ENERGY-EFFICIENT DUAL-SINK ALGORITHMS FOR SINK MOBILITY IN EVENT-DRIVEN WIRELESS SENSOR NETWORKS

MOHAMMADREZA ESLAMINEJAD

UNIVERSITI TEKNOLOGI MALAYSIA

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MOHAMMADREZA ESLAMINEJAD

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To my wife, Maryam,

For her support, patience, and love

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ABSTRACT

Improving energy-efficiency especially in routing mechanisms is one of the main goals in wireless sensor networks (WSNs). One of the issues of multi-hop routing is the phenomenon of fast energy depletion around the sink known as "sink neighborhood problem". Recently, employing a dual-sink algorithm has become a popular trend to solve this problem. However, sink selection problem, optimizing the next destination for mobile sink, and finding the optimum next-hop in routing scheme are three other issues that need to be addressed properly in dual-sink approaches. This research firstly presents an energy-efficient dual-sink algorithm with role switching mechanism (EEDARS) to address the sink selection problem in scenarios with non simultaneous events. To this end, a role switching mechanism is applied to the dual-sink algorithm for sending the nearest sink to the event area, hence shorten the path. Secondly, an energy-efficient dual-sink algorithm with fuzzy-based sink mobility (EDAFSM) is developed in which the mobile sink adaptively relocates to an optimum location among multiple events using fuzzy logic. Finally, a fuzzy logic scheme for routing optimization is proposed to improve further energy-efficiency in EEDARS and EDAFSM. The aforementioned proposed algorithms are known as joint dual-sink and fuzzy-based geographic routing in single-event (JDFGR-S) and multi-event (JDFGR-M) WSNs. These algorithms are compared to seven recent and established techniques. Extensive simulation of these algorithms with different conditions through NS2 framework showed significant improvements on the network metrics especially lifetime, residual energy, number of nodes alive, delivery ratio and load distribution without negative effect on the end-to-end delay. The lifetime of JDFGR-S is 10% higher than EEDARS and the lifetime of JDFGR-M is 22% more than EDAFSM. The validation of simulation results show 96.53% and 98.98% reliability for lifetime and energy consumption metrics, respectively. As a conclusion, the proposed algorithms have improved the energy-efficiency in event-driven based WSNs.

ABSTRAK

Meningkatkan kecekapan tenaga terutamanya dalam mekanisme penghalaan adalah salah satu matlamat utama dalam rangkaian sensor tanpa wayar (WSNs). Salah satu isu berkaitan penghantaran menerusi banyak lompatan ialah fenomena kehabisan tenaga yang cepat di sekitar pengumpul yang dikenali sebagai masalah perjiranan pengumpul. Baru-baru ini, penggunaan dwi-pengumpul adalah kaedah popular untuk menangani masalah ini. Walau bagaimanapun, mengoptimumkan destinasi seterusnya untuk pengumpul mudah alih, masalah pemilihan pengumpul, dan mencari lompatan optimum dalam penghalaan adalah tiga isu yang perlu ditangani dengan betul dalam pendekatan dwi-pengumpul. Kajian ini pertamanya membentangkan algoritma dwi-pengumpul cekap tenaga dengan mekanisme pensuisan peranan (EEDARS) dalam usaha untuk menangani masalah pemilihan pengumpul dalam senario dengan peristiwa-peristiwa yang tidak serentak. Untuk tujuan ini mekanisme pensuisan peranan digunakan terhadap algoritma penghantaran pengumpul terdekat ke kawasan peristiwa terkini, dan seterusnya memendekkan laluan. Keduanya, algoritma dwi-pengumpul cekap tenaga dengan pengumpul mudah alih kabur (EDAFSM) dibangunkan yakni pengumpul mudah alih diubah lokasinya mengikut kesesuaian ke lokasi yang optimum di antara peristiwa-peristiwa menggunakan logik kabur. Akhirnya, satu skim logik kabur untuk pengoptimuman laluan dicadangkan untuk kecekapan tenaga lebih baik bagi EEDARS dan EDAFSM. Algoritma yang dicadangkan di atas dikenali sebagai dwi-pengumpul bersama dan penghalaan geografi berasaskan logik kabur dalam peristiwa tunggal (JDFGR-S) dan pelbagai acara (JDFGR-M). Algoritma-algoritma tersebut dibandingkan dengan tujuh teknik yang terkini. Simulasi menyeluruh dengan keadaan berbeza yang dilakukan menerusi NS2 menunjukkan peningkatan ketara dalam metrik rangkaian terutamanya hayat rangkaian, tenaga tersisa, bilangan nod yang masih hidup, nisbah penghantaran dan pengagihan beban tanpa kesan negatif dari aspek kelewatan di antara dua nod. Hayat JDFGR-S adalah 10% lebih tinggi daripada EEDARS dan hayat JDFGR-M adalah 22% lebih tinggi daripada EDAFSM. Pengesahan keputusan simulasi menunjukkan 96.53% dan kebolehpercayaan 98.98% untuk masa hidup dan metrik penggunaan tenaga. Kesimpulannya, algoritma yang telah dibangunkan meningkatkan kecekapan tenaga di WSNs berasaskan dorongan acara.

