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THREE DIMENSIONAL REAL-TIME GEOGRAPHICAL ROUTING PROTOCOLS FOR WIRELESS SENSOR NETWORKS

by

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Three Dimensional Real-Time Geographical Routing Protocols For Wireless Sensor Networks

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DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship Declaration

I hereby declare that this dissertation incorporates some materials part of which are results of joint researches. The investigations and evaluations done throughout this dissertation used some technologies that were developed in the WiCIP research laboratory. The investigations were supported by collaborative help from my colleagues in WiCIP LAB in the form of advice, critiques, and mentoring. This dissertation also incorporates the outcome of joint research undertaken in collaboration with Mehmmood A. Abd and Brajendra K. Singh, under the supervision of Professor Dr. Kemal E. Tepe. In all cases, the main ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-authors was primarily through the provision of suggestions, comments, critiques, verification and other supports. I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my dissertation, and have obtained written permission from each of the co-author(s) to include the above material(s) in my dissertation.

II. **Declaration of Previous Publication**

This dissertation includes three original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

Dissertation chapter	Publication title/full citation	Status
Part of Chapter 3 and 5	Sarab F. Al Rubeaai, Brajendra K. Singh, Mehmmood A. Abd, Kemal E. Tepe, *"Adaptive Packet Forwarding Region Based Three Dimensional Real-Time Geographical Routing Protocol (3DRTGP) for Wireless Sensor Networks*, Proceeding of IEEE Wireless Communication and Network Conference (WCNC), Istanbul, Turkey, 2014.,	Published
Part of Chapter 4	Sarab F. Majed Rubeaai, Brajendra K. Singh, Mehmmood A. Abd, Tepe, Kemal E., *"Region based three dimensional real-time routing protocol for wireless sensor networks"*, Proceeding of IEEE Sensors, vol., no., pp.1,4, 3-6 Nov. 2013.	Published
Part of Chapter 3 and 5	Sarab F. Al Rubeaai, Mehmmood A. Abd, Brajendra K. Singh, Kemal E. Tepe, *"3D Real-Time Routing Protocol with Tunable Parameters for Wireless Sensor Networks."*, IEEE Sensors journal.	Submitted

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ABSTRACT

One of the most important concerns in the operation of Wireless Sensor Network (WSN) is the real-time data delivery. This dissertation addresses the problem of real-time data delivery and void node problem in three dimensional WSN, which has a significant impact on the network performance. In order to provide an accurate route calculation for reliable data delivery the third coordinate of the location sensor nodes is considered in this dissertation. Additionally, two different heuristic solutions for void node problem in three dimensional space have been provided to elevate the effect of long route and spares regions on assurance of real-time data delivery.

In order to provide a wide applicable soft real-time routing protocol two decentralized geographical routings are proposed: Three Dimensional Real-Time Geographical Routing Protocol (3DRTGP) and Energy-Aware Real-Time Routing Protocol for Wireless Sensor Networks (EART). 3DRTGP and EART are designed to fit with WSNs that are deployed in 3D space. Both protocols benefit from utilizing the third coordinate of nodes' locations to achieve less packet end to end (E2E) delay and packet miss ratio.In 3DRTGP, void node problem in 3D space was solved based on adaptive packet forwarding (PFR) region. 3D-VNP solution solely was done locally and without any messaging overhead. In EART, 3D-VNP was solved based on an adaptive spherical forwarding wedge (SFW).

A network tunning parameters guide is presented to make the proposed protocols applicable and fit with a large number of networks in terms of network deployment and size. The effect of location errors on the network performance is also investigated. The protocols are evaluated analytically and experimentally under realistic simulation environment and the results show that combining real-time and solving 3D-VNP solution can enhance WSN performance. Moreover, considering nodes' energy in EART cooperated in extending the network lifetime. The results demonstrate that 3DRTGP enhanced the packet E2E delay by 40% to 90% and decreased the packet miss ratio by 5% to 60% in comparison with other competing geographical routing protocols (GRPs). The results also showed that EART extended the network lifetime by 25% to 88% more than other competing protocols.

DEDICATION

to my

MOTHER, FATHER, and CHILDREN

with love

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I would like to thank my advisor Dr. Kemal E. Tepe for introducing me to the research area of wireless sensor networks, for his help and support during all phases of this dissertation and mainly for the many fruitful discussions, which always inspired and motivated me. I appreciate the time and effort he dedicated to me and my work despite he has many other students who also need his support. He became a good friend and I hope this relationship will last after the end of this study period too.

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LIST OF ABBREVIATIONS

$2D$	Two dimensions.
$3D$	Three dimensions.
$2D - RGRP$	Two dimensional region based geographical routing protocol.
$3D - RGRP$	Three dimensional region based geographical routing protocol.
S	Sender sensor node.
β	Initial angle of conical forwarding region.
η	Number of sensor nodes in wireless sensor network (WSN).
η_s	Number of a sensor node in spherical transmission range.
η_s	Number of neighboring nodes in a node's transmission range.
γ	Forwarding probability parameter.
λ_s	Number of the sensor nodes in the spherical transmission range of any node.
$\|\overrightarrow{\mathrm{SD}}\|$	Euclidean vector norm of $\overrightarrow{SD}$.
$\|\overrightarrow{\mathrm{SN}}\|$	Euclidean vector norm of $\overrightarrow{SN}$.
$\|\overrightarrow{\mathrm{SO}}\|$	Euclidean vector norm of $\overrightarrow{SO}$.
$\overrightarrow{SA}$	Vector from sender S to the node A
$\overrightarrow{SD}$	Vector from sender node S to the destination node D.
$\overrightarrow{SN}$	Vector from sender node node S to any node N.
$\overrightarrow{SO}$	Vector from sender node S to the polar of the transmission range O.
ϕ	Angle of packet forwarding wedge.
ρ	Network density.

τ_{av}	Average velocity in node's neighborhood.
τ_h	the time required in each hop.
$\acute{\tau}_h$	Estimated required time in every hop.
τ_{pr}	Processing time of the packet in the forwarding node.
τ_{req}	Required time for a packet to reach the destination.
τ_p	Packet propagation time.
τ_q	Queuing delay in a node.
τ_t	Required time to transmit a packet.
θ	Angle between any two vectors.
τ_s^i	The hop delay for ith packet.
D	Destination sensor node.
(D_x, D_y, D_z)	Location coordinates of destination sensor node D.
E_{av}	Average energy in node's neighboring nodes in Joules.
E_{rx}	Receiving energy cost in Joule.
E_{tx}	Transmission energy cost in Joule.
E_0	Initial energy of a node in Joules.
E_n	Energy in potential forwarding node in Joules.
E_s	Expected energy in the node's neighborhood in Joules.
h	Expected number of hops.
N	Sensor node N.
(N_x, N_y, N_z)	Location coordinates of a node n.
O	Polar point of a node's transmission sphere.
P_τ	Delay metric of forwarding probability.
P_E	Energy metric of forwarding probability.
p	Forwarding probability.
q	Forwarding probability in EART.
r	Spherical radius of transmission range.
(S_x, S_y, S_z)	Location coordinates of a sender node S.
V	Volume of the deployment terrain.
V_{PFR}	Volume of the packet forwarding region (PFR).
V_s	Volume of spherical transmission region around the sender node.
2D-VNP	Void node problem in two dimensional space.
3DRTGP	Three dimensional real-time geographical routing protocol.
3D-VNP	Void node problem in three dimensional space.
BS	Base station.

