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Sink Mobility Schemes in Wireless Sensor Networks for Network Lifetime Extension

by

Jingxing Guo

A Thesis
Submitted to the Faculty of Graduate Studies
through Department of Computer Science
in Partial Fulfillment of the Requirements for
the Degree of Master of at the
University of Windsor

Windsor, Ontario, Canada

2012

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Sink Mobility Schemes in Wireless Sensor Networks for Network Lifetime Extension

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ABSTRACT

Sensor nodes in Wireless Sensor Networks (*WSNs*) are normally battery-powered and remain stationary after deployment. When a sensor node runs out of energy it will no longer provide sensing and data processing. This can lead to a huge loss in the network due to the routing path re-allocation and failure of sensing and reporting events in the environment. Hence energy conservation has been receiving increased attention in *WSN* research works. The concept of *mobile sink* has been recently introduced for *WSNs* in order to improve the overall performance of *WSNs* as it shifts the burden of energy consumption from the sensor nodes to sink nodes, which are typically considered to have unconstrained energy supply and larger computational power.

In this thesis we present two sink mobility schemes: Load Base sink Movement (*LBM*) and Residual Energy Aware Routing (*REAR*) to prolong network lifetime in a random event-driven scenario. *LBM* computes the optimal tentative sink node position considering both the geographical distance from sensors to sink and transmission load of sensors as well. *REAR* is a routing strategy that considers the residual energy of sensors when establishing routing paths. Experimental results confirm that the proposed schemes can significantly extend the network lifetime, compared to existing techniques.

DEDICATION

To all those people who help me all the way through, especially to my family, who offered unconditional love and support, and my girlfriend Minfei Fu, who keeps my spirits up and remains willing to engage with the struggle.

ACKNOWLEDGEMENT

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I. INTRODUCTION

1.1. Wireless Sensor Network

Wireless sensor networks (WSN) are generally used to monitor activities and report events, such as fire, overheating etc. in a specific area or environment. In the recent past, wireless sensor networks have found their way into a wide variety of applications and systems, with vastly varying requirements and characteristics [1]. The actual implementation of a wireless sensor network is widely used in many areas, especially in military applications, biological and health applications, environmental applications and some commercial applications. In such applications WSN can perform sensing activities in multiple environmental conditions, including the following [2]:

- Temperature,
- Humidity,
- Vehicular movement,
- Lightning condition,
- Pressure,
- Soil makeup,
- Noise levels,
- The presence or absence of certain kinds of objects,
- Mechanical stress levels on attached objects, and
- Current characteristics such as speed, direction, and size of an object

1.2. Wireless Sensor Network Model

There are basically two components in the infrastructure of a wireless sensor network: sink nodes and sensor nodes. Sink nodes are considered as base stations in the network that wirelessly receive and collect data packages generated from all the sensor nodes in the network and provide them to users. From the base station users can access the data, possibly through internet, for further processing of the data and to extract useful information [3]. Depending on the network size and network topology, there could be one or multiple sink nodes and the sink nodes can either be stationary at one position or patrolling in the network area [6][7]. The sink node with base station functionality is usually supplied with large energy reserve and large computational power as it works as a pivot in the sensor network system.

Recent advances in Micro-Electro-Mechanical System enable sensor nodes to be lower in production cost, smaller in size and multi-functional technically and economically feasible [4]. Sensor nodes are electronic devices that are widely deployed throughout the network area to completely cover the environment and are equipped with sensing devices that can monitor a wide variety of ambient conditions.

In addition to sensing components, sensor nodes are also capable of data processing and data communication. The workflow of sensor nodes includes generating data packages, which contains the information within the sensing area, and wirelessly transmitting them to the base station or other sensor nodes. Due to the limitation of maximum transmission range, data packages from a sensor node may not be able to reach the sink node directly. In this case, other sensor nodes are needed to forward the data to the destination. Thus data transmission may involve multiple sensor nodes to receive the data package and route them back to the sink node(s).

In this scenario each sensor node can be assigned dual roles [5] as both a data generator and a data router (sometimes referred to as a relay node). Sensor nodes which are closer to the sink are typically required to forward data packages from other sensor nodes that are far away from the sink in the network topology (as shown in Figure 1.1).

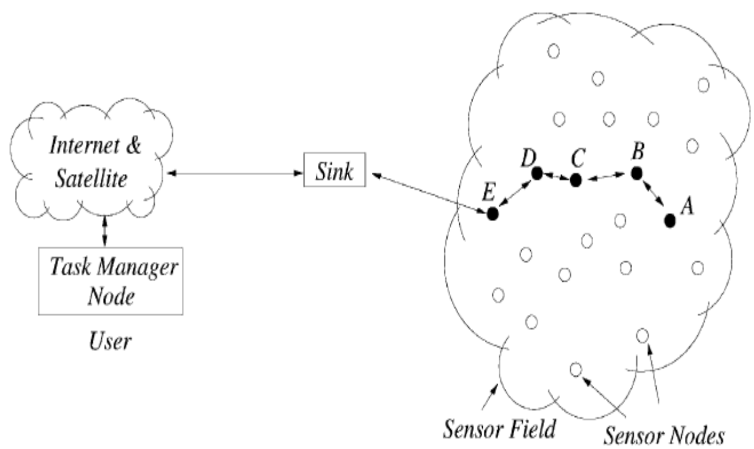

Figure 1.1: Sensor nodes scattered in a sensor field [6]

In a wireless sensor network (WSN), sensors are scattered in the field and communicate with each other wirelessly. However, sensor nodes are battery-powered with limited energy supply. Moreover, compared to the sink nodes, computational power of a sensor is also weaker. A sensor node consumes energy from the battery (usually <0.5 Ah, 1.2 V, according to [6]) and when a sensor node runs out of energy it cannot provide any service, including sensing, data processing or data communication any more. When this occurs, sensor is considered to be “dead” and will be removed from the network topology. The lifetime of a sensor network is defined to be the time interval from its deployment to the time a “critical” number of sensor nodes die, rendering the network unusable [7] [8]. Hence the lifetime of a sensor node depends strongly on the battery power. A small portion of “dead” sensor nodes could directly affect the entire network lifetime, and possibly lead to a huge loss in the network due to the routing path re-allocation and failure of sensing and reporting events in the environment. Therefore, in order to prolong network lifetime and guarantee the robustness of the sensor network, efficient energy consumption and energy conservation are of great importance in wireless sensor networks when designing and deploying networks for practical use.

Another important issue is the performance of the network. In some environments, sensor network systems are required to be highly sensitive to the change in some ambient conditions (for example, the temperature of the reactor in a nuclear power plant) and require rapid response to the events or phenomenon within the environment. Therefore the assurance of successful data delivery and quickness of data processing and data transmission plays a crucial part in providing reliable sensing services. Usually researchers take the transmission delay as a measurement to assess the performance and quality of service of a sensor network system and hence, to minimize the transmission delay and maximize the output in an energy-efficient way is also a primary concern in the research works.

1.3. Problem Description

As the sink nodes are usually supplied with larger energy support and computational power, the energy conservation research works are mostly conducted to minimize the power consumption among the sensor and/or relay nodes [6]. According to the functions of sensor nodes, in general, power consumption can be divided into three domains: sensing, communication, and data processing. Of the three domains, a sensor node expends maximum energy in data communication [6]. That leads to the research preference in the networking area to mainly focus on minimizing communication costs in data transmission to achieve the optimal power efficiency.

Sensor data is sent from the place of event occurrence through intermediate sensor nodes to the sink [9]. According to the multi-hop data transmission model (shown in Figure 1.1), data packages are sent to the sink node through different sensors and sensors closer to the sink need to receive and forward data from other sensors that are far away from the sink. The closer to the sink a sensor is, the more data it needs to forward. Therefore a lot of computational and communication resources are required to process the data relaying work for those sensors which are very close to the sink, especially those sensors that are only one hop away from the sink, which means they can transmit data directly to the sink node. This leads to a situation where these sensors consume much more energy and consequently deplete their energy much faster than the others. These sensors ultimately become the bottleneck [10] that negatively affect the network lifetime. This happens because a large portion of sensors are depending on those "closer-to-the-sink" sensors and when they die, a large amount of data cannot reach the sink, resulting in a severe downgrade of the network performance. This problem has been identified and addressed as a "Hotspot" problem in early research work [11], and an example of this situation is shown in Figure 1.2.

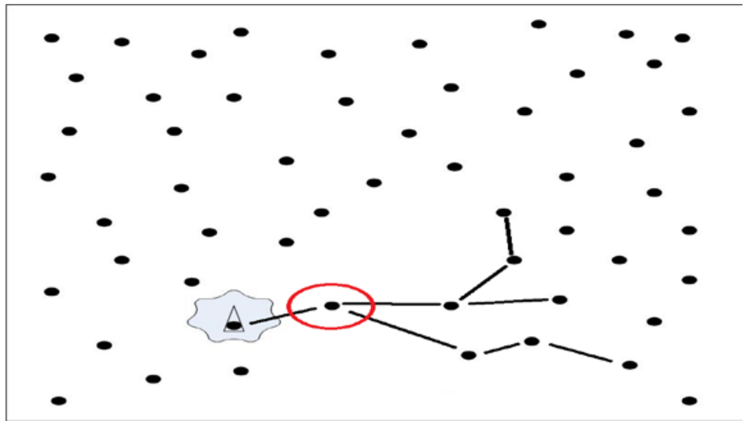

Figure 1.2: Demonstration of “Hotspot Problem”

In Figure 1.2, we can see the sensor node A in the circle is noted as heavily loaded node. According to the data transmission paths, which is denoted as lines in this figure, sensor A is responsible to forward data from other sensors and therefore the energy dissipation is concentrate on that particular sensor.

1.4. Motivation

A number of recent approaches, for reducing energy consumption, focus on shifting the burden from the sensors to the sink node [13][14][51]. In contrast to a classic system model where the sink nodes remain stationary somewhere in the network and passively receive data from sensors, we can allow the sink node to be mobile and traverse in the network area to actively look for the sensors which are sending data and move closer to them. The general idea for this sink mobility approach is to shift the burden of data processing and energy consumption from the sensors to the sink in order to extend the network lifetime as sink nodes are generally much more fertile in computational power and energy supply. Also, as transmission range is an important parameter in determining energy consumption in data communication, active movements of sink nodes closer to active sensors result in reduced transmission distances, and fewer intermediate nodes to relay data. Therefore, the energy consumption tends to be more evenly distributed in the network and the “Hotspot” problem is alleviated so that the performance of network can be improved in terms of lifetime and quality of service.

The issues of maximum network lifetime with a sink mobility approach include how to control the movement of the sink to achieve most efficient data gathering both to guarantee the quality of service and to reduce energy consumption. For example, depending on the system requirements, mobility approaches can decide

i) when to move the sink to respond to any event or change in the network

ii) the actual position of a sink node and the routing paths to the sink

iii) the trajectory of the mobile sink .

1.5. Contributions

This thesis introduces two sink node placement schemes in wireless sensor networks in an event-driven scenario, with one mobile sink capable of traversing within the entire sensing area. The first scheme focuses on selecting an optimal position for mobile sink based not only on the locations of random events but the transmission load of sensors as well. Sensor load refers to the total data transmitted per second. The final position of the sink is selected to be closer to the most heavily loaded sensors, to reduce the energy used for data transmission.

The second scheme focuses on selecting appropriate routing paths back to the sink, based on the residual energy of the sensor nodes. As time goes by, the energy levels of the sensor nodes vary. So, the proposed scheme reads the residual energy of a sensor node and aims to reduce the usage of those sensors with relatively low residual energy and instead selects those sensors with higher residual energy when computing routing paths. Therefore, all sensors can live longer based on this routing management scheme to increase the lifetime of network. The goal of both proposed approaches is to evenly distribute the energy consumption among the sensors and further improve the network performance in terms of lifetime.

1.6. Structure of the Thesis

The rest of this thesis organized as follows. Chapter II introduces the basic concepts and reviews the literature relevant for this thesis. Chapter III discusses the system model and presents our two proposed approaches: Load Based sink Movement (LBM) and Residual Energy Aware Routing (REAR) in detail. Chapter IV describes and analyzes the results of our simulations and Chapter V presents our conclusions and some directions for future work

II. LITERATURE SURVEY AND RELATED WORK

In order to implement the idea of mobile sink in sensor network system, broad kinds of strategies, protocols and algorithms have been proposed and most of them show notable improvements in wireless sensor network area. To balance the energy dissipation in the network, several previous works are introduced multiple layers sensor nodes and relay nodes to improve network performance in terms of including network lifetime, load-balanced routing and fault-tolerance [12] [13]. Moreover, a number of papers have shown that the use of some mobile nodes or mobile data collectors (MDC) can significantly improve the performance of a network in terms of lifetime, coverage and connectivity [12][13][14]. This chapter reviews different approaches that move the sink node within or around the network area to collect the data from the active sensor nodes in both time-driven and event-driven basis. This chapter reviewed several different topics, including routing schemes, routing algorithms, data collecting schemes, sink mobility protocols, and the contribution of employing multiple sinks based on sink mobility approach. We can see how those approaches can further improve the network in terms of energy conservation and the transmission delay.

