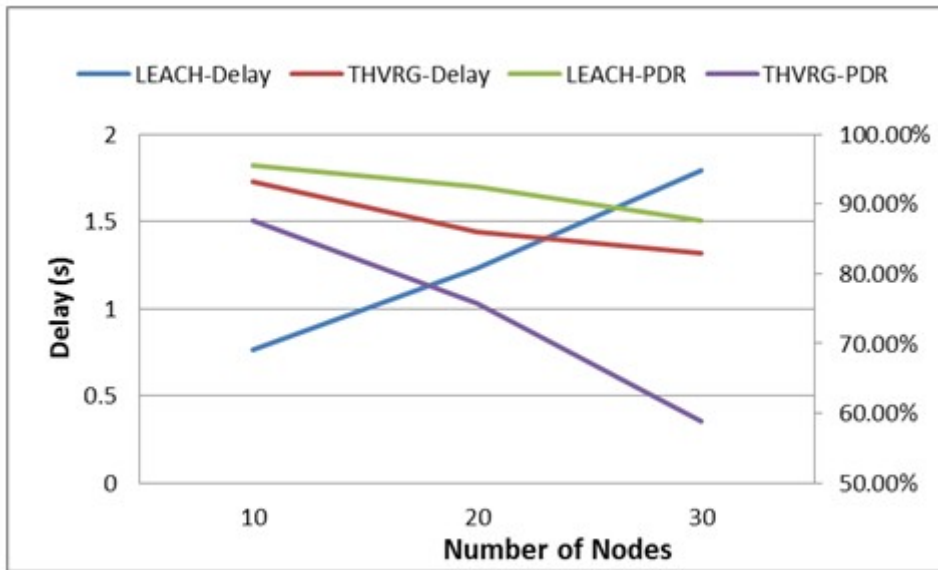


Figure 23: Relation between delay and PDR

### 6.3.4 Lifetime

A wireless sensor network might be deployed in a harsh and lossy environment, in other words, sensor nodes might die or exit from the network. Thus, lifetime is an important criterion to evaluate a protocol.

The initial energy of each node is 0.25J, and the number of nodes is 20. Figure 24 shows the comparison of two routing protocols in relation to the number of rounds under a varied percentage of dead nodes.

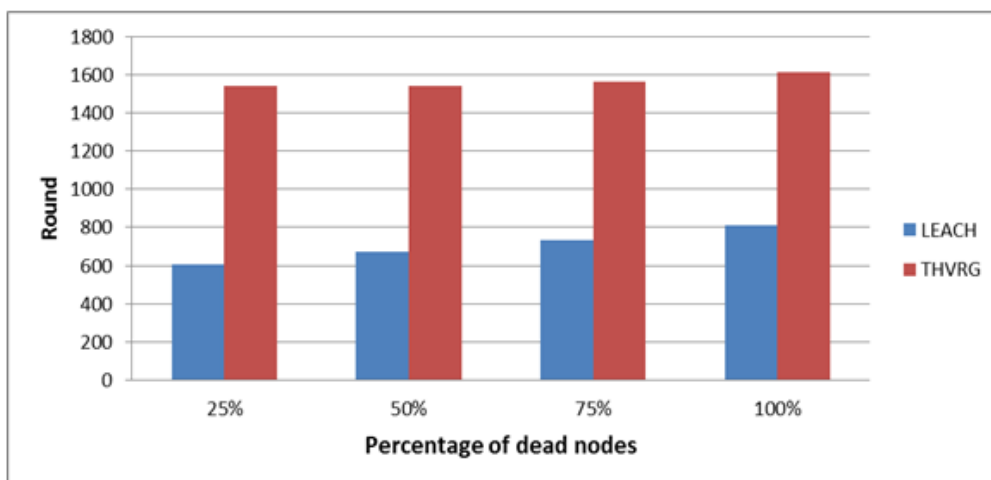


Figure 24 : Comparison the number of rounds under the varied percentage of dead nodes.

From the figure, it can be seen that it takes approximately 3 times longer for the first node to die and approximately twice as long for the last node to die in the THVRG as it does in LEACH.

Then, by changing the initial energy of each node, this work gives a comparison of the number of rounds(first node dead and network invalid) with different energy thresholds in both topologies. The network invalid round is the round after which the sink node can no longer receive packets. The data from these simulation is shown in Tables 8 and 9.

Table 8: Lifetimes using different amounts of initial energy for each sensor in a square network.

<b>Initial Energy (J/node)</b>	<b>Protocol</b>	<b>First node dead (Round)</b>	<b>Network Invalid (Round)</b>
0.25	LEACH	352	682
	THVRG	655	812
0.5	LEACH	702	1353
	THVRG	1219	1541
1	LEACH	1532	2863
	THVRG	2563	3044

From the table, it is found that no matter how much energy each node is given, it takes a longer time for the first node to die and for the network to be invalid in THVRG as it does in LEACH.

Table 9: Lifetimes using different amounts of initial energy for each sensor in a straight network.

<b>Initial Energy (J/node)</b>	<b>Protocol</b>	<b>First node dead (Round)</b>	<b>Network Invalid (Round)</b>
0.25	LEACH	347	668
	THVRG	430	547
0.5	LEACH	689	1278
	THVRG	990	1132
1	LEACH	1323	2754
	THVRG	1873	2293

As in Table 9, it takes a longer time for the network to become invalid based on a dead node in LEACH as it does in THVRG.