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ACO	-	Ant Colony Optimization
ADV	-	Advertisement
AGEM	-	Adaptive Greedy-Compass Energy-Aware Multi-path
AODV	-	Ad hoc On-demand Distance Vector
APTEEN	-	Adaptive Periodic Threshold-sensitive Energy-Efficient sensor Network protocol
CAGIF	-	Channel-Aware Geographic-Informed Forwarding
CD	-	Critical Degree
CDMA	-	Code Division Multiple Access
CHs	-	Cluster Heads
CPL	-	Cumulative Path Load
CPU	-	Central Processing Unit
CTS	-	Clear To Send
DD	-	Directed Diffusion
D-MPR	-	Disjoint Multi-path Routing
DSA	-	Dynamic Sampling Algorithm
DSR	-	Dynamic Source Routing
DT	-	Delaunay Triangulation
DT-MSM	-	Delay-Tolerant Mobile Sink Model
EAM	-	Efficient Advancement Metric
EAR	-	Energy-Aware Routing
EEABR	-	Energy-Efficient Ant Based Routing
EEDARS	-	Energy-Efficient Dual-sink Algorithm with Role Switching Mechanism
ED	-	Exploratory Data
EDAFSM	-	Energy-efficient Dual-sink Algorithm with Fuzzy-based Sink Mobility Pattern

ELBR	-	Energy Level Based Routing
EM-GMR	-	Energy and Mobility-aware Geographical Multipath Routing
FEEM	-	Fault-tolerant and Energy-Efficient Multi-path routing
FGF	-	Fuzzy-based Greedy Forwarding
GAF	-	Geographic Adaptive Fidelity
GEAR	-	Geographic and Energy Aware Routing
GLOBAL	-	Gradient-based routing protocol for LOad BALancing
GMR	-	Geographical Multipath Routing
GPS	-	Global Positioning System
GPSR	-	Greedy Perimeter Stateless Routing
ID	-	Identifier
IEEE	-	Institute of Electrical and Electronics Engineers
ILP	-	Integer Linear Programming
JDFGR-M	-	Joint Dual-sink and Fuzzy-based Geographic Routing for enhancing lifetime in Mingle-event
JDFGR-S	-	Joint Dual-sink and Fuzzy-based Geographic Routing for enhancing lifetime in Single-event
LEAN	-	Local Event ANnouncer
LEACH	-	Low-Energy Adaptive Clustering Hierarchy
MAC	-	Media Access Control
MCFA	-	Minimum Cost Forwarding Algorithm
MFR	-	Most Forwarding Routing
MGF	-	Merely Greedy Forwarding
MLBRF	-	Multi-Sink Load Balanced Reliable Forwarding protocol
M-MPR	-	Mesh Multi-path Routing
MS	-	Mobile Sink
MSDD	-	Multi-Sink Directed Diffusion
MSLBR	-	Multi-Sink and Load-Balance Routing
MSRP	-	Mobile Sink Based Routing Protocol
NS2	-	Network Simulator 2
OBGR	-	Online-Battery aware Geographic Routing algorithm
PBR	-	Primary Based Routing
PEGASIS	-	Power-Efficient Gathering in Sensor Information Systems
PR	-	Packet Replication

QoS	-	Quality of Service
REDR	-	Residual Energy Depletion Rate
REM	-	Rule Evaluation Method
RFID	-	Radio Frequency Identification
RTS	-	Request To Send
RWP	-	Random Way Point
SF	-	Selective Forwarding
SPIN	-	Sensor Protocols for Information via Negotiation
SPR	-	Shortest Path Routing
SS	-	Static Sink
TDMA	-	Time Division Multi Access
TEEN	-	Threshold-sensitive Energy-Efficient sensor Network protocol
TTDD	-	Two Tier Data Dissemination
TTL	-	Time To Live
WLDT	-	Weighted Localized Delaunay Triangulation-based data forwarding
WLDT w/c	-	Weighted Localized Delaunay Triangulation-based data forwarding without checkpoints
WSNs	-	Wireless Sensor Networks

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CHAPTER 1

INTRODUCTION

1.1 Overview

Wireless sensor networks (WSNs) are formed by hundreds even thousands small, low cost sensor nodes communicating together to measure a variety of the environmental parameters and send the data to the end users through one or several sinks (Anastasi *et al.*, 2009). These kinds of networks have a wide range of uses in industry, medical, military, and metropolitan venues. WSNs are engaged in many applications such as target tracking, intrusion detection, habitat and battlefield monitoring, and surveillance purposes (Rathnayaka and Potdar, 2013; Yick *et al.*, 2008).