2.1 Energy Consumption Model

A sensor node is typically small in size and capabilities of a sensor node, in terms of processing power, memory, communications and energy provisioning are limited. A sensor node typically consists of a sensing circuit, a digital signal processor, and a radio transceiver. The communication parts in a sensor are responsible for the majority of energy consumption. To compute the energy dissipation in wireless transmission, this work uses radio energy dissipation model present in [30] and [53] as shown in Figure 2.1

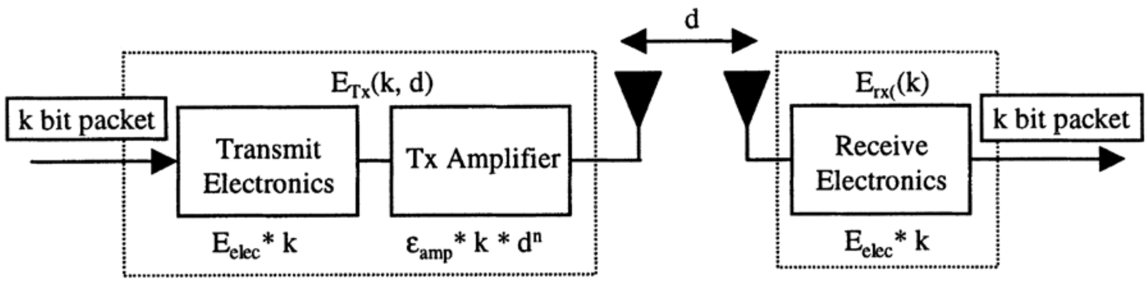

Figure 2.1:Radio energy dissipation model [30]

In this model, energy is used by the transmitting/receiving circuitry and power amplifier. The energy consumed in receiving k bits of data is:

$$Receiving\_Energy(k) = k \cdot E_{elec} \tag{1}$$

Where $E_{elec}$is a constant representing energy used in circuitry to transmit or receive one bit of data.

Energy consumed to transmit *k* bits of data from sensor *u* to *v* is

$$Transmitting\_Energy(k) = k \cdot [E_{elec} + E_{amp} \cdot d^q(u,v)] \tag{2}$$

Where E_{amp} is a constant represents energy used in power amplifier to transmit one bit of data and *d(u,v)* denotes the distance between node *u* and *v*.

In this thesis, we assume appropriate protocols at the physical layer and MAC layer are used to ensure reliable data transmission.

2.2 Performance Metrics

Multiple performance metrics can be used to evaluate the performance of WSNs in the experimental simulations. One important metric is the operational *lifetime* of the network. The lifetime of a sensor network is usually defined as the time interval from the inception of the operation of the network, to the time when a number of critical nodes “die" (i.e., the power supplies of the critical nodes are depleted to such an extent that the network no longer remains useful) [7] [8]. A number of different metrics have been used in the literature to measure the lifetime of a sensor network [55] [56]. In [55], the lifetime of a sensor network is defined as the minimum of

i) the time when the percentage of nodes that are alive (i.e., nodes whose batteries are not depleted) drops below a specified threshold,

ii) the time when the size of the largest connected component of the network drops below a specified threshold, and

iii) the time when the coverage drops below a specified threshold.

In [22], the authors focus on coverage and considered the network lifetime as the period during which the entire region can be covered. i.e. the time when some sensor nodes can no longer route their data to the sinks.

Some researchers have used *normalized forwarding overhead* and *packet delivery ratio* [15] to evaluate their contribution to data gathering. Normalized forwarding overhead is used to see the data overhead generated to find the routing. Packet delivery ratio represents the total data received divided by total data transmitted by sensors. This ratio represents the success rate of data delivery.

In [11], the authors use *average energy per packet* to measure the energy efficiency. Also the throughput is used to determine the scalability of the network. In time-based scenarios, the *average delivery delay* is introduced to evaluate the performance of their four protocols and study the advantage of disadvantage of the implementation. In the event-driven based scenarios, such as [16], it is possible to measure the network lifetime based on the network load. The idea is that the more the load of a node, the less time it will be able to operate. For the network delay, average hop counts can be used to measure the overall transmission delay in the network.

2.3 Sink Mobility in Wireless Sensor Networks

In [17] the authors first introduced the concept of using mobile sinks to balance the energy consumption. A numbers of works have been done in this area such as in [18] [19] and [20]. There are 3 major parts involved in implementing Sink Mobility to Wireless Sensor Networks to improve the performance of network: Sink node movement, data packets routing and data gathering.

2.3.1. Sink Node Movement

In [21] the authors proposed a base station location computation method using Integer Liner Programming to prolong network lifetime and data throughput considering the base stations located at the boundary of the network area. Also in [22] the optimal positions of relay nodes are computed using an ILP to extend lifetime. A data gathering model using Data MULEs [23] in conjunction with a Random Walk strategy [24] has been proposed to save energy and collect sensor data in sparse sensor networks. This model can achieve a reduced transmission range for sensors to save transmission energy. However, as this model cannot predict when the sink node moves towards those sensors ready to send data, the data packets may get significantly delayed.

In [25] and [26], authors propose a protocol-based sink mobility pattern. According to the authors' claim, their work is one of first few attempts in introducing mobile sink to efficiently deliver the data and enhance the network robustness.

Mobility for the sink mostly indicates that the system puts more burdens on the sink node instead of focusing on the sensor nodes, because the sink node is considered to have unconstrained power supply and much larger processing capability than the sensor nodes. However, how to traverse the whole network area is also an important issue as failure to visit some areas will potentially lead to data loss. Moreover, it is also necessary to use the energy in an efficient manner when moving the sink node.

Based on the random walk approach, 4 approaches that can fit into different types of application scenarios are introduced in [25]:

i) Random Walk and Passive Data Collection

ii) Partial Random Walk with Limited Multi-hop data Propagation

iii) Biased Random Walk with Passive Data Collection

iv) Deterministic Walk with Multi-hop data Propagation

Each of the above approaches has both advantages and disadvantages, depending on the system requirements of the application. Authors in [25] claim that their work is a first step towards sink mobility in WSNs.

2.3.2. Data Packets Routing

As mentioned in the previous sections, energy efficiency is a crucial topic in designing WSNs. The energy consumption is largely due to data transmissions - both sensor-to-sensor and sensor-to-sink. Therefore an efficient transmission path will improve the energy utilization in the system and save more energy. In [27] the authors propose a routing approach that makes routing decisions locally and when selecting a neighbouring node, it depends on two major factors: average energy and distance in transmission. In [28], a unique scheme to handle the transmission in a mobile sink network system with fast re-establishment function is proposed.

In [29] the authors introduce their Mobile Sink Routing Protocol to achieve energy-efficient routing. By reviewing LEACH [7] and LEACH-C [30], they point out that those two classic cluster-based routing techniques cannot always select the cluster head such that performance guarantees are met. Based on LEACH [7] and LEACH-C [30], the authors in [29] proposed their routing protocol that enables the network system to deploy the cluster head itself and improve the network in terms of energy efficiency. The overall protocol can be divided into 2 parts: Pre-estimation scheduling scheme and Routing scheme.

In the scheduling scheme the schedule queue is set up based on the average residual energy of the sensors and the distance from the current cluster head to another head. All information is stored in the sink's routing table. In the Routing scheme, the protocol establishes the network by LEACH and sets up the scheduling queue by random walk to the sink for the first time. Based on the average energy consumption, the protocol calculates the time period T. After T time, the protocol updates the scheduling table and

T and repeats the previous steps over again. The authors in [29] set up a self-adaptive protocol to improve the performance of LEACH such that the energy efficiency can be guaranteed, because the scheduling queue is based on average residual energy of the sensors.

In [11] the authors propose another cluster based routing protocol, *Mobile Sink Based Routing Protocol* (MSRP) to solve *hotspot* problem. In order to solve the hotspot problem, MSRP also clusters the network and registers the cluster head based on the residual energy information. The dynamic mobile sink architecture in MSRP avoids energy concentration on a small portion of sensors and prolongs the network lifetime. Moreover, MSRP also sets up a moving strategy for the sink. Based on the residual energy of cluster heads, sink will always be closer to the cluster head with higher residual energy and those cluster heads will relay data from other cluster heads.

2.3.3. Data Gathering

The problem of data collection in sparse sensor networks is encountered in many scenarios such as monitoring physical environments, animal migrations in remote-areas, weather conditions in national parks, habitat monitoring on remote islands, city traffic monitoring etc [31]. The objective is to collect data from sensors and deliver it to an access point in the infrastructure [32].

One important issue in implementing mobile sink nodes in Wireless Sensor Networks is how the sink gathers data from static sensor nodes while sink node is moving. As the location of the sink is changing, sensor nodes are enabled to send the data packages to the sink when sink is nearby. Therefore, traditional data gathering and routing schemes are not suitable in this case. In [32] the authors present an analytical model to understand the key performance metrics such as data transfer, latency to the destination, and power. In [15] the authors summarized the previous works, pointed out that the major disadvantage of both Data MULEs and Random Walk is the delivery delay. In order to improve the performance of data gathering, authors in [15] introduced their two data gathering protocols: AVRP and TRAIL, and claimed that those two protocols bring an efficient data gathering performance that reduces the delivery delay in the networks with heavy and light load respectively.

The AVRP protocol is derived from the previous anchor-based Voronoi-Scoping [33] routing protocol. Voronoi divides the network into multiple clusters. It is efficient in the way that the sensors only need to send their data to the closest anchor nodes and the anchor nodes communicate with the sink node. In order to adapt to a mobile sink, the authors improved Voronoi-Scoping that associate the mobile sink with the anchor nodes. AVRP builds up a delivery structure and refreshes the structure periodically based on the movement of the sink. Therefore all the sensors only need to store the closest anchor node's routing information and AVRP removes the need for the dynamic routing path information, which is a large data overhead in transmission. AVRP stabilizes the data transmission and it is suitable for networks with heavy load.

The authors in [15] present another protocol in their work, TRAIL. The general idea is the protocol will record the trail of sink movement and the data gathering route will be along this trail. The protocol starts with a random walk and once the sink detects a data transmission request from sensors it moves towards them and the trails are recorded and updated for the next data gathering route. An example illustration is given in Figure 2.2

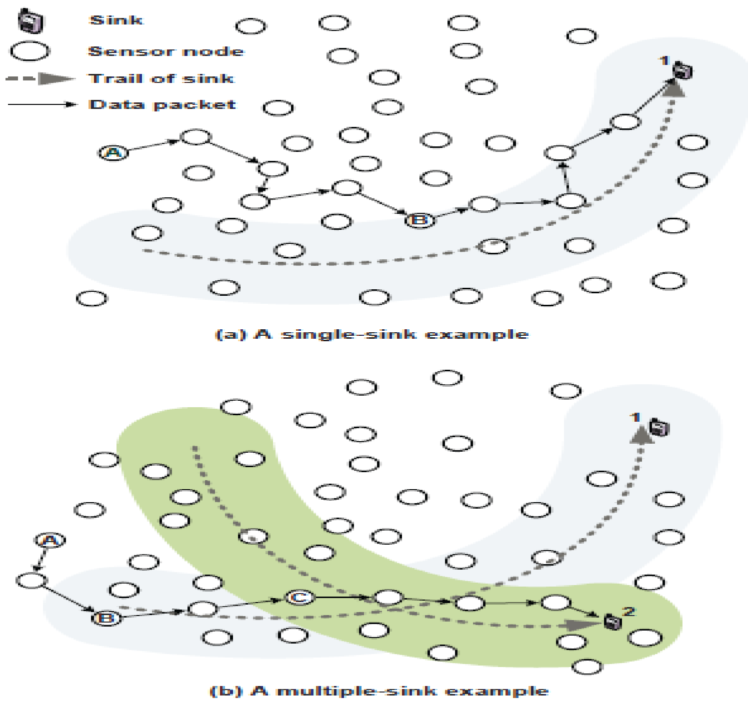

Figure 2.2: An example of how data forwarded to sink in TRAIL [15]

As Figure 2.2(a) demonstrates, the sensor node A randomly transmits data to sensor B as no mobile sink track is found. When data reach sensor B, which remembers the trail of sink movement, it routes data packets along the trail of sink node and the packets reach the sink. Figure 2.2(b) explains when another newer trail of mobile sink intercepts the data transmission to sink node 1 and routes them to sink 2.

In the actual implementation of TRAIL, the authors formalized the problem into an optimization problem that decides the optimal routing along the trail of the sink to improve the performance. According to the claim, this protocol is suitable in light traffic networks due to the very low data packet overhead. Both AVRP and TRAIL strive to reduce the delivery latency issue of previous methods.