Actually, THVRG’s balance of energy in the network is significant better than for LEACH. Therefore, the lifetime of THVRG is longer than LEACH in a square network. In a straight network, there are many hops in THVRG to transmit data to the sink, and almost each hop is a node. If one of them is dead, it significantly affects the performance of THVRG. For LEACH, its cluster heads change in every round, so a node death has a lesser effect.

**6.3.5 Complexity**

The complexity of a routing protocol can make a protocol impractical for many applications. Here, the number of maintained packets is used to evaluate the complexity of a protocol.

Figure 25 shows the comparison of two routing protocols for the total number of maintained packets.

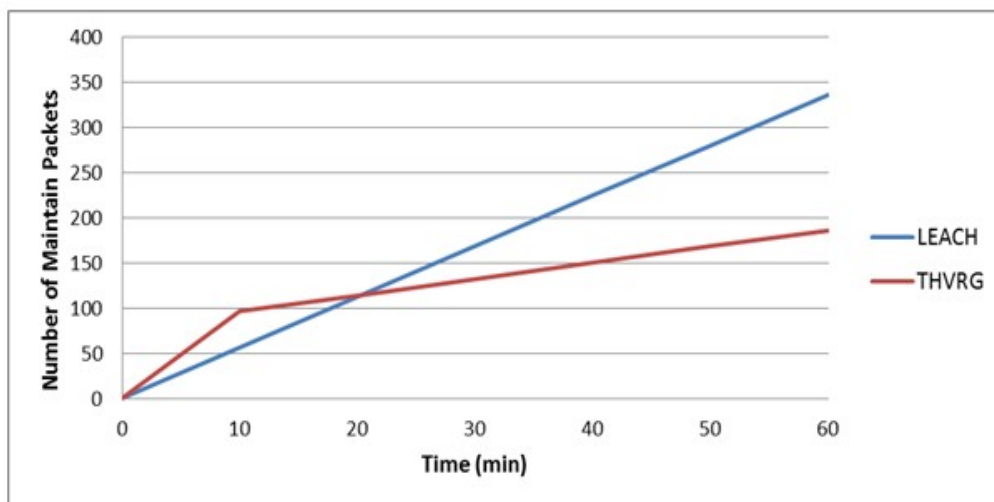


Figure 25: Comparison the total number of maintain packets.

As shown in Figure 25, the number of maintained packets for LEACH increases continuously from the beginning. While, the growth rate of the number of maintained packets in THVRG is greater than that of LEACH. After about 10 minutes, the growth rate for the number of maintained packets in THVRG is less than that of LEACH.

So, considering the whole process, the number of maintained packets of LEACH is much greater than that of THVRG.

The reason is that THVRG has a initialization phase which requires a significant number of maintained packets to build a gradient-based network. Most of maintained packets in THVRG come from its initialization phase. In addition, it only requires to initialize the network once, at the beginning. In the later process, it merely requires to maintain the two hop information, which is neither too much nor too large. For LEACH, it only requires to maintain packets at the beginning of each round with regards to selecting cluster heads. Therefore, its growth rate for the number of maintained packets is very stable.

In a word, the overhead of LEACH is greater than that of THVRG, so its complexity is higher than that of THVRG.

### **6.3.6 Priority**

There are many applications which require a priority scheme in wireless sensor networks. For instance, in the temperature monitoring of a factory, if there is a sudden increase in some local temperature, it is very possible that a fire will occur. The sensor node monitoring the soaring temperature will transmit a data packet, which is an emergency package and which is required to be transmitted to the sink immediately.

For comparing the priority adaptability of the two protocols, this work builds an easy priority scheme by changing the packet queue waiting for transmitting in each sensor node. The packets are divided into Level-1 packets(emergency package) and Level-2 packets(normal packet). The Level-1 packet is always at the beginning of the queue. The network topology used is a normal square network. Then, the delay and PDR are used as the measurement criteria.

Figure 26 shows the delay of Level-1 packets in two routing protocols under the priority scheme.

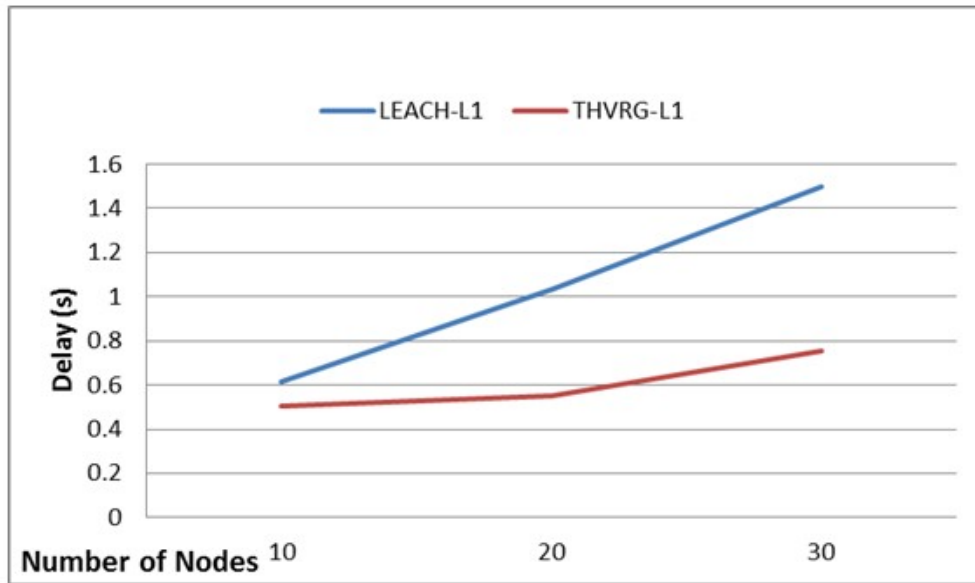


Figure 26: The delay of Level-1 packets under the priority scheme.