Although small-sized wireless sensor nodes are always improved by new technologies, these tiny devices still suffer from limited power supply. In some situations, the sensor nodes are deployed in geographically constrained environments such as battlefields or oceans to work for a long period of time. Since battery replacement of dead nodes in such areas is very challenging, they may become nonfunctional in a short time; hence negatively affect the network lifetime, fault tolerance, and connectivity. Therefore, optimizing the current methods for energy conservation is an important issue, especially to prolong the sensors lifetime in WSNs (Basagni *et al.*, 2008). Since the energy utilization for send and receive data is much higher than the power needed for computations, designing an energy efficient routing scheme is one of the main concerns in this area (Anastasi *et al.*, 2009).

The routing protocols are classified into three categories based on the network structure i.e. flat, hierarchical, and geographic routings. The energy-efficient mechanisms applied in these schemes are different from each other, since they are very application dependent. Generally the applications in WSNs are divided into three categories: time-driven, query-driven and event-driven. In time-driven scenarios, the data are sent to the sink continuously by all or special groups of sensor nodes. This causes a rapid depletion of energy throughout the network. In event-driven applications, on the other hand, only the data about an interested event is forwarded to the sink while in the query-based method, the data has to be transmitted according to the sinks' requests. For example, in flat protocols (Al-Karaki and Kamal, 2004; Akkaya and Younis, 2005) which consist of many wireless sensor nodes with the same role and functionality, a query-based mechanism is employed to prevent continuous data reporting, hence save power by reducing the total number of packets in the network. Hierarchical routing algorithms proposed by many researchers (Awwad *et al.*, 2011; Karaboga *et al.*, 2012; Jeon *et al.*, 2009; Kumar *et al.*, 2009) are one of the main solutions for mitigating the redundant data sent to the sink nodes in WSNs. In this manner, the cluster heads (CHs) collect data from cluster members and send it to the sink directly or through multi-hop routing after they eliminate the extra packets. Nevertheless, this kind of routings are mostly employed for time-driven applications in which, sensor nodes have to periodically report all of their sensed data to the sink. Finally, the location information is used in geographic routing to forward the data to the desired areas rather than the entire network. It can limit the flooding phenomenon (Akkaya and Younis, 2005). Developing the GPS-free approaches makes the implementation of geographic routing very cheap (Khalaf-Allah, 2008). Small sized routing table in each node (Medjiah *et al.*, 2010) and using minimum hops to sink (Karp and Kung, 2000) are the other advantages of geographic routing. This kind of routing is better fitted to event-driven scenarios.

Greedy forwarding in geographical multi-hop routings is a method in which a relay node selects the next hop based on the distance to the destination. In this way, the shortest path can be formed for sending the data packets from a source node to the sink. GPSR (Karp and Kung, 2000) is the first geographic routing that uses a merely greedy forwarding mechanism. However, using distance parameter as the single factor to decide next-hop can cause unbalanced energy consumption along the path. This can threaten the network lifetime. This is known as the *forwarding problem*. Optimizing the next-hop selection methods by using several factors in greedy forwarding is a state-of-the-art solution for this problem (Manjunatha *et al*., 2010). QoS-based (Li and Kim, 2012) and fuzzy logic based (Isik *et al*., 2012) forwarding are two optimization techniques in this area. However, fuzzy logic based forwarding method is very simple to implement. It is also a powerful tool for decision making in real-time applications with a low cost computational complexity (Torghabeh *et al*., 2010).

In WSNs, the network lifetime is threatened by network partitioning phenomenon that disconnects the sink node from some sources in the field. Unbalanced energy consumption due to multi-hop routing is one of the main reasons behind the network partitioning. Although many methods based on protocol operation are employed in routing algorithm for more energy-efficiency, multi-sink and mobile sink mechanisms directly address the network partitioning problem.

The network partitioning caused by unbalanced energy consumption around the sink is called sink neighbor problem (Yang *et al.*, 2010). Due to multi-hop forwarding, the sink neighbors have to tolerate a huge amount of traffic load from all over the network. Employing only one static sink increases the risk of fast energy depletion in sink neighbors (Basagni *et al*., 2008; Li and Mohapatra, 2007). Thus, applying a multi-sink scheme can mitigate this problem. However, increasing the number of sinks is economically costly and application dependant (Oyman and Ersoy, 2004). Therefore, minimizing the number of sinks is a key point in algorithm design. Nevertheless, there is an unsolved problem in multi-sink approaches. In fact, it is finding the nearest sink node to shorten the path for more energy efficiency. This is known as *sink selection problem* (Nazi *et al*. 2013; Hou *et al*., 2006; Mitton *et al*., 2011).