2.4. Mobile Sink Solutions

2.4.1. Event-Driven Mobile Sink Approach

According to the actual application of WSNs, a large number of scenarios are used to monitor the activities in the sensing area and report any events when necessary. Hence an event-driven approach is much more suitable to fit into those scenarios than a time-driven approach [34], where sensors send data to the sink periodically. In [34] the authors introduce the event driven pattern in a WSN with a mobile sink. And later, the authors enhanced the performance in the event-driven WSN by researching and defining the path and trajectory for the movement of sink. The work is based on Data MULEs [23] with a random walk approach, where network transmission load and average hop counts are used to evaluate the performance of the approach. After a mathematical analysis, the authors claimed that the trajectory of a square rotated 45 degree with center O is proven to be optimal, illustrated as Traj A in Figure 2.3: Optimal mobility trajectory [34]

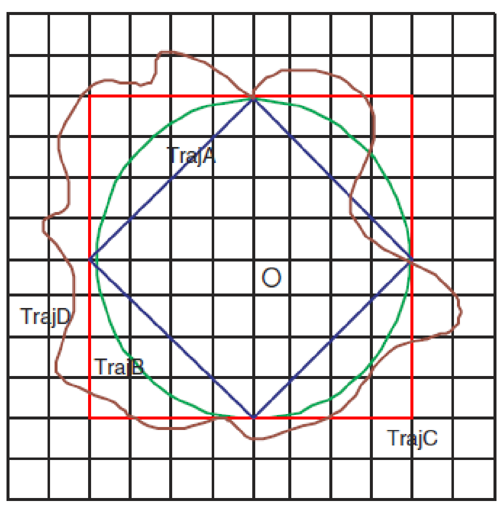

Figure 2.3: Optimal mobility trajectory [34]

By moving the sink node along the optimal trajectory, the system performance is enhanced in terms of lifetime and delivery delay.

In [16], the authors discuss the contribution of deploying multiple mobile sinks in the same network with an event-driven scenario. The system model and performance metrics stay the same. The authors also use a mathematical analysis to identify the performance improvement in terms of network load and average hop counts. They claim that using more than one sink moving in the sensing area can decrease the load as the data transmission is more evenly distributed. But the average hops increase because the average radius increases. In general, it concludes that with the increase of mobile sinks in the system, the performance can be improved. However the improvement diminishes if too many sinks are deployed.

2.4.2. The Energy Balanced Model

In [35] the authors proposed their approach to solve the problem of lost connectivity due to energy limitations. They point out that actual performance of using a pure mobile sink approach is doubtful, since the utilization of computational resources such as buffer size and transmission resources is not optimized. Furthermore, as the location of the sink cannot be predicted in advance, sensors are probably required to send data to a sink which is far away at the moment or wait until the sink travels towards the sensors. This could lead to an additional inefficient energy consumption and huge delivery delay. The idea is that the system can use both a fixed location sink and a mobile sink. Sensors can send their message either to the sink nearby or send them to the next relay node and route the data to the fixed sink. According to their claim, the performance of the hybrid approach exceeds the classic fixed sink approaches in [36] and [37] as simulation time increases.

2.4.3. The Intelligent-based Routing Scheme

This is a particular approach to implement hierarchical structures in WSN with mobile sinks. In [38] the authors point out that when a sink moves in the network, sensors need to frequently update the location of the sink, leading to excessive power consumption. The authors claim that very little research has been conducted in the way of setting up multiple layers in the WSN system. One of them is Two-Tier Data Dissemination (TTDD) [39]. The authors state that TTDD works well in event-driven systems but not very well in systems where sink locations change very frequently, as TTDD needs to change the structure every time.

In order to address this, a new layer of *agent* nodes, responsible for data gathering, are introduced between the sink node layer and the sensor node layer . Initially, the sink sends a broadcast message to determine the location of the agent nodes and then, by flooding, all the sensor nodes receive agent node information and decide the next hop of data transmission. Sink gathers data from agent nodes while traveling in the network. Figure 2.4 illustrates the agent-based data transmission scheme

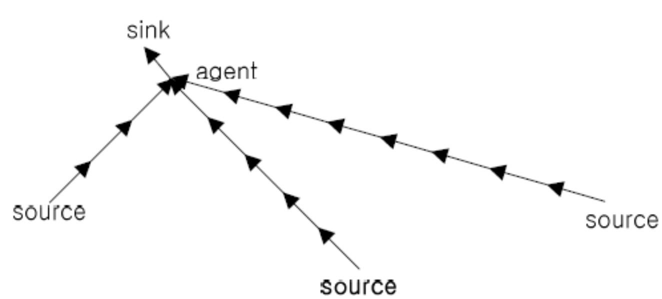

Figure 2.4: Agent-based data gathering in [39]

However, this scheme can be degraded in optimality as the sink moves, since the sink can move closer to the sensors than the related agent nodes. Therefore, a path selection scheme is proposed, where a sensor node communicates with its closest nodes, called *immediate relay* (IR), and IRs then communicate their distances from each other. This is done recursively to calculate the total distance to the sink compared with the original agent-based path length. The scheme will select the optimal path based on the total distance, as illustrated in Figure 2.5 below. The optimal path is send data directly to the sink instead of using agents as the total distance is smaller than the paths using agents to forward data:

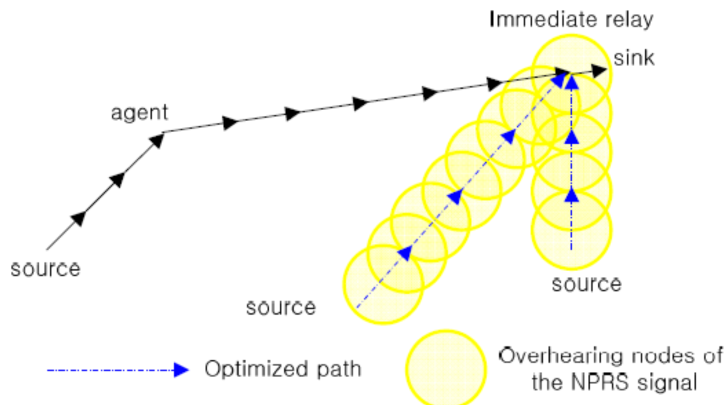

Figure 2.5:Optimal path selection in [38]

2.5 Sink Mobility Algorithms

2.5.1. Distributed Algorithm in Routing

Achieving maximum lifetime in a WSN can be done by setting up an efficient routing scheme. In order to introduce sink mobility to the WSN, classic routing algorithms [40], [41] are no longer suitable as the network topology constantly changes due to the movement of the sink. In [42] a load balancing algorithm is used to distribute the load evenly among all the nodes. In [43] the authors propose a joint mobility and routing algorithm and show that a better routing strategy is obtained using a combination of round routes and short paths. In [44] the authors propose a *distributed* routing algorithm for maximum lifetime in WSN, in contrast to the centralized approaches in [45], [46].

2.5.2 Distributed Algorithms in Delay-Tolerance

Delay-tolerance is another important issue among the research topics in WSNs regarding the application requirements. In [47] the authors propose a framework that implements the mobile sink approach taking into account the delay tolerance requirements. This model permits certain level of delay in data delivery and guarantees the quality of service. The model is called the Delay-Tolerant Mobile Sink Model (DT-MSM). Later in [48] the authors introduce an efficient, distributed algorithm to implement DT-MSM in order to maximize network lifetime in the system and enhance the performance of the sensors and mobile sinks.

2.6 Energy Efficient Strategy

In [51] the authors take the unpredictable event occurrence into consideration and propose an Energy-Efficient-Strategy (EES) in an event-driven sensor network system with sink mobility. Sensing activity is based on random events which are not known in advance. When a new event takes place, it triggers the sensors within the event region to start sending data to report the event. Other sensors that are beyond the event area remain on-hold and do not send any sensed data (for this event). EES is a self-adaptive algorithm to select the tentative position for the sink node. So EES decides

i) where to move the sink node and

ii) when to move the sink node.

The general idea of EES is that the sink node moves towards active sensors to reduce the overall transmission distance for all sensors, in response to a new event starting or an existing event ending. This approach is shown to significantly improve network lifetime, compared to networks with a stationary sink node as well as those with a mobile sink using random walk approach. However, EES only considers the locations of affected sensor nodes and does not take into account their load or residual energy.

In the actual implementation of network process, multiple events may take place simultaneously. The optimal position of sink should be closer to those events that cover larger area, as they trigger more sensors to report events and hence generate more data to be transmitted to the sink node. Based on the above reasoning, the optimal position of the sink, $p_{\text{optimal}} = (X_s, Y_s)$ is given by the following equations:

$$X_s = \frac{\sum_{v \in E} x_v}{|E|} \qquad (3)$$

$$Y_s = \frac{\sum_{v \in E} y_v}{|E|} \qquad (4)$$

Here E is the set of all *active* sensor nodes in the network and (x_v, y_v) are the co-ordinates of sensor node $v \in E$.

Figure 2.6 illustrates this concept, using two random events E1 and E2 that arise in the network activating two sensor nodes and four sensor nodes respectively. Since event E2 covers a larger area and has more active sensors, it generates more data (assuming the data packet size, transmission rate etc. for all the sensors are the same). Under these circumstances, the sink should move closer to event E2, as shown in the figure.

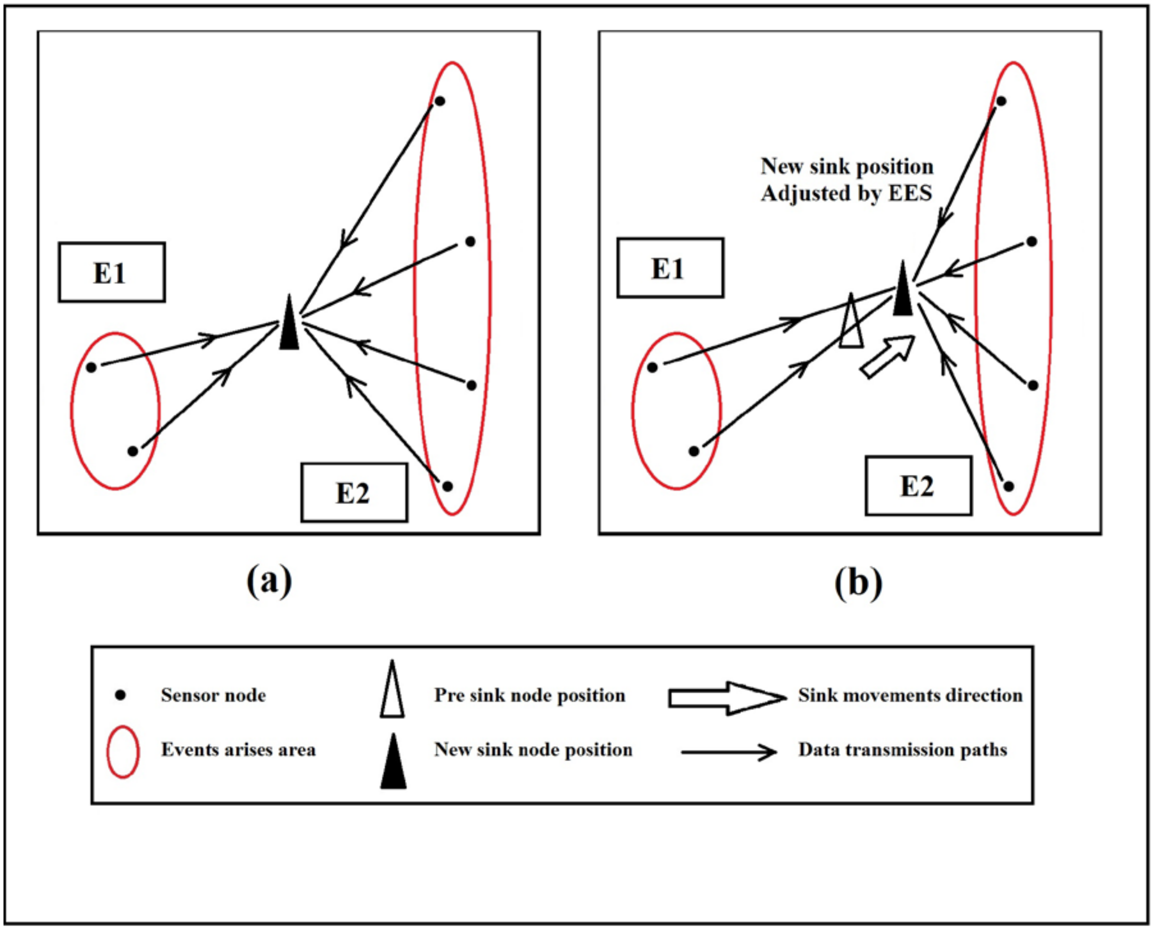

Figure 2.6: Distance only sink node placement

III. LOAD AND ENERGY AWARE SINK NODE PLACEMENT

In this chapter, we first describe our system model, including the network topology and communication schemes and then present a number of new sink placement schemes. Unlike existing approaches, our proposed approach takes into consideration both the load on the sensor nodes as well as their residual energy levels.