As shown in Figure 26, the delay of Level-1 packets in LEACH is much longer than that of THVRG. The delay of Level-1 packets in THVRG increases only when there are too many nodes in the network.

Figure 27 shows the delay of the Level-2 packets in the two routing protocols under the priority scheme.

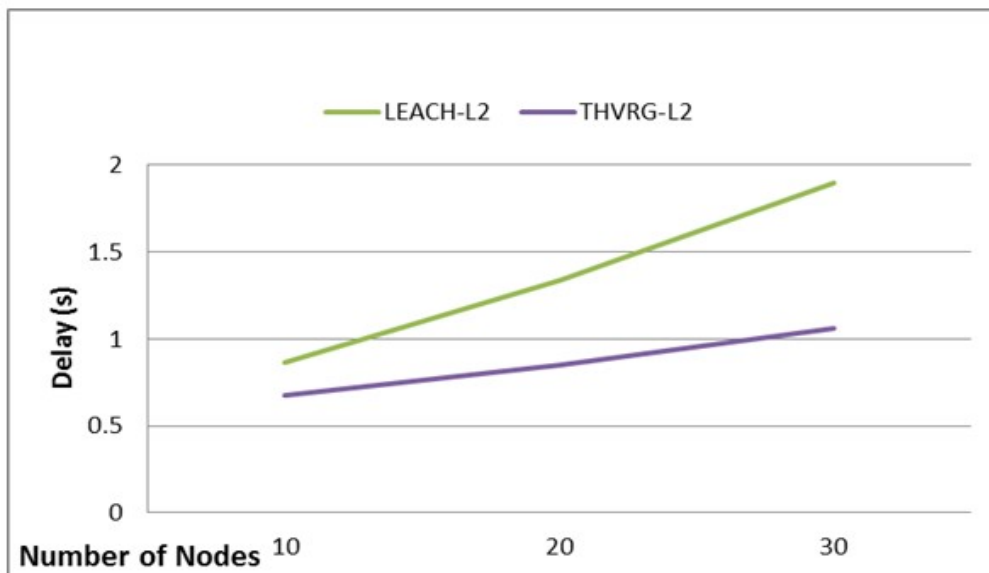


Figure 27: The delay of Level-2 packets under the priority scheme.

The delay of the Level-2 packets in LEACH is also much longer than that of THVRG, which is shown as Figure 27. Their growth rates are very stable. However, the growth rate of the delay in LEACH is much higher than that of THVRG.

LEACH uses a TDMA Schedule to set the time for which each normal node is able to transmit data in each round. Therefore, it is fixed when every packet has been transmitted to the sink successfully. In addition, LEACH must select cluster heads at the beginning of each round, which cannot be avoided.

However, it is the case that, after the initialization phase, THVRG merely require to transmit the packets waiting in the queue via its gradients to the sink.

Thus, the delays for each level packet in LEACH is much higher than that of THVRG under the priority scheme.

If comparing Level-1 and Level-2 packets together, the result can be seen from Figure 28.

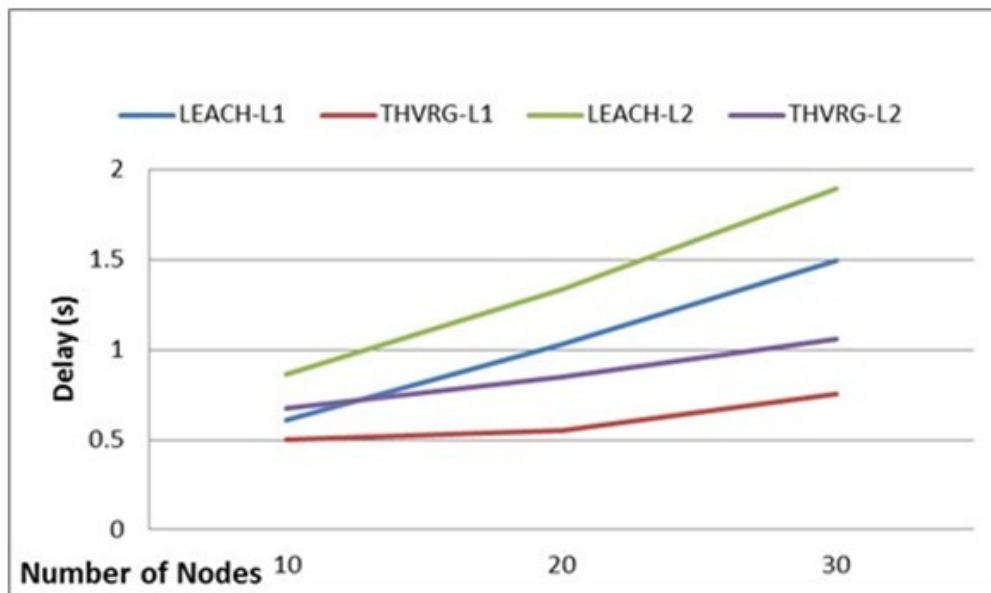


Figure 28: The delay of Level-2 and Level-2 packets under the priority scheme.