To prevent network partitioning around the sink, the sink neighbors in some approaches change their position periodically through a limited mobility (Ahmed, 2013). Since the nodes energy is limited, another smart choice is to move the sink itself. Many protocols in the literature are proposed for sink mobility (Marta and Cardei, 2009; Konstantopoulos *et al*., 2012). However, two problems in this area are still unsolved. Firstly, the mobile sink has to inform its position to all sensor nodes after each repositioning. It imposes a large amount of sink localization overhead on the network (Kim *et al*., 2010a; Chen *et al*., 2010). Based on this problem, the simulation results performed by Wu and Chen (2007) prove that the network lifetime in algorithms which use a single mobile sink is not higher than the one with a single static sink in some cases. Some researchers (Park *et al*., 2013; Wang *et al*., 2009) proposed a restricted flooding for sink location update instead of broadcasting to whole network. The second problem is finding an *optimum position for mobile sink* across the network. Predefined (Luo and Hubaux, 2005) and stochastic (Chatzigiannakis *et al.*, 2006) mobility are two kinds of uncontrolled sink mobility patterns. However, they impose a high latency for packet delivery. It seems the controlled sink mobility is a better choice in which the sink autonomously determines the next destination. Nevertheless, the main problem is the unlimited possible locations where the sink can be moved that known as NP-hard problem. Most of the optimization approaches in this area that use linear programming are involved in complex mathematical modeling (Yun and Xia, 2010; Zhao *et al*., 2011; Luo *et al*., 2006). Centroid-based sink mobility (Akkaya *et al*., 2005; Hanoun and Nahavandi, 2009) is also involved in high computations to find a position among sink neighbors as polygon vertices. On the other hand, fuzzy logic sink mobility (Torghabeh *et al*., 2010; Porshokooh *et al*., 2011) presents a low cost scheme for controlled mobility pattern with desired input factors. Based on the discussion above, it is necessary to address the sink selection problem, the optimum position for mobile sink, and forwarding problem to have more energy-efficient routing.

1.2 Background of Study

Multi-hop routing in wireless sensor networks is very challenging. In fact, the radio transmission range of sensor nodes is so much limited due to small size of their power supply. Therefore, the nodes which are far from the sink node and their transmission range are shorter than their distance to the sink have to hand over their data base on multi-hop manner. It results in partitioning phenomenon due to unbalanced energy consumption around the sink and along the path. Consequently, this issue affects the network lifetime negatively. By using multiple static/mobile sinks, it is possible to solve the sink neighbor problem (Kim et al., 2008). Optimized greedy forwarding in geographic routing is a smart choice to change the next-hop periodically and balance the energy consumption in the field. However, to have an energy-efficient routing, some unsolved problems in these areas have to be addressed properly. This thesis addresses the three common problems which include looking for the nearest sink in multi-sink mechanism (*sink selection problem*), finding the *optimum position of mobile sink* among multiple events while mitigating the sink localization overhead, and selecting the best next-hop node in geographic routing (*forwarding problem*). The next sub-sections discuss these problems in details.

1.2.1 Finding the Nearest Sink in Multi-sink Mechanism

One problem which affects the data delivery from all the sensor nodes to the sink is caused by communication to nodes near the sink. It imposes a high traffic on this kind of nodes. This problem is more complicated if the sink is static. In this state, the energy consumption in sink's neighbors is much faster than the rest of the network. The reason is that the sink's neighbors with only one hop distance not only are involved in sending their own data, but also have to forward the generated packets from all over the network to the sink. After a while, they stop working so that the sink is isolated from other sensor nodes in the network. However, there is still a huge potential for most of the sensor nodes to continue performing their tasks normally. This problem that leads to premature network disconnection is known as "sink neighborhood problem," (Akkaya *et al*., 2007; Basagni *et al*., 2008; Torghabeh *et al*., 2010; Keskin *et al*., 2011) causes the network disconnection prematurely.

Employing more than one static sink in the network is one of the basic solutions for the sink neighborhood problem. It is possible to spread traffic load uniformly among the sensor nodes by using multiple sinks (Eghbali *et al*., 2009; Wang and Wu, 2009; Yoo *et al*., 2010) that are statically distributed across the sensor field. This can decrease the end-to-end delays and enhance the network lifetime significantly. Nevertheless, finding the nearest sink node to shorten the path for more energy efficiency and less delay is one of the main problems in this area. It is known as *sink selection problem* (Hou *et al*., 2006; Mitton *et al*., 2011; Lászka *et al*., 2012).