3.1. Network Model

3.1.1. *Sensor Node Structure*

Each individual sensor node in our architecture can sense and/or forward data or remain idle, and the actual status of the node typically changes multiple times over the lifetime of the network. The change in status may occur as a response to the start/end of random events, or due to energy levels within the node. We define the following 4 status conditions for each sensor node:

- ***Active***: Sensor node is operational and it is generating data
- ***Relaying***: Sensor node is operational and it is forwarding data from other sensors
- ***Idle***: Sensor node is operational, but it is not generating or forwarding data
- ***Dead***: Sensor node has depleted its energy and is not operational

Each sensor node is identified by a unique SensorID. We record the SensorID of each sensor node, as well as other attributes such as its position i.e. (x,y) co-ordinates, status and residual energy, in a table, as shown in Table 3.1. During the process of network operation all the nodes, including sensors and sink can access this table to acquire status information of sensors and set up sink mobility approach and dynamic routing paths. Table 3.1 demonstrates the structure of the status table:

Sensor ID	X coordinate	Y coordinate	Living?	Sensing?	Residual Energy

Table 3.1: Status and attribute table of all the sensor nodes [51]

The positions of the sensors are fixed at initial deployment, but the location of the sink changes over time, depending on the occurrence of events. The “Living” and “Sensing” attributes are binary values initialized to 1 and 0 respectively for each sensor node at deployment to represent the whether or not it is generating data. If a sensor is not activated by events but forwarding data from sensors, “Sensing” will remain 0. The data size and energy consumption will be recorded separately. When a new event occurs, certain sensor nodes will be activated and start transmitting data. When the residual energy of a node reaches 0 or below a threshold value, it indicates that this sensor node has depleted its energy and the value of “Living” will be set to 0, which means it is no longer operational. In this case, the node will not be taken into consideration for sensing events, data generation or data forwarding in the future. The “Residual Energy” field records how much battery power is left in a sensor node. The value in this field decreases continuously from its initial value, as the node participates in various sensing and forwarding activities.

3.1.2. Network Topology

Our network configuration is similar to the model presented in [8]. It consists of a set of homogenous sensor nodes that are randomly distributed within the network area. Each sensor node is supplied with a limited amount of energy at the beginning, and there is one (mobile) sink node, which is not energy constrained. All data generated by the sensor nodes ultimately flow to the sink node.

The area of interest is a 2-Dimensional square area, within which all the sensor nodes are located. The sink node can move freely anywhere inside this region. Figure 3.1 shows a typical network topology, where sensor nodes are represented by black dots and the sink is represented by a triangle.

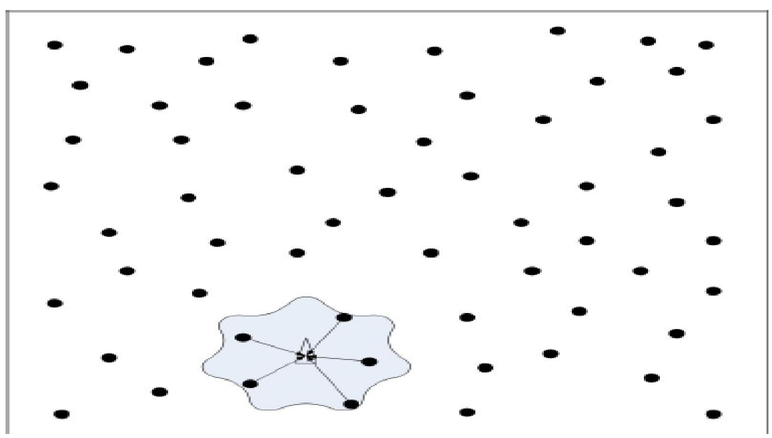

Figure 3.1: The network as a graph [51]

3.1.3. Routing

Once the position of the sink has been determined, the sensors use multi-hop data transmission to wirelessly route data packets back to the sink. It has been shown in the literature that multi-hop transmission typically consumes less energy than direct long range transmission in wireless communication with the sink [6]. Furthermore, in cases where the sink lies outside the maximum transmission range of a sensor node, multi-hop communication is the only feasible alternative.

To set up the routing paths to the sink for each sensor node, we use the standard Dijkstra shortest path algorithm [52], assuming the sink node is the root. The cost of each edge can be set appropriately, for different approaches. For example, in our first scheme, the cost of edge $e(u \rightarrow v)$ is taken as the square of the distance between nodes u and v. The farther the distance between two nodes, the higher the cost of edge $e(u \rightarrow v)$. In the second approach, on the other hand, the edge cost depends on both the distance and the residual energy of the destination node.

Other than the initialization, new routing paths need to be calculated whenever there is a change in network topology. This can arise due to two circumstances:

i) The sink node moves to a new position; the movement of sink leads to a change in root position therefore new paths should be established

ii) Certain sensor nodes deplete their energy and need to be removed from the network. This leads to a topology change and transmission paths are rercalculated.

3.1.4. Random Event Model

In this thesis, we propose an adaptive sink placement algorithm that can respond to randomly generated events. An event n is represented by the following parameters:

- event start time ($Start_{\text{n}}$)
- event end time (End_n)
- event location (X_n, Y_n)
- event radius (R_n)

For our simulations, we have a specified maximum number of events. For each event, the values of each field are generated randomly (within the appropriate range). The active duration of an event n is given by (End_n – $Start_n$). The radius (R_n) of event n defines the amount of area affected by the event. For an event at location (X_n, Y_n) and of radius R_{n}, all sensors lying within the circle of radius R_{n} centered at (X_n, Y_n) will start generating and sending data packages to report this event while the event is active. Figure 3.2 shows two events n_1 and n_2 with radius $R_1 > R_2$, and the sensors triggered by these events.

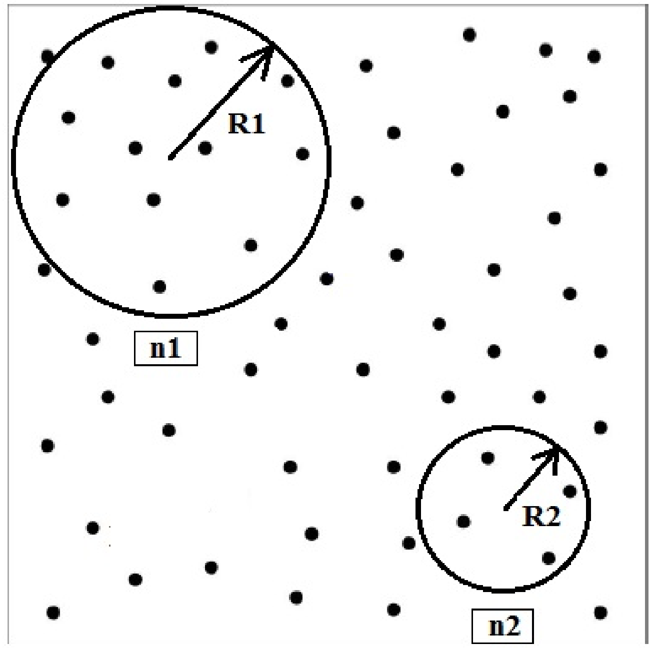

Figure 3.2: Two random events in a sensing area

3.2. Load Based sink Movement (LBM)

As mentioned earlier, one major problem affecting network lifetime is due to the fact that energy dissipation becomes highly concentrated on the sensor nodes which are closer to the sink node, especially those that are only one hop away from the sink node. The goal of most energy-efficient routing and/or data gathering protocols is to distribute the energy dissipation evenly in the network, as much as possible. However, due to the limited transmission range of sensor nodes, it is difficult to completely alleviate this “Hotspot problem”. The problem becomes particularly acute with a single stationary sink node, since the same set of sensor nodes close to the sink must be responsible for transmitting all the data to the sink. However, when sink mobility is introduced, different sensor nodes have higher data loads at different times, as the sink moves from one location to another. Figure 3.3(a) shows the sink in its initial position, and the "heavily loaded" sensor nodes around the sink in the shaded region. If the sink is stationary, this same set of nodes always remain heavily loaded; but, if the sink is allowed to move to a new location, as shown in Figure 3.3(b), the load is transferred to a completely new set of nodes. Over time, as the sink moves around, the set of heavily loaded sensor nodes changes, and the energy dissipation is more evenly distributed among all the nodes.

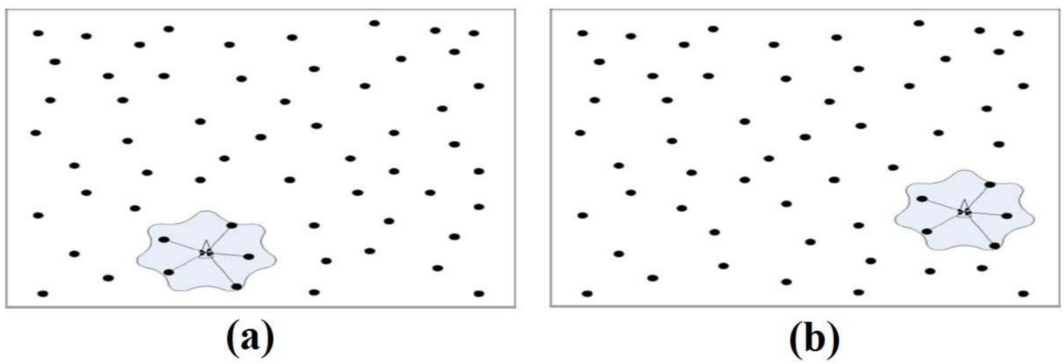

Figure 3.3: Sink node at (a) initial position (b) final position [51]

In this section we present our first adaptive sink node placement scheme called *Load Based Sink Movement* (LBM) that calculates the new location of the sink node, in response to random events, based on

- the geographical location of the active sensors and
- transmission load on each active node,

According to the energy model given in Sec. 2.1, the total energy consumption of a node depends primarily on two factors:

i) the transmission distance to the next node and

ii) the "load", i.e. the number of bits transmitted.

As random events are introduced, there are more data generated in certain regions of the network compared to others. Furthermore, there may be more paths from one *active* sub-region than another. This will lead to uneven distribution of load among different sensor nodes. Therefore, in addition to the geographical distance from active sensors to the mobile sink, the final sink position should take the load on the sensor nodes into account as well. So the sink should move closer to the sensor nodes with heavy transmission loads to reduce the energy consumption of those heavily loaded sensor nodes.

For example, consider the situation in Figure 3.4(a), with two events E1 and E2, both of the same size. According to the scheme in [51], the sink node should be approximately mid-way between E1 and E2. However, in our proposed LBM scheme we consider not only the locations of the sensors, but also their load. Furthermore, in addition to the sensors generating data, i.e. those inside regions E1, and E2, we also try to minimize the load on *all* sensors, i.e. also those that are forwarding data. This means that the load on sensors s_1, s_2, and s_3 are also taken into consideration. It is clear that the sink node placement in Figure 3.4(a) puts a much higher load on s_3, and consequently results in a higher energy dissipation for node s_3, compared to s_1 and s_2. If the sink node is moved closer to s_3, as shown in Figure 3.4 (b), the transmission distance for s_3 is reduced and can compensate for the higher data rate, leading to reduced energy consumption. Of course, this is achieved at the cost of increased energy consumption at nodes s_1 and s_2. However, by distributing the energy dissipation more uniformly over all nodes, we can expect an overall improvement in the network lifetime.

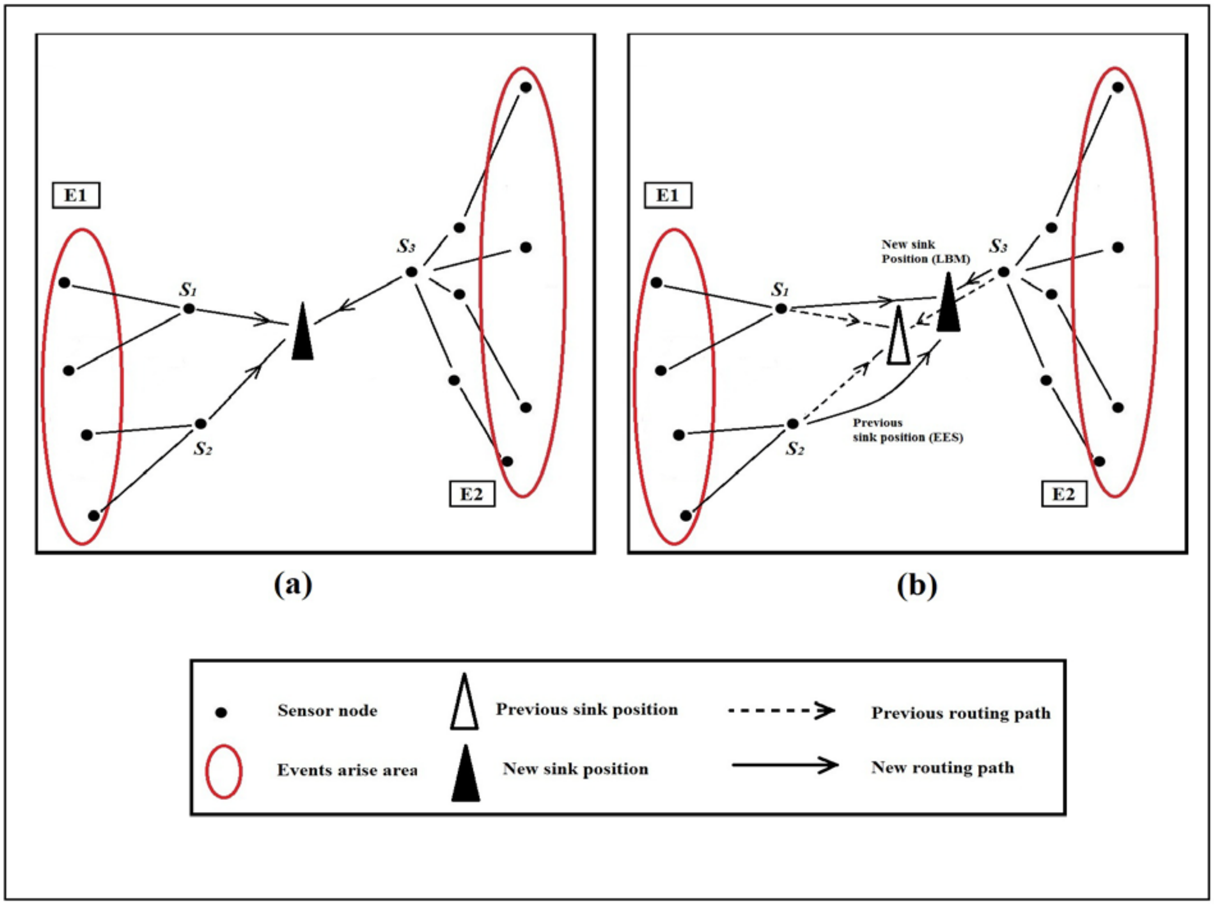

Figure 3.4: Examples of *LBM*

3.2.1. Detailed Algorithm

In this section, we will present our Load Based Sink Movement (LBM) scheme. We use the following notation in our discussion.