GPS	Global positioning system.
GRP	Geographical routing protocol.
J	Joule.
m	Meter.
MANET	Mobile ad hoc networks.
PFN	Potential forwarding node.
PFR	Packet forwarding region.
QoS	Quality of service.
RTT	Round trip time.
SFW	Spherical forwarding wedge (SWF).
SFW	Spherical forwarding wedge.
VNP	Void node problem.
WSN	Wireless sensor network.
$(\overrightarrow{\mathrm{SN}} \bullet \overrightarrow{\mathrm{SD}})$	Dot product of $\overrightarrow{\mathrm{SN}}$ and $\overrightarrow{\mathrm{SD}}$.
τ_w	Time duration before retransmissions.
Q	Maximum number of retransmissions.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The impressive development of micro-sensor technology has enabled small and smart devices to provide new application opportunities with low power and low cost hardware. These smart devices are called sensor nodes which are equipped with different kinds of sensing, processing, storage, power source and wireless communication units. Many physical phenomena can be observed and monitored by deploying a large number of sensor nodes. These sensors can network wirelessely and collect data cooperatively about a physical environment and then route it to the base station (BS). BS is a more powerful node that has more processing, storage capacity, power source and acts as a gateway between sensor network and a special computer server. This group of connected sensor nodes is called wireless sensor network (WSN).

WSNs can be employed by many applications which require hundreds or even thousands of sensor nodes in remote and inaccessible areas. Current and future applications of WSNs entail real-time data gathering and delivery such as in smart grid monitoring, disaster control and operation, military applications, object tracking, environment monitoring, health care, home automation, industrial monitoring and surveillance.

Routing data from the nodes to BS, in WSNs, is a challenging task due to infrastructure-less communications and frequent topology changes. The main weaknesses of the WSNs are the limitations associated with storage capacity, bandwidth, communication range and power resources. This chapter discusses examples of some of WSN applications, challenges in WSNs, problem statement, and contributions of this dissertation.

1.1.1 Applications of wireless sensor networks (WSNs)

WSNs applications can vary from simple surveillance to very sophisticated applications. Some examples of sensor network applications are:

1. **Ocean monitoring applications:** These applications are mainly utilized to collect oceanographic data and monitor the creatures that live in the sea [1,2]. These types of applications enable scientists to take urgent action to deal with disasters such as the eruption of pollution as well as protect and study the habitats of sea animals.

2. **Industrial process monitoring and control applications:** These applications need to make an accurate and instant decision. Therefore each sensor node must have the ability of sensing and evaluating the usefulness of acquired information and send it to the control units. Then the control units take an action accordingly for operation and management. The primary properties of these applications are the high sensitivity of gathered data and unpredictable event occurrences which correlate with time and place. Sensing and monitoring nuclear reactors [3], traffic control [4], disaster relief applications [5], intrusion detection applications [6] and mining [7] are some examples of such time sensitive industrial monitoring applications.

3. **Health monitoring applications:** Monitoring patients with serious diseases such as heart disease, Parkinson's disease, and patient rehabilitating from strokes or heart attacks entail constant monitoring and urgent care. Therefore, these types of applications must be designed to alert nurses and doctors to provide in time care. The artificial retina [8], and Parkinson's disease [9] are two examples of WSN applications can be used in the health care system.

4. **Smart grid applications:** Smart grid applications provide reliable, effective, robust, and safe energy services by integrating communication and information technologies together. Hence, WSNs are utilized by many utility companies in their wireless and automatic control system to collect information about energy usage, which enable engineering staffs to understand the changes in demand and to act accordingly. Additionally, the engineering staffs use the collected information to rapidly isolate faults, restore power, maintain stability in power delivery and many other functions [10–12].

A brief discussion of WSN challenges will be presented in the following subsections.

1.1.2 Challenges in Wireless Sensor Network (WSNs)

WSN consists of very small sensor nodes with limited resources. These limited resources raise new challenges to design routing protocols for WSNs which differ from other regular routing protocols designed for other wireless communication systems. Some of these challenges are:

1. **Energy restriction:** Because operating wireless sensors depends on limited power resources such as batteries and capacitors, these have direct impact on the network lifetime. Therefore, balancing energy consumption is an important challenge and must be considered in designing a reliable routing protocol to extend the network lifetime and provide accurate data [13].

2. **Node deployment:** The deployment of sensor nodes is a fundamental issue that must be considered in order to achieve the required objective of the network. A proper node deployment can reduce the complexity of problems in WSNs, such as routing calculation and extending the lifetime of the sensor nodes [14]. Therefore, one important issue, in network deployment, is considering the third coordinate of sensor locations. Which can significantly enhance the routing accuracy and reduce the redundant transmission by limiting the participated node in forwarding [15–18].

3. **Mobility:** Usually wireless sensors are non stationary and the changes in their locations lead to frequent update in network topology. The frequent changes could cause problems such as route failure, high packet collision rate, and increased energy consumption. This change dramatically affects on the network performance and shorten its lifetime. Hence, network mobility must be considered in the routing protocol design [19, 20].

4. **Scalability:** Because a WSN consists of hundreds or even thousands of sensor nodes, the number of messages that must be routed to BS is very large. For this reason, any routing protocol must be designed to adapt to any changes in density and size of the network. Geographical routing is one of best options to design decentralized algorithms, which can satisfy the scalability requirements [15, 21].

5. **Fault tolerance:** WSNs are inherently subject to failure because of their low cost components and limitation of their energy supplies. That is why, a failure of one or set of sensor nodes should not affect the functionality or performance of the network. For this reason, a network must accommodate any failure and set a new reliable route to BS. In such case, sensor nodes must have the ability to find other routes with better resources and available energy [22, 23].

6. **Quality of services (QoS):** WSNs require various levels of quality of services (QoS) which depends on the type of the application. Because of the scarcity of

resources such as processing ability, memory, bandwidth, and power resources in each sensor node, QoS is a challenging task in WSNs [24]. For example, smart gird application entails minimum E2E delay to ensure fast responses from the corresponding authority. In contrast, ocean monitoring applications require accurate data and better energy usage to reduce the cost of maintenance and prolong the network lifetime [25–28].