Apart from the above comparison results, the delay of a Level-2 packet in THVRG is even lower than that of LEACH. That is to say, in a emergency situation, it will takes less time for normal packets in THVRG to be transmitted to the sink than emergency packets in LEACH.

Therefore, when merely considering the delay in the priority scheme, THVRG performs much better than LEACH.

For a better comparison between LEACH and THVRG in the terms of priority adaptability, a PDR of two kinds of packets is also compared. Figure 29 shows the PDR of Level-1 packets in two routing protocols under the priority scheme.

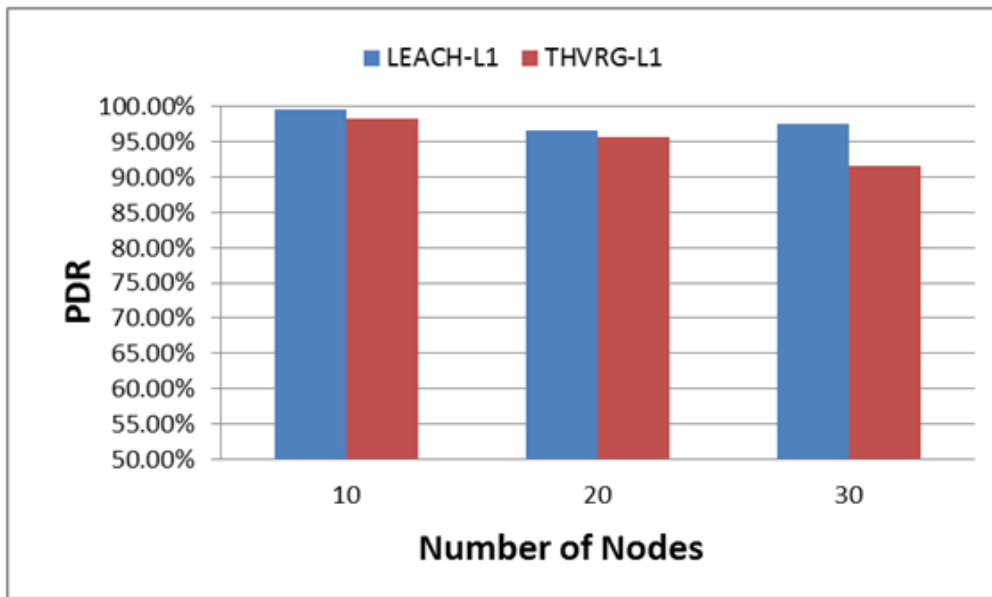


Figure 29: The PDR of Level-1 packets under the priority scheme.

In Figure 29, the PDR of the Level-1 packets in LEACH is always higher than that of THVRG no matter how many nodes there are.

Figure 30 shows the PDR of the Level-2 packets in two routing protocols under the priority scheme.

In Figure 30, the PDR of the Level-2 packets in LEACH is still higher than that of THVRG no matter how many nodes there are, which is similar to the case for Level-1.

The same reasons hold true, in that LEACH uses a TDMA Schedule to set the time for which each normal node is able to transmit data in each round, then the cluster heads transmit data directly to the base station via the CSMA MAC protocol. However, the number of cluster heads in each round is small, so the collisions are not intense. While, as THVRG uses the CSMA MAC protocol from the beginning to end, as the number of nodes increase, its collision become very intense.

Thus, the PDR of each level packet in LEACH is much higher than that of THVRG under the priority scheme.

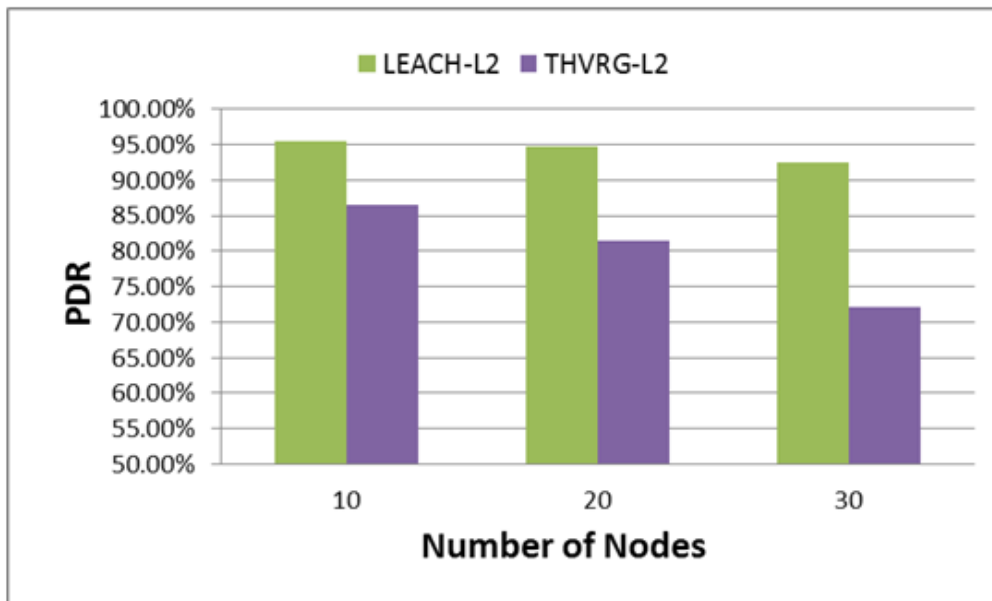


Figure 30: The PDR of Level-2 packets under the priority scheme.