Notations:

- S = the set of all sensors in the network
- $p_{final} = (X_s, Y_s)$ the final position of the sink node
- $p_{tentative} = (X'_s, Y'_s)$ the tentative position of the sink node (for finding routes)
- $p_i = (x_i, y_i)$ the position of sensor node $s_i \in S$.
- b_i = Total number of bits transmitted by sensor node $s_i \in S$.
- w_i = Total number of bits generated by sensor node $s_i \in S$.
- d_{ij} = distance from node s_i to node s_j
- c_{ij} = cost of edge $e(i \rightarrow j)$
- d_{max} = maximum transmission range of a sensor node
- $r_{ij} = 1$ if and only if node s_i transmits its data directly to node s_j

Algorithm 1: *Load Based Sink Movement (LBM)*

Step 1: Calculate tentative sink position $p_{\text{tentative}} = (X'_s, Y'_s)$

- Based on EES [51], use equations (3) and (4) to compute values for X'_s and Y'_s

Step 2: Calculate paths

- Use Dijkstra's algorithm [52] to compute the path from each sensor $s_i \in S$ to sink node at (X'_s, Y'_s)
- For edge $e(i \rightarrow j)$ in the topology, set $r_{ij} = 1$ if the edge is on the path from node s_i to the sink node.

Step 3: Determine load on each sensor node

- Load on node s_j is: $b_j = \sum_{s_i \in S} r_{ij} \cdot b_i + w_j, \forall s_j \in S$

Step 4: Calculate final sink position $p_{\text{final}} = (X_s, Y_s)$

Figure 3.5: Outline of *LBM* algorithm

Figure 3.5 outlines our *LBM* algorithm, which considers the load on each sensor node. In order to determine the load, it is first necessary to find a tentative location for the sink node. This is done in Step 1, using the approach presented in EES [51]. Once the tentative position of sink node (X'_s, Y'_s) is acquired (in Step 2), the network routing paths are calculated using the well-known shortest path algorithm [52].

For the LBM algorithm, the cost c_{ij} of edge $e(i \rightarrow j)$ is computed as follows:

- $c_{ij} = d_{ij}^2$, if $d_{ij} \leq d_{max}$;
- $c_{ij} = \infty$, otherwise

Based on the paths from each sensor node to the sink node, it is possible to calculate the total load (i.e. number of transmitted bits) for each node $s_i \in S$ (Step 3). By doing that we have the transmission load of the sensors to routing data packets to the sink node. Finally, the new location of the sink is determined in Step 4, using equations (5) and (6).

- $X_s = \frac{\sum_{s_i \in S} b_i \cdot x_i}{\sum_{s_i \in S} b_i}$ (5)
- $Y_s = \frac{\sum_{s_i \in S} b_i \cdot y_i}{\sum_{s_i \in S} b_i}$ (6)

The final co-ordinates are calculated as the weighted sum of the sensor co-ordinates of all sensor nodes that are transmitting data. The higher the transmission load of a sensor, the higher is the weight of its co-ordinates. So, the final sink node position will tend to be closer to those heavily loaded sensors.

LBM is designed to utilize the battery-powered energy of the sensors more efficiently in an energy-aware way to balance the energy dissipation and alleviate the "Hotspot problem". By implementing this, the overall network lifetime can be extended, as indicated by the experimental results in the following chapter.

3.3. **Residual Energy Aware Routing (*REAR*)**

The LBM algorithm discussed in the previous section results in more balanced energy dissipation among nodes compared to existing techniques such as EES [51]. However, one potential limitation of the approach is that certain nodes may be used over and over again. As a result such nodes will tend to deplete their energy compared to other nodes that are less frequently used. In other works, LBM has no "memory" of previous data transmissions and simply chooses routing paths based on distance, even if the selected intermediate nodes may be running low on energy. If the same nodes are selected repeatedly, they will deplete all their energy and may cause the entire topology to become disconnected.

In order to address this limitation, we propose the *Residual Energy Aware Routing* (*REAR*) scheme. The goal of this algorithm is to avoid using *low-energy* nodes, when calculating the routing paths from each sensor to the sink. The low-energy nodes can still be used, if there are no other alternatives; however, there is an increased cost for using such nodes.

The main contribution of *REAR* algorithm is that the edge costs are calculated differently, to account for the energy levels in each node. These updated edge costs are then used in Step 2 (Figure 3.5), to create the routing paths. In addition to the notation given in Sec. 3.2.1, we use the following new items for *REAR*:

- *IE* = Initial energy level for each sensor node, when the network is first deployed. This is assumed to be the same for all sensors.
- RE_i = Residual energy level of sensor node s_i.

The main rationale for *REAR* is that the cost of using $e(i \rightarrow j)$ should reflect not only the distance from s_i to s_j, but also the residual energy at node s_j. If s_j has very little energy left, then it is preferable not to use the edge. Hence, in this case, c_{ij} should be increased accordingly. So, we define the edge cost as follows:

$$c_{ij} = d_{ij}^2 \text{d\_ij} + \alpha \cdot (IE - RE_j) \qquad (7)$$

Here, α is a pre-specified weight to determine the relative importance of the distance and the residual energy components in determining the overall edge cost. According to Equation (7), it is clear that the lower the residual energy of a node (i.e., lower value of RE_j), the higher will be its cost. Once the routing paths are calculated, using the assigned edge costs, the load on each sensor node and the final position of the sink can be determined in a manner similar to *LBM*.

The purpose of REAR is to avoid using sensors that are running low on residual energy. Instead it attempts to first utilize sensors with higher residual energy to set up alternative routing paths, so that the energy dissipation can be balanced. As a result each individual sensor node can achieve a longer lifetime and extend the lifetime of the network.

In addition to *LBM* and *REAR*, we also propose another scheme, called *Hybrid* scheme, which combines the techniques of both *LBM* and *REAR*. This approach calculates the routing paths based on residual energy, as in *REAR*. Then, the sink position is calculated using eqns (5) and (6), similar to *LBM*, to account for the load on each sensor node.

IV. PERFORMANCE EVALUATION

In this chapter, we evaluate the performance of our proposed schemes and compare the achieved lifetime with those for existing sink placement schemes EES [51]. We first present a brief description of the experimental setup and then discuss and analyze the results of our simulations. In the last section we will discuss experimental results and evaluate the performance.

4.1. Experimental Setup

It has already been shown that allowing sink mobility can significantly extend the network lifetime [51]. The Energy-Efficient-Strategy (EES) for mobile sink placement introduced in [51] has also produced considerable improvement compared random walk approach [24] as well. In this work, we will evaluate our proposed schemes and see show that they can be used to achieve even further improvements, compared to EES in prolonging network lifetime.

In these experiments, we measure how the network lifetime is improved under a set of random events. The start time, duration, location and coverage area of each event is generated randomly. The simulation is programmed using C and is running in both Dev C++ under Windows 7 [57] and Xcode in Mac OS X Lion [58]. We also use a number of different network sizes, and for each network size we randomly generate several sensor distributions.

4.1.1. Network topology setup

To validate the proposed schemes, the simulations run on 3 different size networks with randomly distributed sensor nodes:

- 100 sensors in 160m x 160m square sensing area
- 200 sensors in 220m x 220m square sensing area
- 500 sensors in 360m x 360m square sensing area

In addition to the random topologies, we also consider a uniform grid topology, in which all the sensors are evenly distributed in the network area (Figure. 4.1).

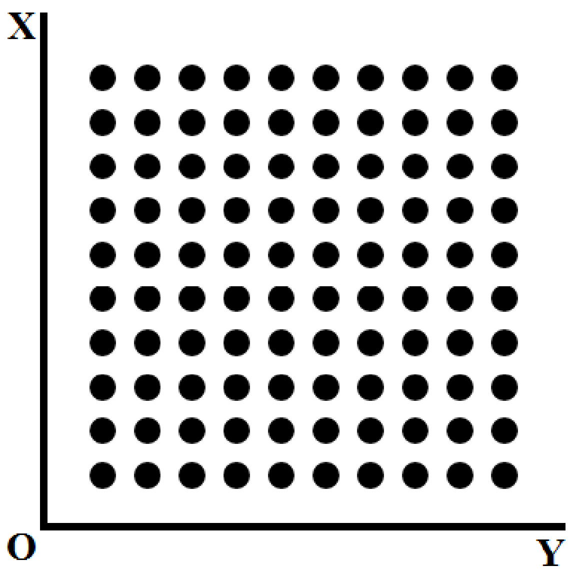

Figure 4.1: Grid topology

The following grid topologies are used in our simulations:

- 100 sensors evenly distributed in 160m x 160m square sensing area.
- 225 sensors evenly distributed in 240m x 240m square sensing area.
- 400 sensors evenly distributed in 320m x 320m square sensing area.

4.1.2. Random Events Setup

For each set of simulations, we consider 500 random events. The event attributes, such as start time, end time etc are randomly generated and stored in file, which is given as input to the simulator. Compared to the performance evaluation in EES [51] with 50 events in the simulation, our experiment takes a higher event occurrence rate (500 random events are put into launch sequence during one simulation) to evaluate the contribution of our proposed schemes. For each event, the coverage radius varies from 6m to 30m meters in the network; the duration of an event can vary from 1 time unit to the maximum operation time (3000 time units) in the system. The actual duration of an event will depend on the specific application, and may vary from several milliseconds to several minutes or even hours.

At each time interval, certain events can start, certain events can end and others can continue. The simulator uses a timeline to define each time unit of the simulation, accesses the events file, reads $Start_n$ and End_n of each event and puts them into launch sequence at the corresponding time, as Figure 4.2 demonstrates. Each square on the left side represents a time interval and the simulation program reads the $Start_n$ and End_n of each event and puts the events into the corresponding launch sequence at each time interval. When the simulation program reaches that time interval, it will pop the events in the sequence and perform event start/end activities.

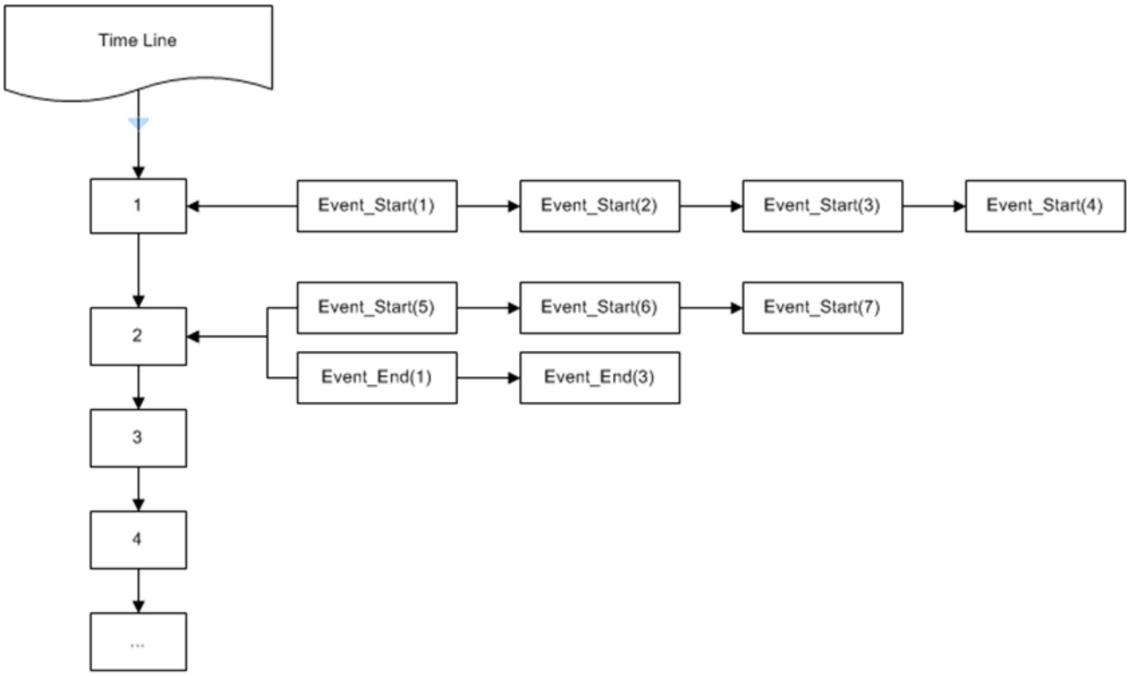

Figure 4.2: The random events launch sequence in the experiment

4.1.3. Other Parameters

Additional parameters for our simulations are listed below in Table 4.1

Parameters	**Value**
Maximum transmission range	40~60 meters
Initial Energy of sensors	10.0 J
Data generating rate of active sensors	1 packet/unit time
Size of the data packet	10 bits
Energy dissipation for electronic processing (E_{elec})	100 nJ/bit
Amplifier energy dissipation (E_{amp})	100nJ/bit/m^2
Path loss component (q)	2

Table 4.1: List of parameters

The simulation is time based and it refreshes the event launching sequences and the residual energy at intervals of 1 time unit during the network operation.