7. **Security:** In wireless communication, routing traffic in the network make its subject to the security threats. For instance, shared wireless medium is vulnerable to the denial of service attacks. For this reason, WSNs requires special security solutions that work with their wireless communication and limited resources [29, 30].

8. **Real-time data delivery:** Delivering data in real-time has become essential for wireless sensor networks (WSNs) due to emerging time sensitive applications such as in smart grid, industrial control and process automation [28, 31–33].The advances in WSNs have led to a rapid development in time sensitive applications such as in smart grid [13], industrial control and process automation [34]. Therefore, designing a routing protocol that can satisfy the requirements of real-time operation is an important task.

The main objective of this dissertation is to design a real-time geographical routing protocols for WSNs deployed in three dimensional space. This dissertation provides real-time routing protocol to enhance the real-time data delivery. This objective is achieved by employing a decentralized, scalable and soft real-time geographical routing protocol (GRP) called 3DRTGRP and energy aware 3D geographical routing called (EART). Both routing protocols are designed to fit with networks that are deployed in 3D space and provide solution to the void node problem (VNP).

1.2 Problem Statement

This dissertation provides solution to the problems related with three dimensional (3D) geographical routing protocols (GRPs) to achieve soft real-time routing protocols. These problems are discussed hereunder:

Problem 1. Real-time requirement: Real-time applications require the packets to be delivered in real-time with maximal reliability and minimal overhead. Thus, it is important to design a 3D soft real-time geographical routing protocol that can satisfy the time sensitive requirements.

Problem 2. 3D network deployment: In real-life applications of WSNs, sensor nodes are deployed in a three dimensional (3D) space such as applications in ocean monitoring [16], forest fire sensing [24], mining [7] and unmanned aerial vehicle (UAV) networks [17]. However, the majority of GRPs consider two-dimensional (2D) coordinate system. Even if two dimensional GRPs can function in network deployed in 3D space, they do not utilize full potential of the network. For instance, in a dense network, there will be more packet forwarding than necessary, which causes packet collisions, congestions and premature energy depletions. Therefore, it is important to utilize three dimensional location information, in GRPs, for accurate operation, enhancing real-time data delivery, and increasing network lifetime.

Problem 3. Void node problem in 3D WSNs: Another problem that is associated with GRPs is the void node problem (VNP), where there is no forwarding node in the direction of the destination that can serve as a forwarder. This problem has been effectively solved in 2D GRPs using planar or face routing techniques, however, these techniques cannot be effectively applied to 3D GRPs. Therefore, routing protocols and avoiding the void region require further investigation in 3D space [35] and 3D VNP is still an open problem.

Problem 4. Redundant transmission problem in GRPs: GRPs usually depend on one of the following techniques to forward the traffic from source/relay nodes to the destination:

I. Region based forwarding (RBF): In this technique, a geographical routing relies on forwarding a packet to a set of nodes that is located in the same region. This causes more packet forwarding than necessary, which leads to packet collisions, congestions and missed deadlines, eventually causing the protocols to not meet the real-time requirements. For this reason, GRPs must have the ability to detect the congested region and dynamically change the forwarding region to avoid packet loss.

II. Greedy forwarding technique (GFT): In this technique packets are forwarded from source to destination along the shortest straight path between source and destination nodes. The nodes that are located on this path will be overused and depleted of their energy which causes traffic congestion and generates VNP. Both congestion and VNP lead to delay in packet delivery and most of them miss their required deadlines. For this reason, it is important to make a routing protocol with the property of congestion detection to avoid packet delay and VNP generation.

Problem 5. Node's energy: Discarding the energy of the nodes in the forwarding decision may result in selecting nodes with low available energy which causes a rapid network partitioning. Therefore, an energy aware property must be integrated in the forwarding decision to enhance the protocol's reliability and efficiency.

In this dissertation, the proposed protocols are designed on the basis of GRPs because the low network overhead. Because they do not rely on pre route discovery and do not require route maintenance. Additionally, GRPs can be implemented locally in each WSN, which simplifies the routing complexity and accelerates the routing decision. These positive characteristics of GRPs make them promising candidates for designing soft real-time routing protocols for 3D WSNs.

In this dissertation, two novel distributed soft real-time GRPs are proposed:

A. Three dimensional real-time geographical routing protocol (3DRTGP): This protocol is designed to achieve real-time data delivery in WSN deployed in 3D space.

B. Energy aware three dimensional real-time geographical routing protocol (EART): This protocol is an enhanced version of 3DRTGP designed to achieve soft real-time data delivery with energy aware property in WSN deployed in 3D space.

The protocols operations were verified through a set of extensive simulation experiments and analytical evaluations which confirmed their validity.

1.3 Contributions

The main contributions of this dissertation are stated hereunder:

1. A novel soft real-time geographical routing is proposed and evaluated analytically and through vigorous simulation, which is called:Three dimensional real-time geographical routing protocol (3DRTGP). This protocol was designed to decrease redundant transmission based on reducing the number of forwarding nodes in a conical forwarding region. This conical forwarding region was chosen based on the network density. Then, one forwarding node will be selected based on its queuing, processing delay and expected number of hops from source to the destination. 3DRTGP was compared to two

other competing GRPs in term of packet end-to-end (E2E) delay and packet delivery ratio.

2. 3DRTGP was extended to energy aware real-time geographical routing protocol which is called (EART). EART considers the energy of node in forwarding decision to provide more reliable data delivery and increase network lifetime. The network lifetime, packet delivery ratio, and average energy consumption per packet were further improved by incorporating node energy in forwarding metric. The results showed that 3DRTGP has successfully met the soft real-time requirements.
3. Both 3DRTGP and EART protocols heuristically solved VNP in 3D deployments (3D-VNP) without explicit or implicit exchange of neighboring information. This solution significantly reduces the network overhead, which in turn enable the protocols to meet the real-time requirement. 3D-VNP solution was extensively and successfully evaluated through a set of experiments under different network conditions and deployments, which clearly showed that 3D-VNP was completely solved. It is demonstrated that the 3DRTGP resolved VNP given that there is no network partitioning.
4. Tuning techniques for 3DRTGP is provided to make the protocol meet the delay and the miss ratio requirements of applications. For example, a low miss ratio requirement of an application can be met by adjusting network density. Functionality of the proposed tuning technique was verified through extensive simulation studies and network performance was evaluated against the competing protocols.

In summary, the routing protocol frameworks designed in this dissertation not only support the WSNs real-time quality of services requirements, but also reduce energy consumption in sensor nodes and provide high reliability (delivery rate).

1.4 Research Methodology

The problems that are discussed in 1.2 are deeply investigated and solved throughout this dissertation. In this dissertation, WSNs conditions, deployment and routing protocols that are commonly used in WSNs were studied and it is found that designing a decentralized routing protocol can enhance the real-time data delivery and extend the network lifetime. Moreover, investigating the network deployment in real-life shows that discarding third coordinates of sensor locations has significant impact on the protocol performance in terms of data delivery, energy consumption and packet miss ratio. The heuristic solution for 3D-VNP was proven through extensive experiments. This heuristic solution allows the proposed protocol to have a reliable operation in the event of having void regions.