If comparing the PDR of Level-1 and Level-2 packets in two protocols together, the result can be seen from Figure 31.

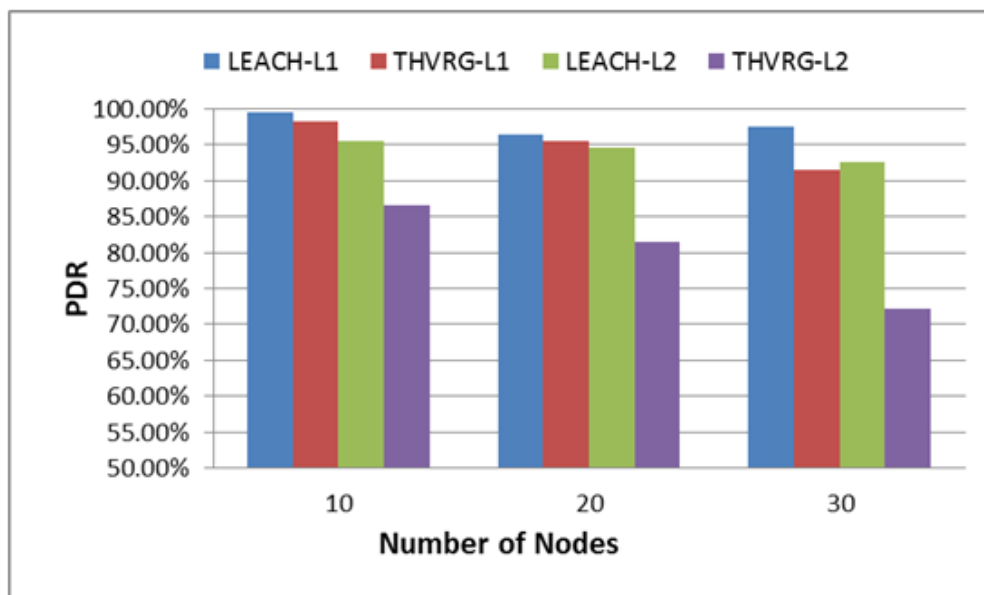


Figure 31: The PDR of Level-1 and Level-2 packets under the priority scheme.

Apart from the above comparison results, the PDR of Level-2 packet in LEACH is always approximately equal to the PDR of Level-1 packet in THVRG. It is even higher than that of THVRG when there are 30 nodes in the network. That is to say, in an emergency situation, LEACH will possibly transmit many more packets especially with regards to emergency packets to the sink more successfully than is the case for THVRG.

Thus, just considering the PDR in the priority scheme, LEACH performs much better than THVRG.

All in all, considering all the aspects, both LEACH and THVRG do not perform well in terms of priority, as this is only the case by changing the packet queue in each sensor node.

This work compares LEACH and THVRG from six aspects based on a large number of simulation results. Both perform well or badly in different aspects. Therefore, choosing, which is a suitable routing protocol should be made according to the different application requirements.

## 7 Conclusion and Outlook

### 7.1 Conclusion

In the recent years, routing in wireless sensor networks has attracted a great deal of attention and has introduced unique challenges compared to the traditional data routing in wired networks. Generally, a routing protocol is required to deal with energy efficiency, delay, scalability, low computation and communication overhead. This survey has summarized recent typical research results regarding data routing in wireless sensor networks and has classified the protocols into five main categories, namely data-centric, address-centric, hierarchical, data aggregation, and QoS-aware. Examples of uni-path, multi-path, flat and query-driven, which follow other protocols, have also been discussed.

Data-centric protocols are categorized since they name the data and query the nodes according to some attributes of the data. The most important aspect of this kind of paradigm is the content of the data generated by the sensor, which drives a majority of implementations of the upper layers, namely, discovery, routing, and querying. In order to avoid the usage of specialized nodes, the overhead of forming cluster heads, etc., much of the research follows this paradigm. However, the naming scheme might not prove to be sufficient for complex queries and is not easily extended to cover a larger area. It is usually dependent on the application.

Protocols which employ location information and topological deployment of sensor nodes is classified as address-based protocols. Routing tables are not required in this network since every node can decide how to relay data packets based on some local information concerning its immediate neighbour nodes and the destination. However, the source must know the position of the destination and this is still an implicit requirement for many applications in WSNs. Moreover, how to aid energy efficient routing by means of intelligent utilization of the location information is still a problem.

The sensed data are efficiently relayed to the sink in hierarchical routing protocols by dividing sensor nodes into different groups. Sometimes, the cluster heads are chosen as the specialized nodes which are less energy constrained. A cluster head performs data aggregation or data fusion and directly transmits data to the sink on behalf of other member nodes within its cluster.

Protocols, which utilize data aggregation are classified as data aggregation routing protocols. This is an important consideration for a routing protocol in terms of traffic optimization and energy saving. In general, it requires to be supported by time synchronization.

Most protocols pay main attention to the energy efficiency without considering many issues such as QoS. QoS-aware routing protocols consider delay, packet delivery ratio and other QoS parameters, and then choose the most suitable route which QoS applications require from a number of possible routes. QoS-aware routing protocols in wireless sensor networks have many applications including real time target tracking in battle environments, emerging event triggering in monitoring applications, etc. Currently, there are almost no research that focuses on dealing with QoS requirements in a very energy constrained environment such as for wireless sensor networks.