4.2. Result Analysis and Performance Evaluation

In our simulations, we compare the following 4 different strategies:

- Location based sink placement (EES) [51]
- Load based sink placement (LBM)
- Residual energy aware routing (REAR) and
- A hybrid approach that combines both LBM and REAR (Hybrid).

For each network size, we generated 5 different random topologies, and tested each topology with 5 sets of random events sequences. So, the results reported for the random networks are averages from the 25 runs.

As mentioned earlier, different researchers have used different metrics to measure the lifetime of a wireless sensor network. In our simulations, we have taken the following commonly used metrics to measure network lifetime:

- *Metric 1*: First sensor node depletes energy
- *Metric 2*: 10% of total sensors depletes energy
- *Metric 3*: Network becomes disconnected, i.e. at least one sensor node cannot find a valid path to route data back to the sink.

4.2.1. Comparison of lifetimes for random networks

Figures 4.3 – 4.5 show the results for different random networks.

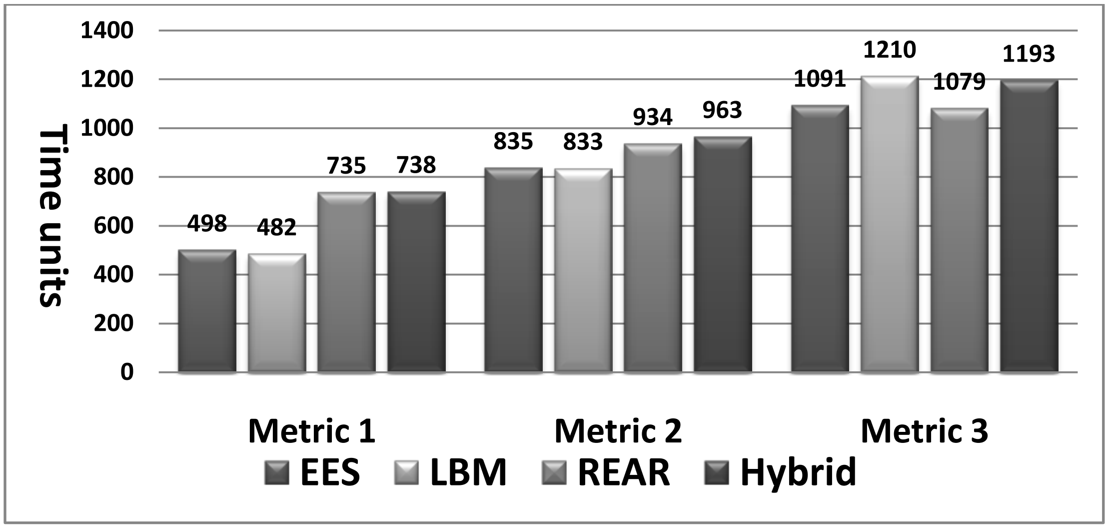

Figure 4.3: Network lifetime in network with 100 sensors

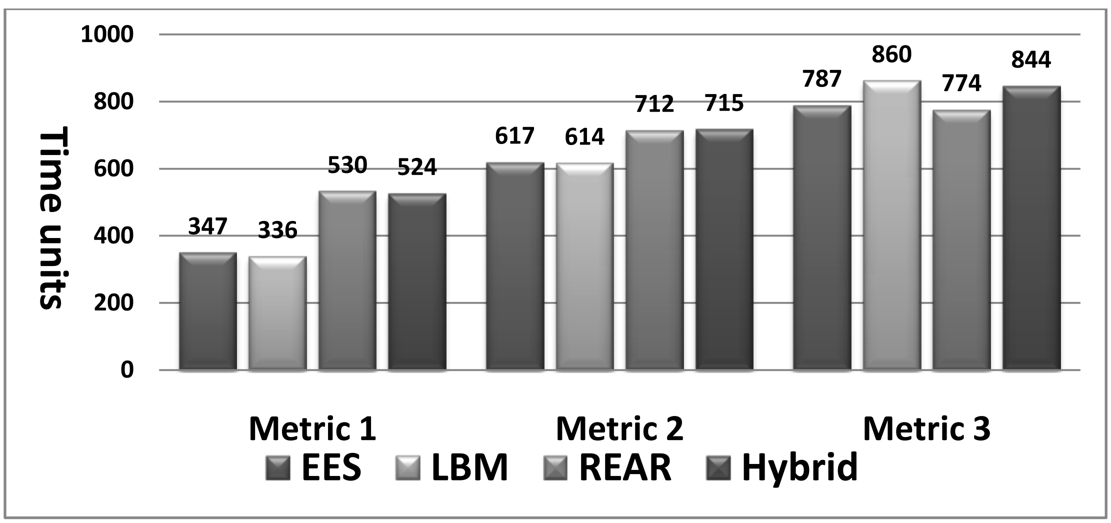

Figure 4.4: Network lifetime in network with 200 sensors

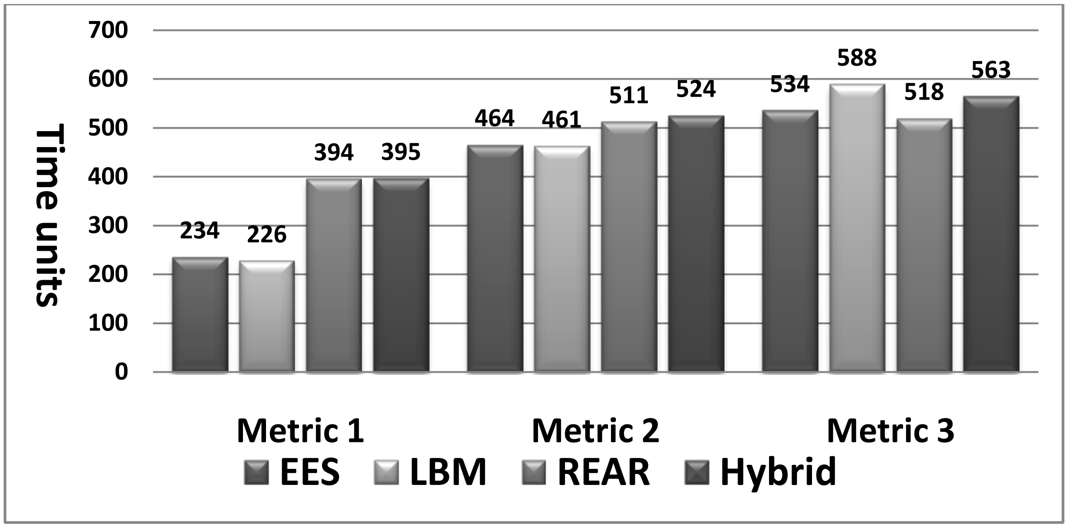

Figure 4.5: Network lifetime in network with 500 sensors

According to the simulation results in Figure 4.3, 4.4 and 4.5, we can see that LBM improves the overall network lifetime (*Metric 3*)compared to EES by 12% to 20%. This is because LBM introduces a balanced method to utilize the energy with heavily loaded nodes and allows these nodes to live longer than EES to provide data forwarding services. However, LBM does not consider the residual energy of the sensors. So, it may continue to use low-energy sensors to setup routing paths. Therefore LBM does not show improvement preserving energy for each sensor node. REAR outperforms EES in terms of prolonging the lifetime of each sensor node. REAR uses alternative sensors to set up routing paths with higher residual energy. Hence each sensor can live longer by reducing its energy consumption, especially when its residual energy is low. The results show that REAR can extend network lifetime by 50% to 60%, if Metric 1 is used. The Hybrid approach which implements both LBM and REAR schemes into the network operation improves the lifetime in each sensor and the overall network lifetime as expected.

The lifetime of network (using any metric) decreases consistently as network size increases. This is because, for larger networks, more sensors are operating and more data will be generated and transferred to the sink. Therefore more energy is needed for data transmission. However the initial energy supplied to each sensor remains the same, leading to an overall decrease in lifetime.

4.2.2. Comparison of lifetimes for grid topologies

The results on grid topologies are consistent with those for random networks. The results in Figure 4.6, 4.7 and 4.8 show that LBM extends the network lifetime (*Metric 3*) and REAR prolong the lifetime of each sensor (*Metric 1*). In general, the grid topology seems to result in a slightly higher lifetime, particularly using *Metric 1*, compared to random networks. This is likely due to better overall connectivity, which leads to more choices for routing paths, among nodes in the grid topology.