Some of the existing approaches in the literature (Alsalih *et al*., 2010; Gao *et al*., 2011; Turgut and Bölöni, 2011) engage multiple mobile sinks to tackle with sink selection problem. However, these mechanisms mostly divide the sensor field into several equal-sized partitions and assign each mobile sink to one individual sub-region. Therefore, the condition of multiple mobile sink is restricted to the state of single mobile sink to simplify the problem. However, those researches have the following drawbacks. First of all, each mobile sink may suffer from imbalanced assigned work load if the sensor field is irregular. Secondly, none of the algorithms guarantees that at least one of the mobile sinks succeeds to collect the data produced by each sensor node at each period of time. Although Lászka *et al*. (2011) proposed a heuristic method to address the above problem, they did not consider the end-to-end delay caused by sink mobility.

1.2.2 Mobile Sink Localization and Optimum Position for Sink Movement

Mobility capability for some of the network elements is another solution for the sink neighborhood problem. It seems replacing the sink neighbors periodically is a good strategy to balance energy consumption due to data transmission across the network. However, the remaining energy of nodes equipped with a mobilizer unit is consumed much faster than static conditions. Moving the sink node to the parts of the network with sufficient energy periodically while keeping the sensors stationary is the key idea for more energy saving. It can avoid network partitioning phenomenon and consequently increase the network lifetime (Basagni *et al*., 2008).

Although, many protocols (Akkaya *et al*., 2005; Marta and Cardei, 2009; Konstantopoulos *et al*., 2012) are proposed for sink mobility, they have their own characteristics in the aspect of mobility itself. For example, in some applications in which the sink node moves across the network for data collection, an uncontrolled sink movement pattern like stochastic (Chatzigiannakis *et al*., 2006) or predefined

(Luo and Hubaux, 2005) scheme is applied to the algorithms. It means that the network is not capable to control the sink movement by determining an efficient trajectory based on the traffic load at each sensor node or their remaining energy (Basagni *et al*., 2008). Controlled sink mobility, on the other hand, (Basagni *et al*., 2009; Nazir and Hasbullah, 2010) can efficiently prolong the network lifetime with much less negative effect on the end-to-end delay.

Although the mobile sink approaches aim to conserve nodes power and improve the network lifetime, the overhead caused by topological changes wastes unnecessary energy all over the sensor field. In fact, the sensor nodes have to be aware about the sink location after each sink repositioning. Therefore, flooding the sink position information all over the field can cancel out the lifetime gain from the sink mobility. Some researches (Park *et al*., 2013; Wang *et al*., 2009) address this problem by using a limited flooding for distributing the sink position after each movement. Dual-sink algorithms that presented by Wu and Chen, (2007) and Chen *et al*., (2010) use the advantageous of both mobile and static sink approaches efficiently. In fact, this model is a hybrid method in which one of the sinks is placed at the center of field permanently while the other one is moving across the network for data collection from one-hop or k-hop neighbors. In this way, the flooding mechanism for disseminating the sink location information is limited to a small part of the network for more energy conservation rather than whole network. The main idea of dual-sink algorithms is that the source nodes which are not aware about the location of mobile sink send their data to the static sink while the source nodes that sense the mobile sink in one-hop or k-hop neighbors report the data to this sink. Furthermore, the traffic flow can be distributed on two sinks based on distance or energy factors. Nevertheless, flooding restricted mechanisms for sink position propagation is mostly developed for time-driven application while there is a huge potential to improve these paradigm for event-driven scenarios.

Finding an *optimum position for the mobile sink* across the network is one of the main issues in the area of WSNs routing (Yun and Xia, 2010; Zhao *et al*., 2011; Luo *et al*., 2006). It is very difficult to find the best place as the next position of sink in controlled sink mobility pattern. The most important factor that makes the problem so hard is the unlimited possible locations that the sink can be moved to. As an NP-hard problem, the mathematical analyzes involved with many input parameters such as localizing all of the sensor nodes in the field, their remaining energy, radio range and determining which one is producing the data at the time. In WSNs with a large amount of sensor nodes, it is impossible to pursue an exact search to find a suitable location for sink node. Additionally, wireless sensor networks are dynamic in nature. The reason is that the sources of data and the sensors condition are variable and may be changed time by time. Therefore, a periodic optimization scheme is required; each time the sink decides to change its position (Lee *et al*., 2013; Akkaya *et al*., 2005). It seems improving the current algorithms with lower complexity and control overhead is necessary for efficient sink repositioning.