The purpose of this work is to survey and evaluate several routing protocols in wireless sensor networks and study their primary routing selection principles. This thesis presents a survey and analysis of various state-of-the-art routing protocols in wireless sensor networks based on a variety of aspects such as energy efficiency, delay, computational complexity and overhead. Clear classifications of routing protocols from many points of view have been provided. The design considerations presented in this thesis should be a significant assistance to designers building a successful routing protocol for a given application. Additionally, this work has achieved the simulations of two outstanding protocols, LEACH and THVRG, and compared them from a number of aspects, including delay, energy efficiency and priority, based on the simulation results. Finally, this survey provides a suitable benchmark for designers to compare their results with various existing routing protocols which are widely used in wireless sensor networks.

## 7.2 Outlook

Due to the limited resources and based on the high relevance to applications, the researchers have used a variety of strategies to design routing protocols. Excellent protocols have the following characteristics: relation to the characteristics for highly constrained energy, efficient use of energy is almost the first strategy for the design; Considering the characteristics such as header overhead and communication energy consumption, node cooperation relations, data correlation and limited node energy, both data aggregation and filtering technology are used; The network is relatively closed and only the sink node connects to the other network; Against that, for nodes prone to failure, a multi-path mechanism is adopted.

Wireless sensor network is a popular research area and has a large amount of applications in the real world. Protocols presented in this survey have their own problems which require improvements. By analysis and a summary of the current routing protocols, there are still many topics, development trend and research strategies that deserve further investigation as follows:

1. Traffic control: Reduce the amount of traffic in order to save energy as data communication is the most energy-consuming part of the WSNs. Investigations are still required as to how to distribute traffic efficiently from a central node to other nodes in the network.

2. Maintain the traffic load balancing: Each node sharing data transmission through a more flexible use of the routing policy, in order to balance the remaining node energy and improve the survival time of the entire network.
3. Fault tolerance: Routing protocols should have fault tolerance. WSNs nodes are prone to failure, thus, a protocol should make full use of the network information which is easily accessed by a node in order to calculate routes, so as to ensure that the routing failure can be restored as soon as possible; multi-path transmission can also improve the reliability of data transmission.
4. Security: Routing protocols should have security mechanisms. Due to the inherent characteristics of WSNs, the routing protocol is highly vulnerable to security threats, especially in military applications.
5. Multiple Source: Most of the current routing protocols in WSNs are designed for single source multicasting. However, a multicast group may contain multiple sources because of different kinds of applications or services simultaneously provided by the network.
6. Mobility: Most of the existing routing protocols assume the situation in which the basestation, the sink and the sensor nodes are stationary. However, there also exists some applications such as a battle environment, where the sink and the sensor nodes possibly need to be mobile.

There are still some more possible future investigation for routing protocols includes the integration of wireless sensor networks with wired networks, such as the Internet.

Routing is an important technology in wireless sensor networks, and researchers are still required to continue to explore and discover.

## References

- [1] I.F. Akyildiz, W. Su, et al., “Wireless sensor networks: a survey”, *Computer Networks* 38 (4) (2002) 393–422.
- [2] D. Goyal, M. R. Tripathy “Routing Protocols in Wireless Sensor Networks: A Survey”, 2012 Second International Conference on Advanced Computing & Communication Technologies. 2012.
- [3] S. Hedetniemi, A. Liestman, “A survey of gossiping and broadcasting in communication networks”, *Networks* 18 (4) (1988) 319–349.
- [4] K. Akkaya, M. Younis, “A survey on routing protocols for wireless sensor networks”. *Ad Hoc Networks* 3 (2005) 325–349.
- [5] W. Heinzelman, J. Kulik, H. Balakrishnan, “Adaptive protocols for information dissemination in wireless sensor networks”, in: *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom'99)*, Seattle, WA, August 1999.
- [6] Heinzelman, Wendi Rabiner, Anantha Chandrakasan, and Hari Balakrishnan. "Energy-efficient communication protocol for wireless microsensor networks." *System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on*. IEEE, 2000.
- [7] Z. Yang, A. Mohammed, “A Survey of Routing Protocols of Wireless Sensor Networks”. *Sustainable Wireless Sensor Networks*.
- [8] University at Buffalo, “OPNET Modeler”, <https://wiki.cse.buffalo.edu/services/content/opnet-modeler> , Published .Retrieved 2013-6-8.
- [9] C. Intanagonwiwat, R. Govindan, D. Estrin, “Directed diffusion for Wireless Sensor Networking”, in: *Proceedings of the 6th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, Boston, MA, August 2000.
- [10] S.K. Singh, M P. Singh, D K. Singh, “Routing Protocols in Wireless Sensor Networks – A Survey”, *International Journal of Computer Science & Engineering Survey (IJCSES)* Vol.1, No.2, November 2010, pp. 570–580.
- [11] D. Braginsky and D. Estrin, "Rumor routing algorithm in sensor networks", *Proceedings ACM WSNA*, in conjunction with ACM MobiCom'02,Atlanta, GA, Sept. 2002, pp. 22-31.