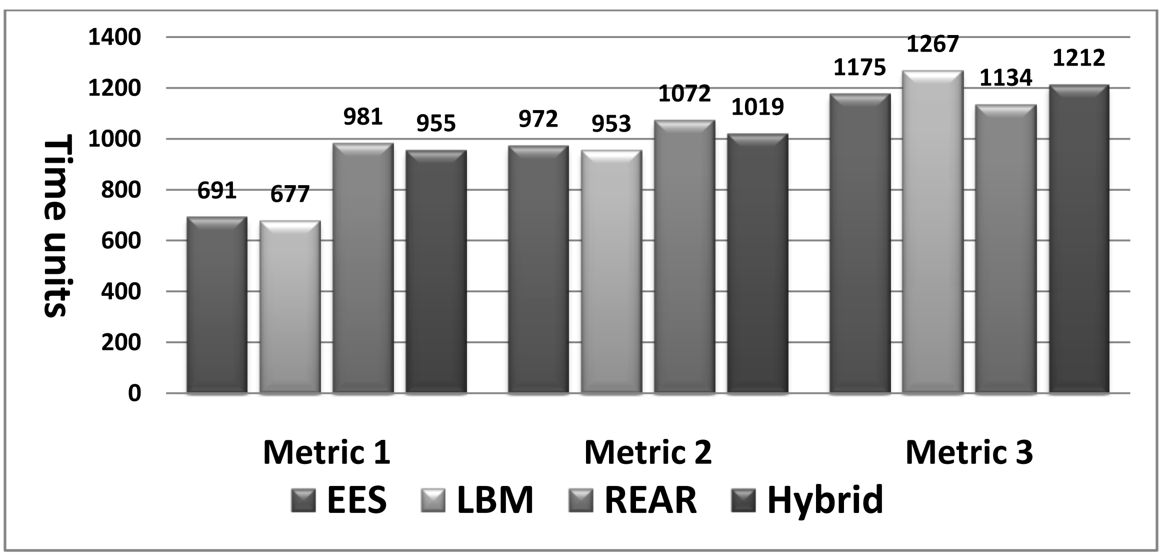

Figure 4.6: Network lifetime in grid network with 100 sensors

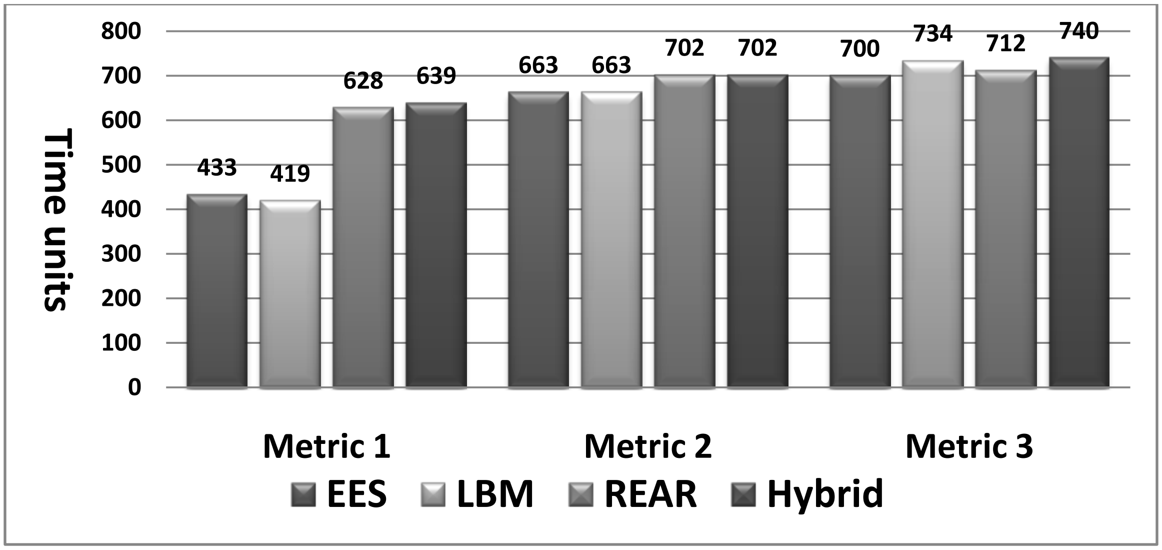

Figure 4.7: Network lifetime in grid network with 225 sensors

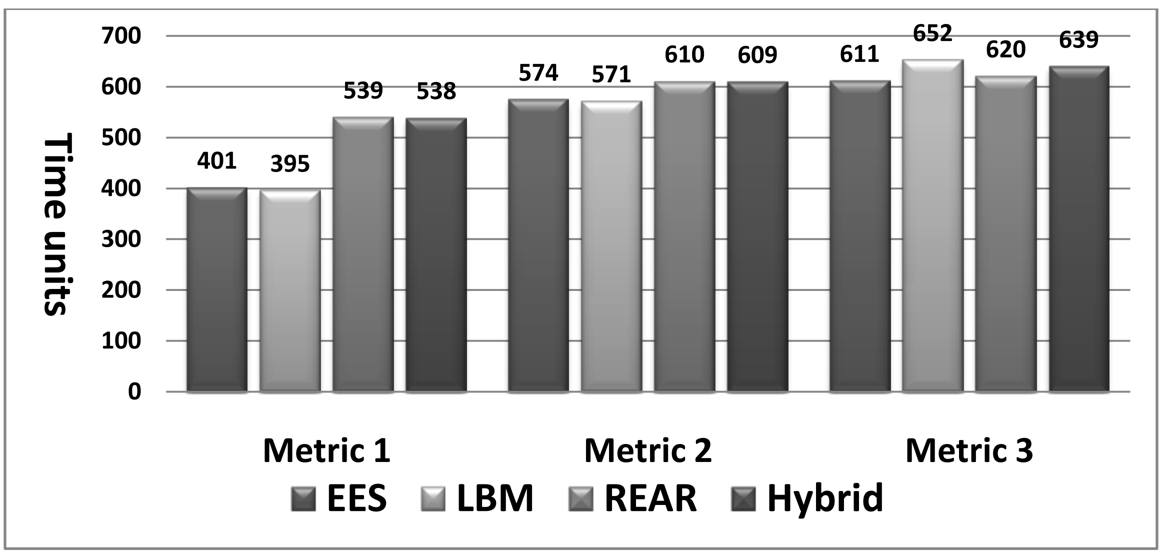

Figure 4.8: Network lifetime in grid network with 400 sensors

4.2.3. Effect of transmission range

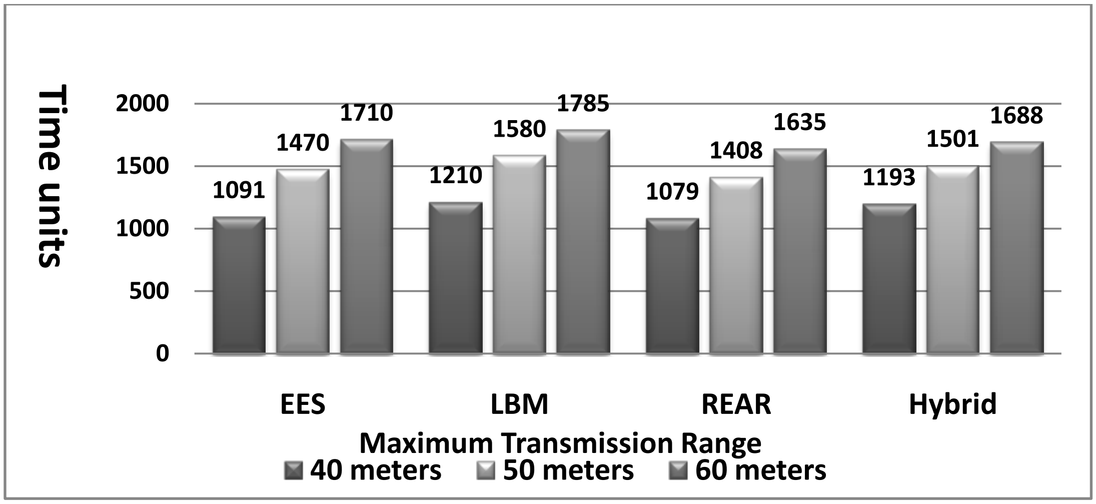

Figure 4.9: Network lifetime under different maximum transmission range in network with 100 sensors

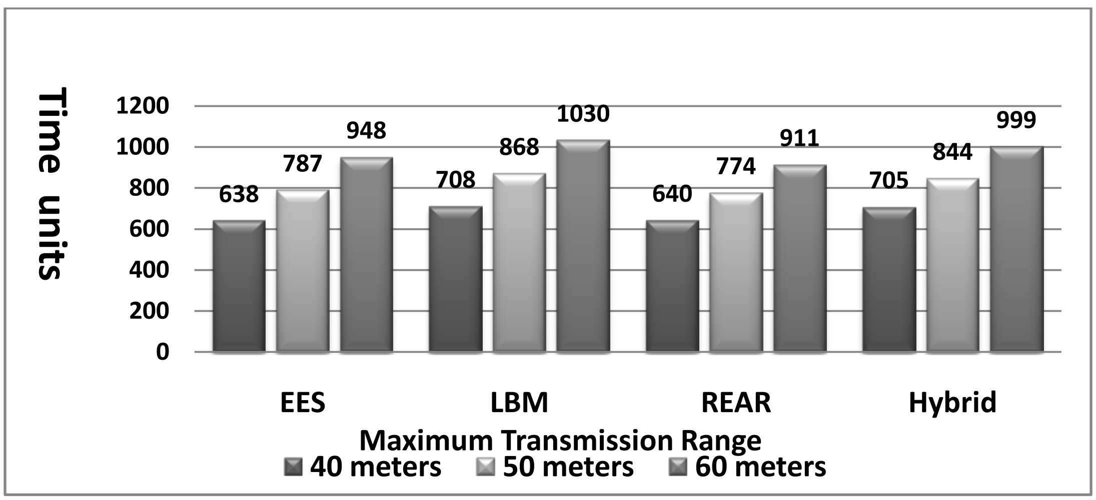

Figure 4.10: Network lifetime under different maximum transmission range in network with 200 sensors

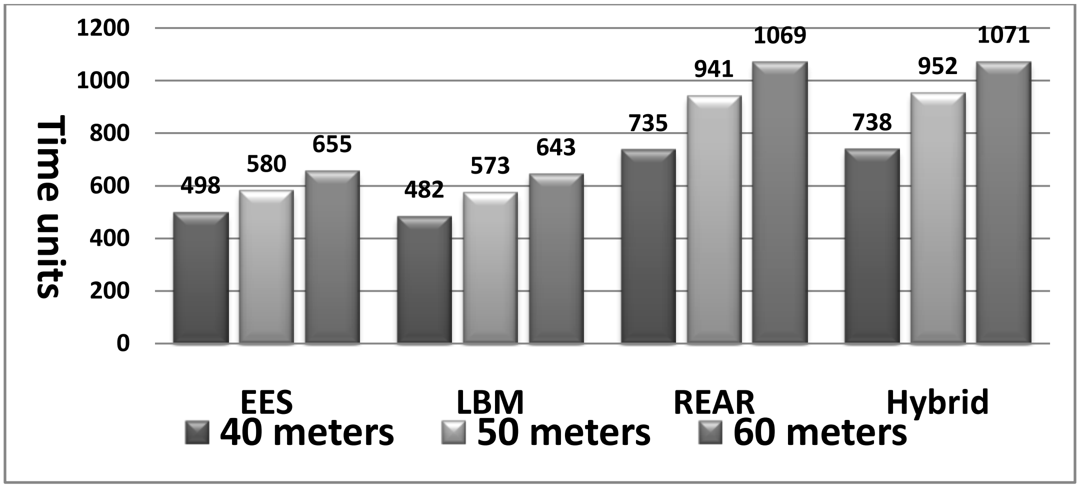

Figure 4.11:Metric 1 under different maximum transmission range in network with 100 sensors

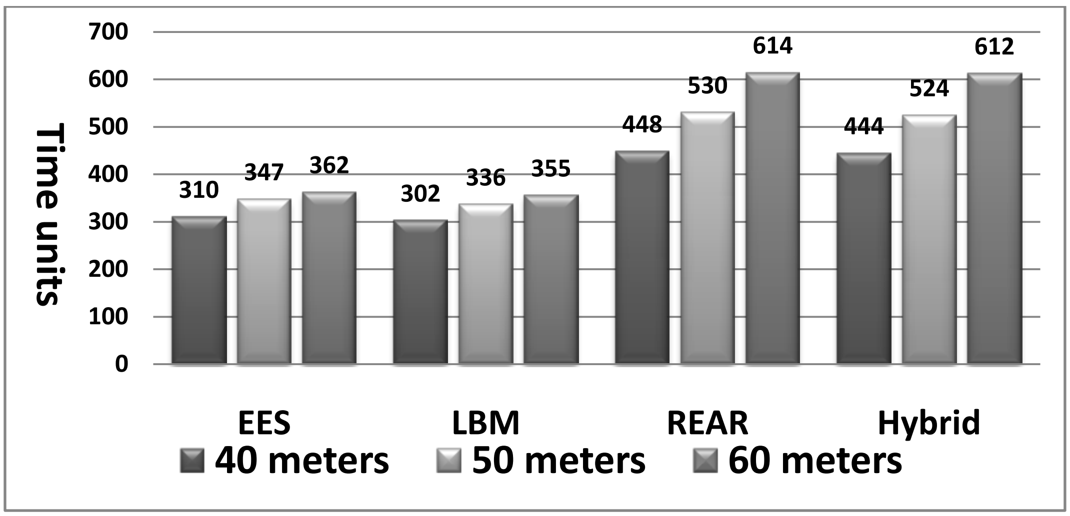

Figure 4.12: Metric 1 under different maximum transmission range in network with 200 sensors

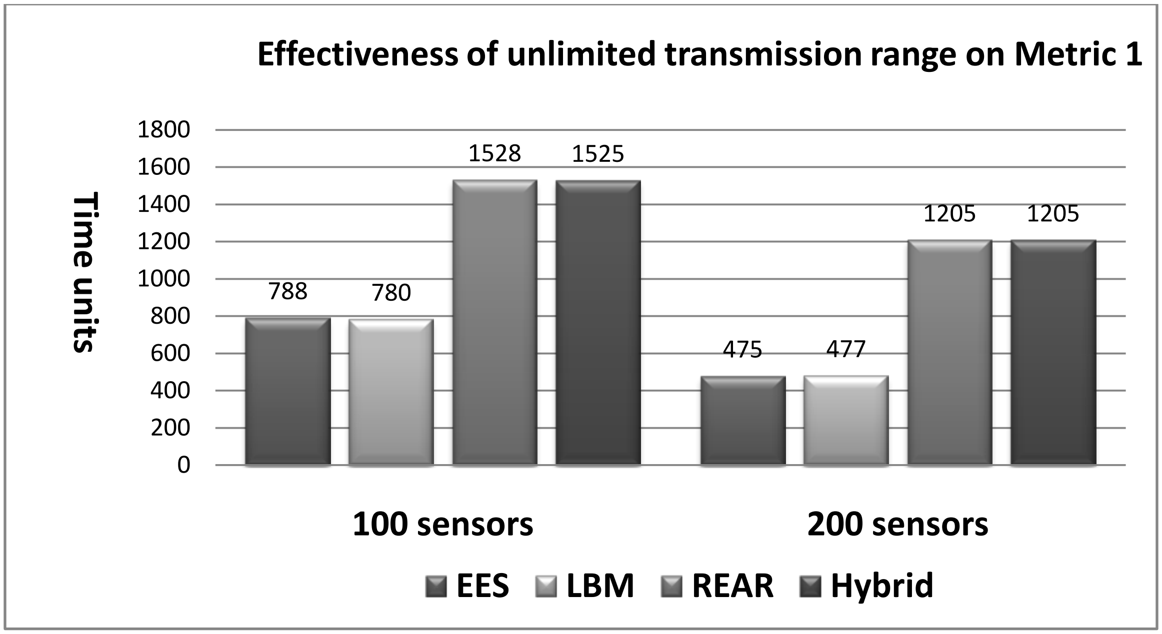

Figure 4.13: Metric 1 with no maximum transmission range.

Figure 4.9 and 4.10 show the effect of applying different maximum transmission ranges for sensor nodes. Figure 4.11 and 4.12 show the effectiveness for Metric 1 with different maximum transmission range. With the increase of maximum transmission range, network lifetime increases because sensors can reach more distant nodes for data transmission and more available paths can be found. Therefore more routing paths can be established and the network can operate longer than the networks with short transmission range. Also, the longer the transmission range, the less sensors needed to relay data. This leads a reduced usage for each sensor, so that a single sensor node is used less frequently and can live longer. If we take out the constraint of maximum transmission range in our experiment, results in Figure 4.13 show that LBM does not improve the performance as each sensor can send the data to sink node directly and there is no intermediate node needed. Therefore each sensor is equal in “Load”. However, REAR greatly improves the performance in preserving the energy consumption for each node as they avoid the usage of sensor nodes with low residual energy and uses additional intermediate sensor node with higher energy to forward the data.

With the increase of maximum transmission range, the effectiveness of proposed schemes remains validated but improvement diminishes as range increases. It is because longer transmission range leads to fewer hops needed on the optimal route. Overall LBM and REAR are both effective for managing the energy dissipation among sensor nodes.