1.2.3 Selecting the Best Next-hop Node in Single Path Geographic Routing

One of the issues of multi-hop routing is fast energy depletion along the path. In fact, the sensor nodes which are located on a path lose their energy quickly due to high traffic imposed on this series of nodes. It results in network partitioning and link failures. Applying multi-path routing (Medjiah *et al*., 2010; Murthy *et al*., 2013) in WSNs leads to traffic distribution all over the sensor field. However, using multiple paths has some problems such as flooding the path request across the network and possibility of interference and collision between the nodes on each path (Sutagundara and Manvi, 2013). Furthermore, using multi-path and mobile sink mechanisms simultaneously can cancel out the lifetime gain from sink mobility. This is due to high overhead caused by continual link breakage that known as offset problem (Chen *et al*., 2010).

Applying a dynamic routing optimization scheme into the WSNs can result in energy and traffic load balancing over the network (Liang, 2005). On the other hand, by distributing traffic load across the network, the energy consumption is balanced on all nodes equally. Geographic routing algorithms (Zhang and Zhang, 2009; Ammari and Das, 2010; Watfa and Yaghi, 2010) are one of the best candidates to make a dynamic routing by using specific metrics such as Euclidean distance and energy factors. GPSR (Karp and Kung, 2000) as a traditional geographic routing originally use a merely greedy algorithm to shorten the path between the source and destination. Based on this algorithm, forwarding decision is bound to information about the current position of forwarding node, its one hop neighbors, and the sink node as the final destination. In this way, a source node compares the location of the sink to itself and also to its neighbors. Then, the neighbor which is closer to the sink node is selected in order to propagate data messages. This greedy scheme is repeated by each relay node until the sink is reached eventually (Villalba *et al*., 2009).

The geographic routings presented by Liang and Ren (2005), Liang (2005), and Manjunatha *et al*. (2010) use some efficient metrics in greedy algorithm to dynamically find the next-hop based on fuzzy logic. Since EM-GMR (Liang, 2005) is an energy-efficient multi-path algorithm proposed for mobile environments, the authors considered the mobility, remaining battery capacity, and distance to the destination node. These parameters are given to the fuzzy logic as input arguments so that the output is calculated as optimum next-hop node. The method presented in (Manjunatha *et al*., 2010) employs three parameters such as distance from the sink, distance from the node, and remaining energy as the inputs of fuzzy logic for determining the next-hop. In algorithm proposed by Li and Kim (2012), instead of applying a merely greedy forwarding, the next hop is selected in such a way to satisfy the QoS metrics like energy-efficiency and delay.

Although these approaches are proposed to prolong the network lifetime in WSNs, none of them are designed for path optimization in single-path geographic routings with mobile sink. By using multi-path routing, the algorithm design is involved in some problems such as interference and collision between the paths that impose unnecessary energy consumption for packet retransmission (Sutagundara and Manvi, 2013). Therefore, it seems developing an optimization method for selecting next-hop node in geographic single-path routing is a gap in mobile sink approaches.

1.3 Statement of the Problem

This thesis addresses three problems in the scope of routing algorithms i.e. efficient sink selection mechanism, optimized controlled sink mobility pattern, and geographical forwarding scheme in dual-sink algorithm for maximizing the energy-efficiency in event-driven based WSNs. WSNs show a great capability in various applications. However, their success is extremely dependent on power management in different layers of protocol stack to satisfy the network metrics especially higher network lifetime and end-to-end delay of scenarios deployed on these networks.

In protocol stack, routing paradigms in network layer are recently more taken into consideration from energy saving point of view. Although these paradigms are different based on the application and network architecture, they have a large potential to be optimized for more energy-efficiency. For example, to have an energy-aware strategy for minimizing the number of produced packet in query-driven and time-driven applications, a flat or hierarchical method is a reasonable choice. However, the geographic routing can support event-driven scenarios as well. Nevertheless, distance-based greedy forwarding mechanism used for selecting the next relay node in geographic routing has to be optimized by considering the efficient metrics for more energy saving along the path. It can avoid partitioning phenomenon across the sensor field, hence prolong the network lifetime.

On the other hand, network partitioning around the sink caused by multi-hop routing is another problem which can addressed by multi-sink and mobile sink mechanisms. Although using multiple static or mobile sink can mitigate the fast energy depletion around the sink (sink neighbor problem), employing a hybrid form of these strategies like dual-sink can benefit from the advantageous of both methods. However, the *sink selection problem* still has to be addressed in this mechanism to find the nearest sink with minimum cost (such as energy and distance) for data transmission. Furthermore, the existing dual-sink approaches lack the mechanism to minimize the traffic load on the static sink. This can rapidly lead to sink neighbor problem and finally isolate the static sink from the rest of network. An efficient sink selection scheme can significantly decrease the energy consumption and end-to-end delay all over the sensor field.