The objectives of the research have achieved throughout the following steps:

Step I. In this phase, the effect of discarding third coordinates of sensor nodes on the routing performance have been investigated. 3DRTGP algorithm is implemented and tested in OMNeT++, and its reliability was proven.

Step II. In this phase, the protocol in Step I was enhanced by solving VNP in 3D network deployment. The new version of this enhanced protocol was investigated in OMNeT++ to prove its reliability.

Step III. In this phase, 3DRTGP was evaluated based on analytical analysis and compared with other two state-of-art three dimensional geographical routing protocols: ABLAR [36] and 3D-Greedy. This routing protocol was designed to adapt with WSNs deployed in 3D space and is applicable to any network topology with different network conditions.

Step IV. In this step, 3DRTGP was further enhanced and the energy in sensor nodes were considered in forwarding decision. This enhanced version protocol is called: Energy aware three dimensional real-time routing protocol (EART). EART's reliability and efficiency was investigated in OMNeT++ and evaluated by comparing the network lifetime and the packet delivery ratio against 3DRTGP.

1.5 Dissertation Organization

A background and literature review is given in Chapter 2. Chapter 3 identifies the solution for data propagation protocol and presents the results of three dimensional real time geographical routing protocol for wireless sensor network (3DRTGP). Chapter 4 describes the design of Energy aware three dimensional real-time routing protocol (EART). The evaluation details of the proposed protocols are presented in Chapter 5. In Chapter 6, the conclusions of the proposed research in this dissertation is summarized and some recommendations for future work are presented.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

The primary objective of routing protocols is to discover available routes from any given sensor node to the destination through multi-hops or single hops and to make routing decisions. The task of routing establishment is the main responsibility of the network layer in the hierarchy of the communication protocol stack. WSNs usually are infrastructureless and are comprised of a large number of sensors which produce a very large amount of data. Hence, a multi-hop routing approach is necessary for a WSN to permit channel utilization in various regions of the network and overcome the effects of long distance communication [37]. Moreover, wireless sensors are usually deployed randomly, which makes the network topology unpredictable. Therefore, sensor nodes must have the ability to coordinate and learn their location as well as neighboring node locations. Additionally, routing protocols must be designed with the properties that adapt to topological changes and fits with the limited resources of WSN.

In WSNs, the collected data about a phenomena must be delivered at the right time to a controlling authority. For this reason, a routing protocol with real-time data delivery properties is important. Routing reliability has a significant influence on packet E2E delay, packet delivery ratio, energy consumption per packet and network lifetime. This chapter presents the WSN routing protocols metrics, routing protocol categories, void node problem (VNP), real-time routing protocols, and related work.

2.2 Wireless Sensor Network Routing Metrics

The efficiency of WSNs routing protocols is usually measured using a set of evaluation metrics. These metrics are used to ensure that the evaluated protocol can efficiently cope with the limited resources of sensor nodes. This section presents an overview of some metrics related to this study:

A. **End-to-End Delay:** E2E delay is the total delay for each packet from the source to reach the destination. The concept of E2E delay metric is to evaluate the protocol efficiency in term of meeting the real-time requirements. The primary goal of this metric is to evaluate the performance of routing protocol under time restriction requirements [36, 38].

B. **Packet miss ratio:** Packet miss ratio is defined as the ratio between the number of packets that do not meet their deadlines to the total number of transmitted packets [39, 40]. This metric is mainly used to evaluate the network performance and protocols reliability in time sensitive applications.

C. **Average energy consumption per packet:** The term energy consumption per packet refers to the total energy consumed in each sensor node for each packet successfully delivered to the destination node [35, 41]. For better energy usage in WSN the average consumption per packet must be minimized. This metric is essential in the assessment of protocol efficiency in terms of energy usage.

D. **Network lifetime:** Network lifetime metric is an essential metric in evaluating the reliability of the protocol in terms of energy usage in the network and extending its lifetime. It is defined as the time of the network before any sensor node runs out of energy or becomes inoperative [42, 43].

2.3 Routing Protocol Categorizes

In literature, a large number of routing protocols have been proposed to solve multi-hop routing problem [44]. Some of the most common routing protocols include: geographical routing protocols (GRPs) and topological routing protocols (TRPs).

2.3.1 Geographical routing protocol:

GRPs rely on the location information to propagate the data from a given sensor node to the BS or sink. GRPs have gained popularity in WSNs because of their low overhead, low operation complexity, and smaller E2E delay than TRPs. GRPs do not require route maintenance and discovery schemes like TRPs; therefore they can handle dynamic changes in the network much better than TRPs. The main weakness of GRPs is their dependence on the location information. However, this deficiency can be resolved using location services such as Global Positioning Systems (GPS), radio ranging [45, 46], and other localization techniques [18, 47]. In general, GRPs can be classified into two dimensional GRPs (2D-GRPs) and three dimensional GRPs (3D-GRPs):

A. **Two dimensional geographical routing:** In 2D-GRPs, the sensor nodes are assumed to be deployed on flat surface. That means the third coordinate of sensor locations are discarded in this kind of protocols and all sensors are projected on a surface [44, 48]. This assumption is justified for applications where sensor nodes are deployed on ground or where the hight of the network is smaller than the transmission range of sensors [14, 15].

B. **Three dimensional geographical routing:** In real-life applications of WSNs, sensor nodes are deployed in a three dimensional (3D) space such as, application in ocean monitoring [16, 49], forest fire sensing [24], mining [7] and unmanned aerial vehicle (UAV) networks [17,50]. For such applications, GRPs must utilize three dimensional location information for accurate operation. Even if two dimensional GRPs can function in 3D space, they do not utilize the full potential of the network. For instance, in a dense network, there will be more packet forwarding than necessary, which causes packet collisions, congestions and premature energy depletions. Experimental results presented in [51–53] demonstrate that excluding the third dimension from GRPs can significantly reduce reliability of the protocols.

2.3.2 Topological routing protocol:

TRPs count on routing table construction in every sensor node. Routing table contains all possible routes from any given node to the BS. Constructing such routing tables entail a large amount of exchanging beaconing messages, which incur WSN more energy and time delay. Exchanging messages dramatically affects the network performance and causes congestion and collision. For this reason, topological routings are not scalable to the frequent changes in network. For this reason, topological routing approach can not be acceptable solution for time sensitive applications [21].