V. CONCLUSION AND FUTURE WORK

In this thesis, we have introduced two new schemes to prolong network lifetime in a time based, random event driven scenario. In such a scenario, random events arise frequently and last for a specified period of time. The proposed schemes: *Load Based Sink Movement* (LBM) and *Residual Energy Aware Routing* (REAR) are designed to utilize the energy dissipation in a more balanced way to extend the overall network performance in terms of lifetime. *LBM* takes the transmission load into account to adjust the sink node position in response to the occurrence of events and the location of the heavily loaded sensors. *REAR* establishes alternative routing paths to reduce the usage of those sensors running low in residual energy to preserve the energy on each sensor node as much as possible. We also presented a *hybrid* approach that uses the sink placement strategy of *LBM* combined with routing path calculation of *REAR*.

We have used a custom simulator to evaluate the performance of the proposed approaches, and compared our schemes with the existing mobile sink placement strategy(EES) [51]. The simulation results clearly indicate that the proposed schemes consistently outperform traditional distance only sink movement approaches. We have also observed that the particular metric used to measure network lifetime has a significant effect on the performance.

In this thesis we have not considered multiple mobile sinks, or the computation of the trajectory for moving from one location to another. There is considerable opportunity for research in both of these areas to extend the current work. Another open problem is to develop appropriate protocols to route data to the sink, while it is moving from one location to another. Finally, it will be interesting to extend the proposed approaches for hierarchical network architectures. In this context, it will be necessary to determine the number and locations or higher powered cluster-heads to jointly optimize network cost and lifetime.

VI. REFERENCE

[1] Romer, K and Mattern, F. The Design Space of Wireless Sensor Networks. *IEEE Wireless Communications*, 11(6), (2004) 54-61

[2] D. Estrin, R. Govindan, J. Heidemann, S. Kumar, Next century challenges: scalable coordination in sensor networks, *ACM MobiCom'99*, (Washington, USA, 1999), 263–270.

[3] Bari. A. Relay node in Wireless Sensor Network: a survey. Computer Science, University of Windsor, Windsor, (2005)

[4] Chong.C.Y. and Kumar.S.P. Sensor Networks: Evolution, Opportunities and Challenges. *Proceeding of the IEEE, 91(8), (2003)* 1247-1256

[5] Luo.F. Relay node placement and trajectory computation of mobile data collectors in wireless sensor networks. University of Windsor, Windsor, Master Thesis 2011

[6] Akyildiz, I.F., Su, W.,Sankarasubramaniam, Y.,Cayirci, E. Wireless sensor networks: a survey. *Computer Networks*, (2002), 393-422.

[7] W. Heinzelman, A. Chandrakasan and H. Balakrishnan. Energy efficient communication protocol for wireless micro-sensor networks. *HICSS*, *(2000)* 3005-3014

[8] J. Pan, Y. T. Hou, L. Cai, Y. Shi, and S. X. Shen. Topology Control for Wireless Sensor Networks. *International Conference on Mobile Computing and Networking*, *(2003)* 286-299.

[9] Zhi Ang Eu; Seah, W.K.G. Impact of Transmission Power And Routing Algorithms in Designing Robust Wireless Sensor Networks. *Personal, Indoor and Mobile Radio Communications, (2007)* 1-5

[10] Y. Bi, L. Sun, N. Li. 2009. BoSS: a moving strategy for mobile sinks in wireless sensor networks. *International Journal of Sensor Networks*, *5(2009)*, 173-184.

[11] Nazir, B. and Hasbullah, H. Mobile Sink based Routing Protocol (MSRP) for Prolonging Network Lifetime in Clustered Wireless Sensor Network. *Computer Applications and Industrial Electronics*, (2010), 624 – 629.

[12] G. Gupta, M. Younis. Fault-tolerant clustering of wireless sensor networks. *Proceedings of IEEEWCNC, (2003)*, 1579 – 1584

[13] G. Gupta, M. Younis. 2003. Performance evaluation of load-balanced clustering of wireless sensor networks. *10th International Conference on Telecommunications, (2003)*, 1577-1583

[14] Bari, A and Jaekel, A, Techiques for Exploiting Mobility in Wireless Sensor Networks. *Handbook of Research on Mobile Business: Technical, Methodological and Social Perspective, (2008)*, 445-455

[15] Tian, K., Zhang, B., Huang, K. and Ma, J. Data Gathering Protocols for Wireless Sensor Networks with Mobile Sinks. *IEEE Global Telecommunications Conference*, (2010), 1 – 6.

[16] Wang, B., Xie, D., Chen, C., Ma, J. and Cheng, S. Deploying Multiple Mobile Sinks in Event-Driven WSNs. *Communications*, (2008), 2293 – 2297.

[17] Gandham, S.R, Dawande, M, Prakash, R and Venkatesan, S. Energy Efficient Schemes for Wireless Sensor Networks with Multiple Mobile Base Stations. *Global Telecommunications Conference, (2003)*, 377-381

[18] Jea, D, Somasunda, A and Srivastava, M. Multiple Controlled Elements (Data Mules) for Data Collection in Sensor Networks" *International Conference on*

Distributed Computing in Sensor Networks,3560 (2005), 244-257

[19] Liang, W., Luo, J. and Xu, X. Prolonging Network Lifetime via a Controlled Mobile Sink in Wireless Sensor Networks in *IEEE Global Telecommunications Conference*,(2010), 1 – 6.

[20] Alsalih, W, Hassanein, H and Akl, S. Placement of multiple mobile data collectors in underwater acoustic sensor networks Wireless *Communications and Mobile Computing, 8(8), (2008),* 1011-1022

[21] Azad, A.P, and Chockalinqam, A. Mobile Base Station Placement and Energy Aware Routing in Wireless Sensor Networks. *Wireless Communications and Networking Conference, (2006),* 264-269

[22] Bari, A, Jaekel, A and Bandyopadhyay, S. Optimal Placement and Routing Strategies for Resilient Two-tiered Sensor Networks. *Wireless Communication and Mobile Computing, (2008),* 920-937

[23] Shah, R.C. and Roy, S.Data MULEs: Modeling a three-tier architecture for sparse sensor networks. *Sensor Networks Protocols and Applications,* (2003), 30–41.

[24] Zhang, Y and Fromherz, M.P.J. A robust and efficient flooding-based routing for wireless sensor networks. *Journal of Interconnection Networks, 7(4), (2006)* 549-568

[25] Chatzigiannakis, I.,Kinalis, A. and Nikoletseas, S, Sink mobility protocols for data collection in wireless sensor networks. *9th International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, (2006),* 52 – 59.

[26] Chatzigiannakis, I., Kinalis, A. and Nikoletseas, S, Efficient data propagation strategies in wireless sensor networks using a single mobile sink. *Computer*

Communications 31; (2008), 896–914.

[27] Younus, M., Minhas, A.A., Javed, M.Y. and Naseer, A. EEAR: Efficient Energy Aware Routing in Wireless Sensor Networks. in *ICT and Knowledge Engineering*, (*2009*), 57 – 62.

[28] Huang, Q., Bai, Y. and Chen, L. An Efficient Route Maintenance Scheme for Wireless Sensor Network with Mobile Sink. *Vehicular Technology Conference*, (*2007*), 155-159.

[29] Wang, Y., Yu, C., Chen, W. and Wang, C.An average energy based routing protocol for Mobile Sink in wireless sensor networks. *Ubi-Media Computing, (2008)*, 44-49.

[30] Heinzelman, W.B, Chandrakasan, A.P, Balakrishnan, H. An application-specific protocol architecture for wireless microsensor networks. *IEEE Trans.Wireless Commu, 4(2002),* 660- 670.

[31] P. Juang, H. Oki, Y. Wang, M. Martonosi, D. Rubenstein and L. Peh, Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with zebranet. *ASPLOS-X, (2002).* 96-107

[32] Jain, S, Shah, R.C, Bunette, W, Borriello, G and Roy, S. Exploiting Mobility for Energy Efficient Data Collection in Sensor Networks. *Mobile Networks and Applications, (2006),* 327-339

[33] Dubois-Ferriere, H and Estrin, D. Efficient and practical query scoping in sensor networks. *Mobile Ad-hoc and Sensor Systems, (2004).* 564-566

[34] Wang, B., Xie, D., Ma, J and Cheng, S. The Mobility Pattern of Sink in Event-driven Wireless Sensor Networks. *China-Ireland International Conference on Information and Communications Technologies*, (*2007*), 539–546.

[35] Zaki, G.F., Elsayed, H.M., Amer, H.H. and El-Soudani, M.S. Energy Balanced Model for Data Gathering in Wireless Sensor Networks with Fixed and Mobile Sinks. *Computer Communications and Networks,* (2009), 1 – 6.

[36] Efthymiou, C., Nikoletseas, S. and Rolim, J. Energy Balanced Data Propagation in Wireless Sensor Networks. *18th International Parallel and Distributed Processing Symposium*, (2004), 225-233.

[37] Zhang, H., Shen, H. and Tan, Y. Optimal Energy Balanced Data Gathering in Wireless Sensor Networks. *Parallel and Distributed Processing Symposium, (2007)*, 1–10.

[38] Kim, J. and Eom, D. An Intelligent Agent-Based Routing Scheme Supporting Multiple Mobile Sinks in WSNs. *Human-Centric Computing (HumanCom)*, (2010), 1-5.

[39] Ye, F., Luo, H.Y., Cheng. J., Lu, S.W. and Zhang, L.X. A two-tier data dissemination model for large-scale wireless sensor networks. *ACMMobiCom,(2002),* 148-159

[40] Gandham, S, Dawande, M and Prakash, R. An Integral Flow-Based Energy-Efficient Routing Algorithm for Wireless Sensor Networks. *IEEE Wireless Communications and Networking Conference, 4(2004),* 2341-2346.

[41] Wu, S and Candan, K.S. GPER: Geographic Power Efficient Routing in Sensor Networks. *IEEE International Conference on Network Protocols, (2004).* 161-172.

[42] Dai, H and Han, R. A Node-Centric Load Balancing Algorithm for Wireless Sensor Networks. *IEEE Global Telecommunications Conference, (2003)* 548-552.

[43] Luo, J. and Hubaux, J.P. Joint mobility and routing for lifetime elongation in

wireless sensor networks.in*24th Annual Joint Conference of the IEEE Computer and Communications Societies*, (2005), 1735 – 1746.

[44] Gatzianas, M. and Georgiadis, L. A Distributed Algorithm for Maximum Lifetime Routing in Sensor Networks with Mobile Sink. *Wireless Communications,* (2008), 984 – 994.

[45] Luo,J. Mobility in wireless networks: Friend or foe: Network design and Control in the Age of mobile Computing. (2006)

[46] Papadimitriou, I and Georgiadis, L. Maximum Lifetime Routing to Mobile Sink in Wireless Sensor Networks, *13th International Conference on Software, Telecommunications and Computer Networks, (Croatia, 2005,)* 15-17.

[47] Yun, Y. and Xia, Y. Maximizing the lifetime of wireless sensor networks with mobile sink in delay-tolerant applications. *IEEE Transactions on Mobile Computing,*9(9), 1308 – 1318.

[48] Yun, Y., Xia, Y., Behdani, B. and Smith, J.C. Distributed algorithm for lifetime maximization in delay-tolerant wireless sensor network with mobile sink. *Decision and Control (CDC)*, (2010), 370 – 375.

[49] Ying, C, Lau, V.K.N.; Wang, R; Huang, H; Zhang, S. A Survey on Delay-Aware Resource Control for Wireless Systems—Large Deviation Theory, Stochastic Lyapunov Drift, and Distributed Stochastic Learning, *IEEE Transaction on Information Theory* (2012), 1677 – 1701

[50] Neely, M.J, Modiano, E and Li, C.P. Fairness and optimal stochastic control for heterogeneous networks. *IEEE Transactions on Networking, 16(2), 2008,* 396 - 409.

[51] Huang, Z., Liu, S. and Qi, X. An Energy Efficient Strategy for Single Mobile Sink in Event-driven Sensor Networks. *Ad hoc and Sensor Wireless Networks*, (2012)

[52] Yi-hua Zhu,Wan-dengWu, Victor C.M.Leung. Energy-efficient Tree-based Message Ferrying Routing Schemes for Wireless Sensor Networks. *Mobile networks & applications,* 14(2009), 125-135.

[53] Gupta, G. and Younis, M. Performance evaluation of load-balanced clustering of wireless sensor networks. in *Telecommunications, 10th International Conference,* (2003), 1577 – 1583.

[54] K. Akkaya, M. Younis, M. Bangad. 2005. Sink repositioning for enhanced performance in wireless sensor networks. *Computer Networks*, 49, (2005), 512 - 534.

[55] Blough, D.M, and Santi, P. Investigating upper bounds on network lifetime extension for cell-based energy conservation techniques in stationary ad hoc networks. *The proceedings of ACM International Conference on Mobile Computing and Networking (ACM MobiCom2), (2002),* 183-192

[56] Cardai, M and Du, D.Z. Improving wireless sensor network lifetime through power aware organization. *Wireless networks, 11(3), (2005),* 333-340

[57] Microsoft Corp. Windows 7 Product Guide (2009)

[58] Apple Inc. Mac OS X Technology Overview (2008).

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