Sink mobility is another strategy to solve the sink neighbor problem. Although predefined and stochastic sink mobility patterns can balance the energy consumption and traffic load all over the network, these patterns impose a high latency for data delivery. Controlled sink mobility, on the other hand, is an appropriate method in which the sink autonomously visits the sensor nodes or specific sites to collect data based on the efficient metrics (such as energy, traffic load, and distance). However, the sink localization overhead can cancel out the lifetime gain from the controlled sink mobility. Furthermore, one of the main problems which has to addressed in this area is finding *the next destination of mobile sink among unlimited positions in the field.* Most of the recent solutions are involved in sophisticated mathematical computations like linear programming (LP) which is not suitable for resource-constrained sensor nodes with low memory, energy, and processing unit. Therefore, optimizing the current approaches to find the optimum position of mobile sink at the time of sink movement is a big problem need to be solved.

1.4 Statement of Objectives

The aim of this research is to propose and evaluate three energy-efficient routing algorithms through an effective sink selection mechanism, an optimized controlled sink mobility pattern with minimized sink localization overhead, and optimized geographical forwarding scheme for event-driven based wireless sensor networks. The objectives of this research are as follows:

i. To study the existing solution for three of the issues i.e. sink selection problem, sink movement optimization and forwarding problem to specify the limitation of current solutions.

ii. To propose:

   a. A role switching mechanism in dual-sink algorithm for sending the nearest sink towards the event region and shortens the path in event-driven based WSNs.

b. A controlled sink mobility pattern in dual-sink algorithm based on fuzzy logic for finding the optimum position of mobile sink among multiple events in event-driven based WSNs.

c. An efficient forwarding scheme to select the best next-hop node in geographic routing in order to balance energy consumption on the path and incorporate the proposed routing into dual-sink algorithm.

iii. To evaluate the performance of three mechanisms with most widely used approaches in terms of network lifetime, number of nodes alive, residual energy, end-to-end delay, packet delivery ratio, and network load.

1.5 Research Questions

Based on the research objectives, several research questions needed to be answered as in Table 1.1.

1.6 Research Scope

The aim of this research is to propose and evaluate a joint dual-sink and geographic routing in wireless sensor network which cover the following matters:

i. The sensor nodes are all homogeneous.

ii. In all scenarios, an event-driven application is taken into consideration.

iii. The network consists of a series of sensor nodes deployed in two-dimensional dense environment with grid topology.

iv. There is no obstacle in the sensor field.

v. All sensor nodes are considered to be aware about their location information.

vi. There are two sink nodes with high resources in the field. They can communicate to each other for handling the algorithms.

Table 1.1: Research questions related to the study

Research Objectives	Research Questions
Objective 1	i. How to study and classify the existing solution for three of the issues i.e. sink selection problem, sink movement optimization and forwarding problem to specify the limitation of current solutions
Objective 2	i. How to propose a role switching mechanism in dual-sink algorithm for sending the nearest sink towards the event region and shortens the path in event-driven based WSNs. ii. How to propose a controlled sink mobility pattern in dual-sink algorithm based on fuzzy logic for finding the optimum position of mobile sink among multiple events in event-driven based WSNs. iii. How to propose an efficient forwarding scheme to select the best next-hop node in geographic routing in order to balance energy consumption on the path and incorporate the proposed routing into both proposed dual-sink algorithms.
Objective 3	i. How to evaluate the performance of three mechanisms with most widely used approaches in terms of network lifetime, number of nodes alive, residual energy, end-to-end delay, packet delivery ratio, and network load.

vii. There is no data aggregation across the network. In order to have high data accuracy at the sink side, all source nodes that sense an event have to send their data to the sink separately without any data aggregation or data reduction.

viii. Environmental monitoring is the application considered for this research, since it is an event-driven application with high delay-tolerant capabilities.

ix. This research does not consider the QoS issues in algorithm design and implementation. In fact, the proposed algorithms do not guarantee the end-to-end delay for specific period of time, since it is not important for considered delay-tolerant application (non-real time application).

1.7 Research Contributions

The focus of this research is to address sink selection problem at first by choosing the nearest sink node to shorten the path for more energy efficiency. The other issues are sink movement optimization and forwarding problem in dual-sink algorithm. A fuzzy-based solution is proposed for these two problems. The main contributions of this research are summarized as follow:

i. A novel taxonomy of routing protocols for wireless sensor networks in terms of energy-efficiency is presented in this thesis. The algorithms are classified into two category based on network structure and protocol operation. In this taxonomy, special attention has been devoted to the energy-aware multi-sink, mobile sink and bio-inspired routing algorithms which have not yet obtained much consideration in the literature.