2.4 Void Node Problem

Void node problem (VNP) occurs where there is no forwarding node in the direction of the destination. VNP can be observed due to reasons such as sparse network, node failure or region congestion [15, 54]. VNP has a significant effect on decreasing packet delivery ratio. This is either because packets are dropped or take long detour and miss their deadlines before they reach to the destination. This problem has been effectively solved in 2D GRPs by using planar techniques or facing routing algorithms, however, these techniques cannot be applied to an network that is deployed in 3D space. Routing paths and avoiding the void region need further investigation in 3D space [55] and VNP is still an open problem. In this dissertation, a heuristic solution for 3D-VNP will be provided in the next chapters.

2.5 Real-time Routing Protocols

There are large number of real-time applications [12, 34, 56] that entail data packets to be delivered within limited time with minimal overhead and high reliability. There are two classes of real-time routings: hard real-time and soft real-time routing protocols.

2.5.1 Hard real-time routing protocols

In this class of real-time routing approach, the arrival of the packets after their deadlines are considered failure of the routing protocol [57] and such packets are discarded. The objective of hard real-time protocols is to ensure that all packets meet their deadlines. Nuclear systems [3] and seismic applications [58] are examples of hard real-time applications.

2.5.2 Soft real-time routing protocols

In this class of real-time routing, the deadlines of the packets are probabilistic and the delay of the packet is tolerable [32, 33]. The main goal of these protocols is to optimize some application specific criteria. For example, maximizing the packet delivery ratio, maximizing the number of packets that meet their deadlines and average energy consumption per packet. In this dissertation, soft real time routing protocols are considered.

It should be noted that energy efficiency must not be ignored while considering the real-time support [27, 37].

2.6 Energy Aware Real-time Protocols

Since sensor nodes are usually equipped with limited power supply such as a battery they pose a big challenge for network designers in vicious environments like a battlefield, where it is infeasible to replace or recharge their power supplies frequently. Furthermore, when the energy of a sensor drains, the sensor will become inoperative and will not be able to function properly, which will have a major effect on the network performance. Main objective of energy aware routing protocols is to deliver data packets within their E2E deadlines, while optimizing the energy usage in the network [31, 59–61]. Ignoring the energy in sensor usually leads to over utilization of some sensors which can cause VNP [62]. Thus, a routing protocol should consider the nodes with better available energy and low delay to provide timely and reliable data delivery, and extend the network lifetime. In this dissertation, EART is designed based on combining energy aware and real-time concepts in one geographical routing protocol.

2.7 Related Work

The research work in this dissertation is related to the real-time data delivery in 3D-WSNs and 3D-VNP. The related work throughout this dissertation focuses on real-time algorithms and energy aware real-time algorithms with VNP solution.

2.7.1 Review of Real-Time Protocols

Real-time routing in WSNs is gaining popularity because a large numbers of applications are demanding time critical information for monitoring and control. GRPs with their inherent properties offer low control overhead and operation complexity which can help in lowering delay compared to their topological routing counterparts [14, 20, 49, 63]. The real-time GRPs proposed in the literature, such as [20, 39], neglect the third dimension. Neglecting third dimension reduces the protocol accuracy in estimating delay because 3D network deployment projection into 2D coordinate systems eliminates alternative routes and increases the number of participating nodes in packet forwarding [51–53]. There are many scenarios where application demands 3D operation and the third dimension must be utilized. Some applications include UAV networks [64] and underwater acoustic communications [53, 65]. In addition to that, some available real-time GRPs depend on neighborhood information exchange to estimate the number of important parameters such as distance to the destination [38], end-to-end (E2E) delay [19], link quality and energy availability [39]. Incorporating these parameters in protocols increase the control overhead in the form of acknowledgment and beacon messages [63]. Protocols proposed in [38, 61] use the information exchange to identify which particular node is going to be the next forwarder. If this forwarder cannot transmit for a number of reasons, then the reliability and real-time operation of the protocols are compromised. Selecting a PFR instead of one forwarding node in 3DRTGP and coupling this with VNP solution make the proposed protocol reliable while maintaining forwarding efficiency. In [66], reliability of the SPEED protocol [38] is improved by exploiting the multi-path routing. Although the multi-path routing offers better reliability, it increases the interference and collision.

ABLAR [36] is one of the prominent 3D GRPs that uses restricted flooding mechanism in which packets are forwarded to a specific region that consists of the source and destination nodes. In ABLAR, formation of these regions does not depend on network density. Thus, the number of nodes participating in forwarding increases the risk of collisions, which decrease reliability. Another option to provide routing for 3D deployed WSN is the 3D Greedy routing proposed in [36]. However, both ABLAR and 3D Greedy do not provide a solution for the 3D VNP problem. Although there are solutions for 2D VNP such as face routing and planar graph, they are not applicable for 3D VNP [67]. 3DRTGP is designed to provide a real-time and reliable operation in 3D WSNs. Real-time operation is achieved by eliminating control messaging by using adaptive PFR mechanism and selecting nodes in this PFR which are more capable to meet the delay deadlines. Reliability is provided by solving 3D VNP heuristically.

2.7.2 Review of Energy Aware Real-Time Protocols

The diversity of time sensitive applications of WSN motivated many researchers to design routing protocols with real-time properties [38, 66]. However, the energy in nodes was discarded in these protocols, which has dramatic impact on the protocols reliability in term of preserving energy and timely reporting events. This is because, nodes with low energy can not transmit and generate energy hole problems [35]. Recently, various techniques have been used to design power aware routing algorithms such as using sleeping mode scheduling [68], transmission power adjustment [69], and multi path routing techniques [21, 70]. Nevertheless, in all of these techniques the necessity of timely reporting events was ignored.

On the other hand, real-time routing approach with power aware property forwards a packet toward the destination over a set of predefined routes are presented in [25, 43]. These approaches having high network overhead and consider the global energy of the route in their forwarding metrics. Hence, global route energy metric usually fails to satisfy the real-time delivery because it ignores the energy in the individual nodes and node with low energy can not deliver the packets within their deadlines [21].

GRPs have been considered to design real-time and power aware routing protocols due to their low network overhead. For example, a real-time routing protocol with load distribution (RTLD) was proposed in [39] and real-time power aware greedy based approach was proposed in [28]. In fact, both of approaches in [39] and [28] depend on periodical exchange of neighbor information and are designed based on the assumption that WSN is deployed in 2D space. Assuming that WSNs always deployed in 2D space is not valid assumption because in real-life they are deployed in 3D terrain. Therefore, using 2D routing protocol in 3D WSN results in route error calculation. This route mis calculation can degrades the network performance. The studies in [51–53, 71] showed that discarding third coordinate of sensor nodes has significant impact of routing performance in terms of data delivery and energy consumption. Moreover, discarding the solution of VNP in real-time routing increases the routing length and more packets will miss their deadlines. Therefore, in order to solve VNP some researchers tried to used 2D VNP solution for 3D VNP for example, greedy face greedy is used in [72] by mapping 3D network to 2D network. Hence, greedy face greedy solution discards the third coordinate of sensor nodes and it does not provide accurate solution to 3D-VNP. In this dissertation, two different heuristic solutions are presented to solve VNP in 3D WSN.