- [12] R. Shah, J. Rabaey, “Energy aware routing for low energy ad hoc sensor networks”, in: Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), Orlando, FL, March 2002.
- [13] Lindsey, Stephanie, and Cauligi S. Raghavendra. "PEGASIS: Power-efficient gathering in sensor information systems." Aerospace conference proceedings, 2002. IEEE. Vol. 3. IEEE, 2002.
- [14] A. Manjeshwar, D.P. Agrawal, “TEEN: a protocol for enhanced efficiency in wireless sensor networks”, in: Proceedings of the 1st International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing, San Francisco, CA, April 2001.
- [15] Y. Li, C. Chen, Y. Song, Z. Wang and Y. Sun, “Enhancing Real-Time Delivery in Wireless Sensor Networks With Two-Hop Information”, IEEE Transactions on Industrial Informatics, vol. 5, 2009. 113-122.
- [16] J.J. Lotf, S.H.H.N. Ghazani, “Overview on routing protocols in wireless sensor networks”, 2010 2nd International Conference on Computer Engineering and Technology, vol. 3, 2010.610-614.
- [17] K. Sohrabi, “Protocols for self-organization of a wireless sensor network”, IEEE Personal Communications 7 (5) (2000) 16–27.
- [18] S. Misra et al. (eds.), “Guide to Wireless Sensor Networks”, Computer Communications and Networks, DOI: 10.1007/978-1-84882-218-4 4, Springer-Verlag London Limited 2009.
- [19] C. Ho, K. Obraczka, G. Tsudik, and K. Viswanath, “Flooding for reliable multicast in multi-hop ad hoc networks”, In Proceedings of the 3rd International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIAL-M’99), 1999, pp. 64–71.
- [20] M. Liu, J. Cao, G.i Chen, and X. Wang, “An Energy-Aware Routing Protocol in Wireless Sensor Networks”, Sensors 2009, vol. 9, pp. 445-462.
- [21] D.E. Culler, D.Estrin, and M.B. Srivastava. “Overview of sensor networks”, IEEE Computer, 37(8):41 49, 2004.
- [22] Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E. “A survey on sensor networks”. IEEE Communications Magazine, 2002, 40(8): 102 – 114.
- [23] Yang, Ying. “Time Synchronization in Wireless Sensor Networks : A Survey”. Diss. Mid Sweden University, 2012.

- [24] Samina Ehsan, and Bechir Hamdaoui, “A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks”, IEEE Communications Surveys & Tutorials, Vol. 14, NO. 2, 2012.
- [25] OPNET Technologies, Inc: OPNET Modeler Documentation Set, Version: 17.5. 2012
- [26] Wikipedia, “CSMA”,  
[http://en.wikipedia.org/wiki/Carrier\\_sense\\_multiple\\_access](http://en.wikipedia.org/wiki/Carrier_sense_multiple_access) , Published 2013-5-10 .Retrieved 2013-6-10.
- [27] Wikipedia, “TDMA”  
[http://en.wikipedia.org/wiki/Time\\_division\\_multiple\\_access](http://en.wikipedia.org/wiki/Time_division_multiple_access) , Published 2013-6-14 .Retrieved 2013-6-10.
- [28] J.N. Al-Karaki, A.E. Kamal, “Routing Techniques in Wireless Sensor Network: A Survey”, IEEE Wireless Communications, Dec. 2004.
- [29] A.Z.M. Shahriar, M. Atiquzzaman, W. Ivancic, “Route Optimization in Network Mobility: Solutions, Classification, Comparison, and Future Research Directions”, IEEE Communications Surveys & Tutorials, Vol. 12, NO. 1, 2010.
- [30] Luo Junhai, Ye Danxia, Xue Liu, and Fan Mingyu, “A Survey of Multicast Routing Protocols for Mobile Ad-Hoc Networks”, IEEE Communications Surveys & Tutorials, Vol. 11, NO. 1, 2009.
- [31] S. Uludag, K.S. Lui, K. Nahrstedt, and G. Brewster, “Analysis of Topology Aggregation Techniques for QoS Routing”, ACM Computing Surveys, Vol. 39, No. 3, Article 7, Publication date: August 2007.
- [32] R. A. Uthra, S. V. K. Raja “QoS Routing in Wireless Sensor Networks—A Survey”, ACM Computing Surveys, Vol. 45, No. 1, Article 9, Publication date: November 2012.
- [33] C. Ramassamy, H. Fouchal, P. Hunel, “Classification of Usual Protocols over Wireless Sensor Networks”, IEEE ICC 2012 - Ad-hoc and Sensor Networking Symposium, 2012.
- [34] Rachid Ennaji, Mohammed Boulmalf, “Routing in Wireless Sensor Networks”, 2009 IEEE, 2009.
- [35] Qing Bian, Yan Zhang, Yanjuan Zhao, “Research on Clustering Routing Algorithms in Wireless Sensor Networks”, 2010 International Conference on Intelligent Computation Technology and Automation, IEEE Computer Society, 2010.