ii. A role switching mechanism is proposed to address the sink selection problem in dual-sink algorithm. The energy efficient dual-sink algorithm with role switching mechanism (EEDARS) uses one static and one mobile sink. The periodic flooding for sink location update is avoided by engaging the static sink, while the mobile sink moves adaptively towards the event region to collect data. The scheme employs a role switching mechanism to send the nearest sink to the recent event area, hence shorten the path by minimizing the number of hops. The role switching mechanism also guarantees to locate one of the sinks at the center of field to avoid any packet loss for the first messages reported by new events. It also decreases the traffic load on the static sink to significantly mitigate the effect of sink neighbor problem. However, this algorithm can be employed in single event scenarios where there are no simultaneous events.

iii. A fuzzy-based sink mobility pattern is proposed to optimize the trajectory of mobile sink in dual-sink algorithm. The algorithm is called EDAFSM, an energy-efficient dual-sink algorithm with fuzzy-based sink mobility pattern. The mobile sink adaptively relocates to the optimum location among multiple events using fuzzy logic. The core of this contribution is to use a membership function (cost) which is composed of three fundamental parameters. In order to find the optimum next-hop node, the fuzzy-based mechanism has to face a tradeoff between the number of source nodes, amount of traffic rate and distance to event region in different parts of the sensor field. In this method, the next destination for mobile sink is specified by assigning a priority degree to each neighboring node based on the calculated cost and residual energy of sink neighbors. The position of node with minimum residual energy is chosen, if two neighbors have the same priority degree. Furthermore, the periodic flooding for mobile sink localization is avoided by utilizing the static sink at the center of field. The proposed algorithm can be engaged in multi-hop and multi-event scenarios for wireless sensor networks.

iv. A fuzzy-based greedy forwarding (FGF) scheme for routing optimization is proposed for more energy-efficiency of EEDARS and EDAFSM. The aforementioned proposed algorithms are named joint dual-sink and fuzzy-based geographic routing for single-event (JDFGR-S) and multi-event (JDFGR-M) WSNs, respectively. FGF uses efficient parameters i.e. number of hops to sink, residual energy, and distance from the center of field as fuzzy inputs for determining the next-hop. According to the literature, the optimum next-hop node generally has to be nearest to the sink, and have higher residual energy. However, none of the previous works considered a parameter to decrease the load on the center part of the network. The proposed fuzzy-based scheme uses a new membership function that called radius. Based on this fuzzy input, at the same condition, the node which is nearest to the boundary of sensor field has higher priority to forward the packet.

v. To evaluate the performance of three proposed algorithms, a new model in NS2 framework is developed based on C++ and TCL languages. This model includes several procedures to implement system functions and calculate network metrics such as network lifetime, number of nodes alive, residual energy, end-to-end delay, delivery ratio, energy consumption, packet loss and network load. Moreover, by considering the selected energy parameters, a new energy model is designed for the simulation.

1.8 Significance of Research

The intention of this study is to propose and evaluate an energy-efficient routing algorithm through integration of dual-sink algorithm and fuzzy-based geographic routing for wireless sensor networks. Dual-sink algorithm is a state-of-the-art technique to restrict flooding needed for the sink location update in mobile sink approaches. It is mostly proposed and employed in time-driven scenarios. Little efforts use this novel mechanism for event-driven applications. Moreover, none of them investigates an efficient controlled sink mobility pattern for data collection from event region. This research not only proposes an energy-efficient dual-sink algorithm with fuzzy sink mobility (EDAFSM) scheme for optimizing sink movement pattern, but also presents a role switching mechanism (EEDARS) for sink selection problem in event-driven wireless sensor networks. Furthermore, to achieve more energy efficiency, an optimized greedy forwarding method based on fuzzy logic is proposed to apply in EDAFSM and EEDARS. In this thesis, the optimized solutions are known as joint dual-sink and fuzzy-based geographic routing for more energy-efficiency in single-event (JDFGR-S) and multi-event (JDFGR-M) WSNs, respectively.

1.9 Organization of Thesis

The organization of this thesis is as follows: The Chapter 1 is an introduction to the thesis and identifying the research problems. Chapter 2 provides a literature review of the routing protocols accompany with several mechanisms for energy-efficiency in wireless sensor networks. These mechanisms include multiple static and mobile sink, hybrid techniques, and forwarding strategies. The operational framework of research methodology related to this research is presented in Chapter 3. Chapter 4 introduces the EEDARS algorithm including its implementation and performance analysis. Then, EDAFSM algorithm is discussed in Chapter 5. A fuzzy-based greedy forwarding for geographic routing is presented in Chapter 6. The integration of this forwarding scheme and proposed dual-sink algorithms is also presented in this chapter. Finally, Chapter 7 concludes the thesis and discusses the research limitations and future works.

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