2.8 Summary

This chapter discusses Wireless sensor network routing metrics, routing protocol categories, Void node problem, real-time routing protocols,Energy Aware Real-time Protocols, and related work. It is shown that designing a soft real-time routing protocol based on geographical routing approach can provide a better data delivery than routing protocol based on topological approach. An overview of real-time routing protocols were provided. Related work of real-time routing protocols and power aware real-time protocols with void node problem solution are presented in the following chapters.

CHAPTER 3

THREE DIMENSIONAL REAL-TIME GEOGRAPHICAL ROUTING PROTOCOL (3DRTGP)

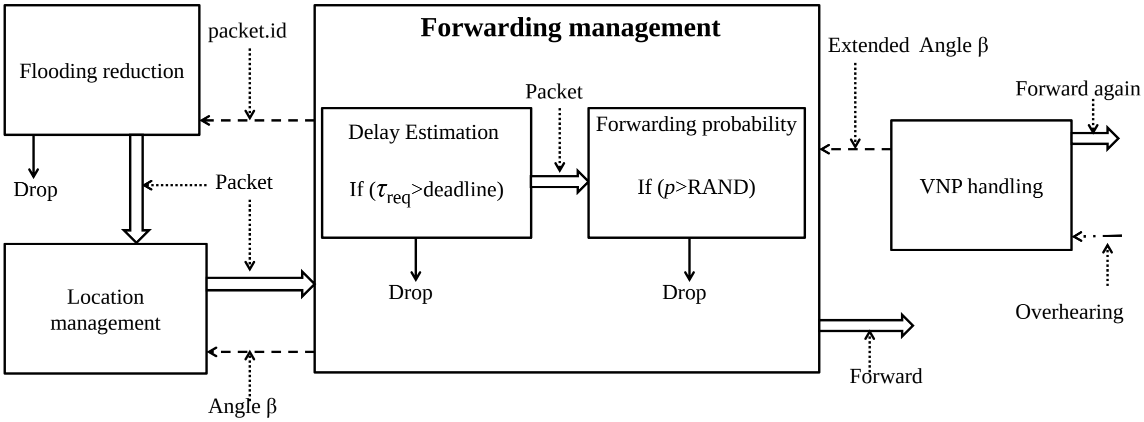
3.1 Introduction

Delivering data in real-time has become essential for wireless sensor networks (WSNs) due to emerging time sensitive applications such as in smart grid, industrial control and process automation. Geographical routing protocols (GRPs) are promising candidates in fulfilling such real-time requirements because they can handle dynamic changes in the network far better than topological routing protocols, which in turn enable GRPs to maintain the delay deadlines effectively [15,44]. Another significant advantage of GRPs is lower network overhead as compared to topological routing protocols since GRPs do not require route discovery and maintenance procedures. The main weakness of GRPs seems to be their dependence on accurate location determination. However, this deficiency can be resolved using location services such as Global Positioning Systems (GPS), radio ranging, and other localization techniques [18,45,73,74].

In real-life WSN applications, sensor nodes are deployed in three-dimensional (3D) space, but the majority of GRPs consider a two-dimensional (2D) coordinate system. This exclusion of the third dimension from routing interferes with the effectiveness of GRPs, which has prompted 3D GRP proposals [52,71]. However, existing 3D GRPs are not designed to support real-time data transfer and do not provide a viable solution to the 3D void node problem (VNP) [15]. This problem has significant impact on the network performance, VNP occurs when the packet arrives at a node that does not have any neighbor that can forward the packet to the destination [32].

The contribution of this chapter is twofold. Firstly, the 3D real-time geographical routing protocol (3DRTGP) is proposed for 3D deployed WSNs, which provides a soft real-time capability. The real-time operation is achieved by the protocol using an adaptive conical packet forwarding region (PFR) and selecting fast forwarding nodes in the PFR. The PFR limits the number of forwarding nodes in the direction of the destination, which reduces channel contention and congestion caused by unnecessary forwarding. Adjusting the forwarding probability of the nodes based on their queue length improves the delay experienced by packets and allows the protocol to provide delay guarantees. Secondly, an effective heuristic solution for the VNP in 3D WSNs is provided. This solution allows the proposed protocol to have a reliable operation in the event of having void regions.

Functionality of the proposed protocol was demonstrated by extensive simulation studies and network performance was evaluated against the competing protocols. Based on evaluations, the proposed protocol is a viable and reliable option for 3D geographical routing in WSNs for a number of time critical applications. With these contributions, the proposed protocol can be employed in WSNs, which are taking a large role in a number of important applications related to smart grid [75], Internet of things [76], machine to machine communications [77] and flying ad hoc networks [78]. This chapter contains 3DRTGP



packet.id: Packet sequence number, τ_{req}: required time , ***p***: Probability, **RAND** : Random number [0,1]

Figure 3.1. Functional diagram of 3DRTGP.

protocol description in Section 3.2. Results and discussion are presented in Section 3.3, and the summarization of this chapter is given in Section 3.4.

3.2 3DRTGP PROTOCOL DESIGN

In the design of this protocol, it is assumed that a WSN consists of η number of uniformly randomly distributed homogeneous nodes. These nodes are stationary and are deployed in a 3D volume of V. It is assumed that the transmission range is r and is radiating spherically. 3DRTGP, being a GRP, assumes that every node knows its own location, and the source nodes know the location of their destination node. In most WSN deployments, the destination (or base station) node is located in a predefined position and this location information can be preprogrammed to all sensors.

One of the objectives of the proposed protocol is to form an adaptive optimal conical PFR. Forming this PFR captures the essence of using the third dimension. With an optimum PFR, the number of forwarding nodes will be reduced and forwarding will be restricted to a smaller volume, which reduces congestion and ultimately helps the protocol to meet delay deadlines.

The other objective of this protocol is to solve 3D-VNP, which is a common problem in GRPs. Providing a heuristic solution to 3D-VNP significantly enhances the reliability of the proposed protocol. Another important feature of 3DRTGP is that nodes do not rely on neighbors' information, which significantly decreases the protocol control overhead. All functions of a receiver and sender node are described in the flowchart given in Fig. 3.2 and Fig. 3.3.