- [36] CHENG Meng-xiao, HUANG Ting-lei, LI Hai-ming, XIN Hong-bo, "Research of Routing Algorithm for Wireless Sensor Network", 2010 IEEE, 2010.
- [37] K. Pavai, A. Sivagami, D. Sridharan , "Study of Routing Protocols in Wireless Sensor Networks", 2009 International Conference on Advances in Computing, Control, and Telecommunication Technologies, IEEE Computer Society, 2009.
- [38] Karyono, I. Martoyo, H.P. Uranus, Junita, B. Kim, "Simulation of Gravity and Flooding Algorithm for Wireless Sensor Network", Proceedings of the 2009 IEEE 9th Malaysia International Conference on Communications 15 -17 December 2009 Kuala Lumpur Malaysia.
- [39] J. Kulik, W. Heinzelman, H. balakrishnan, "Negotiation-Based Protocols for Disseminating Information in Wireless Sensor Networks", Wireless Networks 8, 169–185, 2002.
- [40] Modi Z, Jardosh S, Ranjan P. "Optimized Rumor routing algorithm for Wireless Sensor Networks", Wireless Communication and Sensor Networks (WCSN), 2009 Fifth IEEE Conference on. IEEE, 2009: 1-6.
- [41] Shokrzadeh H, Haghghat A T, Tashtarian F, et al. "Directional rumor routing in wireless sensor networks", Internet, 2007. ICI 2007. 3rd IEEE/IFIP International Conference in Central Asia on. IEEE, 2007: 1-5.
- [42] Braginsky D, Estrin D. "Rumor routing algorithm for sensor networks", Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications. ACM, 2002: 22-31.
- [43] Sann, Zarni, and Khaing Thazin Minn. "Simulation of the Rumor Routing Algorithm in sensor networks." Computer Research and Development (ICCRD), 2011 3rd International Conference on. Vol. 3. IEEE, 2011.
- [44] Haas, Zygmunt J., Joseph Y. Halpern, and Li Li. "Gossip-based ad hoc routing." INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE. Vol. 3. IEEE, 2002.
- [45] Ding, Rong, and Lei Yang. "A reactive geographic routing protocol for wireless sensor networks." Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2010 Sixth International Conference on. IEEE, 2010.
- [46] Zang, Zhe, Jian-Dong Qi, and Yong-Jie Cao. "A robust routing protocol in wireless sensor network." (2010): 276-279.

- [47] Abe, Rey, and Shinichi Honiden. "Adaptive geographic routing in wireless sensor networks." Proceedings of the 13th ACM international conference on Modeling, analysis, and simulation of wireless and mobile systems. ACM, 2010.
- [48] Yin, Guisheng, et al. "An energy-efficient routing algorithm for wireless sensor networks." Internet Computing in Science and Engineering, 2008. ICICSE'08. International Conference on. IEEE, 2008.
- [49] Danyan Luo, Decheng Zuo, Xiaozong Yang, "An Energy-Saving Routing Protocol for Wireless Sensor Networks", IEEE, 2008.
- [50] Chen, Guihai, et al. "An unequal cluster-based routing protocol in wireless sensor networks." Wireless Networks 15.2 (2009): 193-207.
- [51] Zhang, Lei, et al. "Grouping-based clustering routing protocol in wireless sensor networks." Wireless Communications, Networking and Mobile Computing, 2007. WiCom 2007. International Conference on. IEEE, 2007.
- [52] Nurhayati, "Inner Cluster Routing Protocol Wireless Sensor Network", International Conference on Computer and Communication Engineering (ICCCE 2012), 3-5 July 2012, Kuala Lumpur, Malaysia.
- [53] Baghyalakshmi, D., Jemimah Ebenezer, and S. A. V. Satyamurty. "Low latency and energy efficient routing protocols for wireless sensor networks." Wireless Communication and Sensor Computing, 2010. ICWC-SC 2010. International Conference on. IEEE, 2010.
- [54] Min, Rex, et al. "Low-power wireless sensor networks." VLSI Design, 2001. Fourteenth International Conference on. IEEE, 2001.
- [55] R.H. Katz, J.M. Kahn, K.S.J. Pister, "Mobile networking for smart dust", in: Proceedings of the 5th Annual ACM", IEEE International Conference on Mobile Computing and Networking, Seattle, WA, August 1999.
- [56] Heinzelman, Wendi Rabiner, et al. "Energy-scalable algorithms and protocols for wireless microsensor networks." Acoustics, Speech, and Signal Processing, 2000. ICASSP'00. Proceedings. 2000 IEEE International Conference on. Vol. 6. IEEE, 2000.
- [57] Min, Rex, et al. "An architecture for a power-aware distributed microsensor node." Signal Processing Systems, 2000. SiPS 2000. 2000 IEEE Workshop on. IEEE, 2000.

- [58] Woo, Alec, and David E. Culler. "A transmission control scheme for media access in sensor networks." Proceedings of the 7th annual international conference on Mobile computing and networking. ACM, 2001.
- [59] Ye, Wei, John Heidemann, and Deborah Estrin. "An energy-efficient MAC protocol for wireless sensor networks." INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE. Vol. 3. IEEE, 2002.
- [60] Shih, Eugene, et al. "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks." Proceedings of the 7th annual international conference on Mobile computing and networking. ACM, 2001.
- [61] Subramanian, Lakshminarayanan, and Randy H. Katz. "An architecture for building self-configurable systems." Mobile and Ad Hoc Networking and Computing, 2000. MobiHOC. 2000 First Annual Workshop on. IEEE, 2000.
- [62] Ye, Fan, et al. "A two-tier data dissemination model for large-scale wireless sensor networks." Proceedings of the 8th annual international conference on Mobile computing and networking. ACM, 2002.
- [63] Estrin, Deborah, et al. "Next century challenges: Scalable coordination in sensor networks." Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking. ACM, 1999.
- [64] Ganesan, Deepak, et al. "Highly-resilient, energy-efficient multipath routing in wireless sensor networks." ACM SIGMOBILE Mobile Computing and Communications Review 5.4 (2001): 11-25.
- [65] Schurgers, Curt, and Mani B. Srivastava. "Energy efficient routing in wireless sensor networks." Military Communications Conference, 2001. MILCOM 2001. Communications for Network-Centric Operations: Creating the Information Force. IEEE. Vol. 1. IEEE, 2001.