Based on the receiver flowchart in Fig. 3.2, when a node receives a packet, it checks if this packet was transmitted by itself before. If the packet was transmitted before or its deadline has expired, the node drops the packet. Otherwise the node progresses on the flowchart and checks if it is in the PFR. If the node is in the PFR, then it becomes a potential sender. If the previously overheard packet was received again, the node extends the PFR and checks if it is in the newly extended PFR and if it can be a potential sender. When a node becomes a potential sender, it follows the sender's flowchart of the protocol as given in Fig. 3.3. The first process in the sender node is to calculate if the node can meet the delay requirements of the packet. If the node meets this requirement, it forwards the packet; otherwise it drops it. Fig. 3.1 illustrates the functional diagram of 3DRTGP and these functions are given as follows:

A. Location management.

B. Forwarding management.

C. VNP handling.

D. Flooding reduction.

The forwarding management function decides if the node forwards the packet or not according to its forwarding matrices. The location management function determines whether the node is located in the PFR or not. VNP handling is responsible for identifying if the node experiences a void region and activates the VNP handling algorithm to divert the traffic to an alternative PFR. VNP can be also experienced if the nodes in the PFR are congested and cannot meet the packet deadline. For this reason, VNP handling is important in selecting alternative routes to meet the delay deadlines necessary for real-time operation. The flooding reduction function identifies if the received packet has already been broadcast or not. Descriptions of these functions are provided in the following subsections.

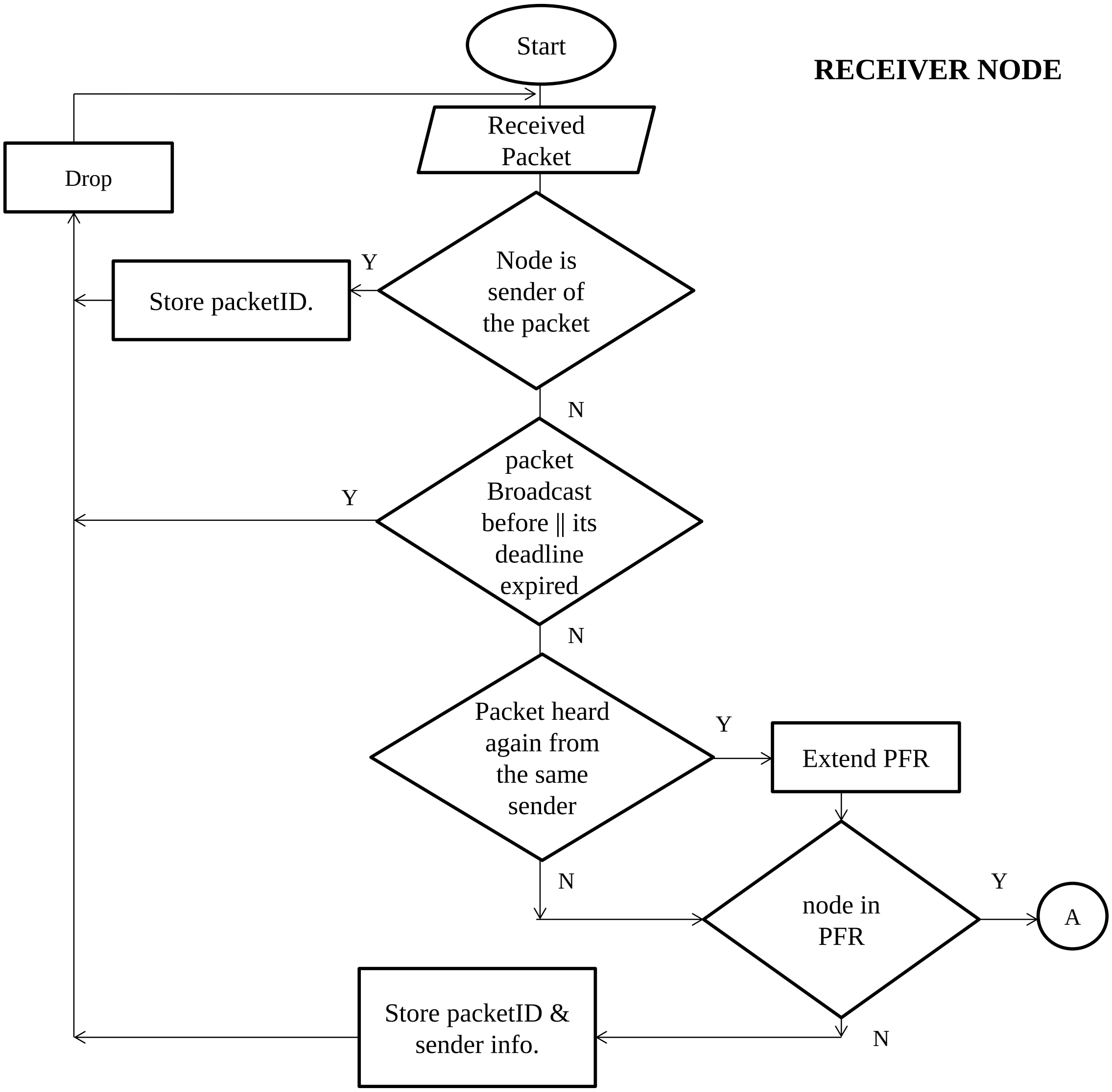


Figure 3.2. 3DRTGP process flowchart: Receiver node operation.

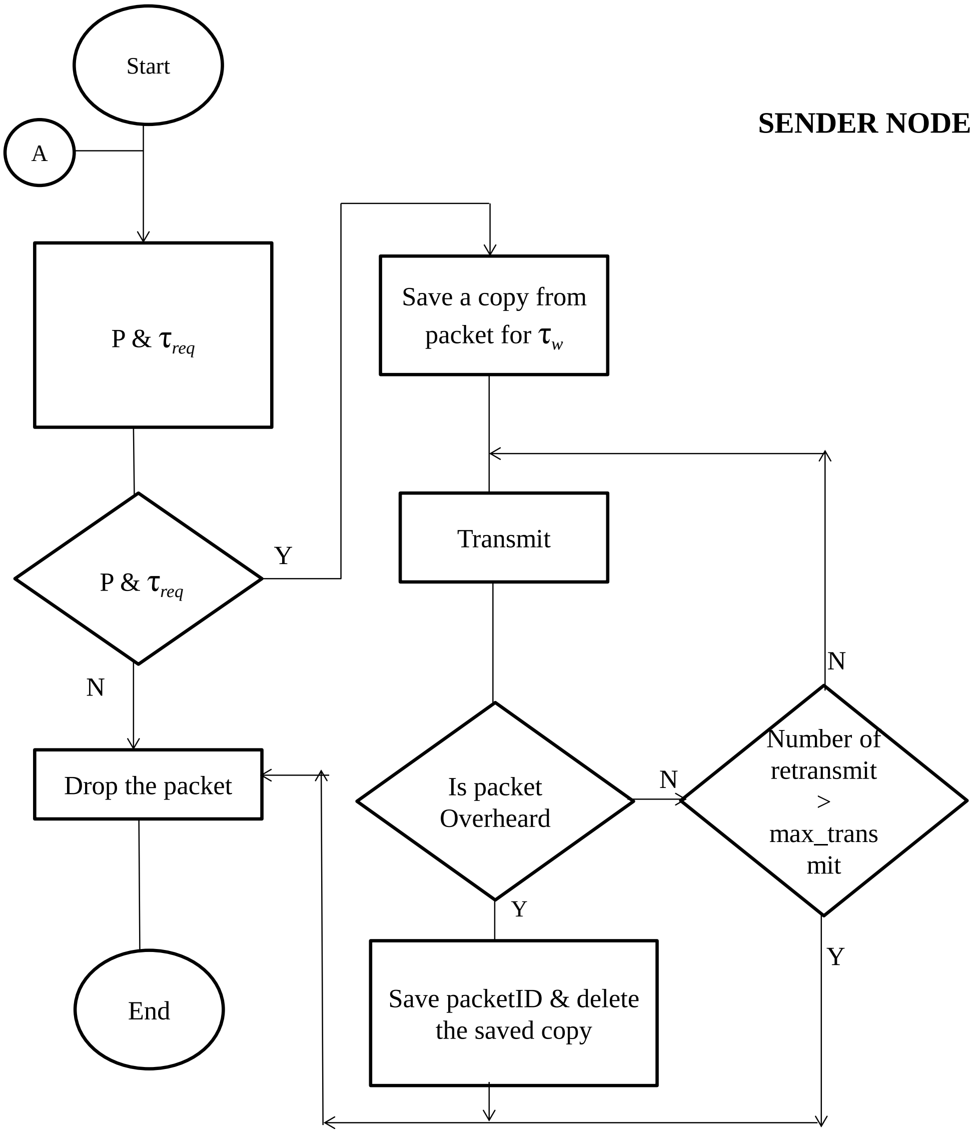


Figure 3.3. 3DRTGP process flowchart: Sender node operation.

3.2.1 Location Management

The function of location management is to identify a PFR where the packet can be forwarded. Nodes that are located inside the PFR are considered as potential forwarding nodes. In order to mimic the behavior of a unicast transmission, the PFR should be as small as possible and should ideally contain one forwarding node. On the other hand, the PFR should be large enough to have at least one forwarding node to ensure successful forwarding. The location management function receives packets that have never been broadcasted before and checks the node's location, (N_x, N_y, N_z), with respect to the sender's location (S_x, S_y, S_z) and the destination's location (D_x, D_y, D_z). In order to identify if a node is located in the PFR, it calculates the angle, θ, between two vectors and uses this angle as a measurement criteria to determine if the node is in the PFR or not. These two vectors are: *a*) the vector from the sender to the destination, $\overrightarrow{\mathrm{SD}}$ and *b*) the vector from the sender to the node itself, $\overrightarrow{\mathrm{SN}}$. Where $\overrightarrow{\mathrm{SD}}$ is given by, $(S_x - D_x, S_y - D_y, S_z - D_z)$ and $\overrightarrow{\mathrm{SN}}$ is given by $(S_x - N_x, S_y - N_y, S_z - N_z)$. The sender's location is provided by the packet and the destination location is preprogrammed to all nodes. Then, the angle, θ, is computed as follows,

$$\theta = \cos^{-1}\left[\frac{\overrightarrow{\mathrm{SN}} \bullet \overrightarrow{\mathrm{SD}}}{\|\overrightarrow{\mathrm{SN}}\| \cdot \|\overrightarrow{\mathrm{SD}}\|}\right], \tag{3.1}$$

where $\|\overrightarrow{\mathrm{SN}}\|$ and $\|\overrightarrow{\mathrm{SD}}\|$ are Euclidean vector norms and $(\overrightarrow{\mathrm{SN}} \bullet \overrightarrow{\mathrm{SD}})$ is the dot product of $\overrightarrow{\mathrm{SN}}$ and $\overrightarrow{\mathrm{SD}}$. In a potential forwarding node, θ must satisfy the following inequality,

$$\theta \leq \frac{\beta}{2}, \tag{3.2}$$

where β is the conical forwarding angle. The angle, β, of a PFR is inversely proportional to the network density $\rho = \frac{\eta}{V}$. In order to ensure that there is one node in the PFR, an intuitive initial value of β is $\frac{360}{\eta_s}$ degrees, where η_s is given by $\rho \times V_s$, with V_s being the volume of spherical transmission region around the sender with radius r. All nodes are preprogrammed with this initial value of β at the time of deployment. If the node experiences a VNP after sending the packet, it retransmits the packet. This retransmission indicates that the PFR does not contain a forwarding node, which signals a void region. Then the nodes outside the initial PFR, receiving this retransmission increase their β adaptively and evaluate if they can be forwarders for this packet. The VNP handling subsection will provide more details about this process.

3.2.2 Forwarding probabilistic mechanism

The forwarding probabilistic mechanism consists of two components: delay estimation and forwarding probability. Delay estimation ensures that the packets meet their delivery deadlines. Forwarding probability increases the chance of forwarding the packet by less congested nodes.

3.2.2.1 Delay Estimation

The node estimates the packet's latency to reach the destination if it is participating in forwarding. This estimated latency,τ_{req}, depends on the expected number of hops, h, between the forwarding node, N, and the destination node, D, as well as the time required in each hop, τ_h. The expected number of hops, h, is given by $\frac{\|\overrightarrow{\mathrm{SD}}\|}{r}$. The total time that is required in each hop, τ_h, for packet transmission can be calculated as $(\tau_p + \tau_{pr} + \tau_q + \tau_t)$, where τ_p is the packet propagation time in the medium, τ_{pr} is the processing time of the packet in the forwarding node, τ_t is the time required to transmit the packet from the forwarding node, and τ_q is the queuing delay in the forwarding node. Here, τ_p can be ignored for RF signals. Thus, the estimated required time in a hop without the queuing delay, $\acute{\tau_h}$, can be expressed as $(\tau_p + \tau_{pr} + \tau_t)$. Hence, the τ_{req} for a data packet to reach the destination node from the forwarding node N is given by,

$$\tau_{req} = (\tau_p + \tau_{pr} + \tau_t) + (h \times \acute{\tau_h}). \tag{3.3}$$

The first term, $(\tau_p + \tau_{pr} + \tau_t)$, represents the estimated packet delay in the forwarding node at the time of the decision. The second term, $(h \times \acute{\tau_h})$, represents the estimated packet delay in the next h hops towards the destination. Ignoring the queuing delay of later hops offers a lower bound for the delay. If τ_{req} in (3.3) is less than the available time margin provided in the packet deadline, the node becomes a potential forwarding node. Hence, the packet has a better chance to be delivered on time. However, the protocol must choose the best forwarding candidate, thus the forwarding probability of nodes are utilized to select the best forwarding node in the PFR. This node selection is explained in the following subsection. If all the nodes in the PFR of a sender do not transmit the packet, then the sender will realize that the nodes in the PFR either cannot meet the delivery deadline or the PFR experiences a VNP. Both scenarios are dealt in a manner similar to the VNP handling subsection.

3.2.2.2 Forwarding Management

If a node located in the PFR finds that it can deliver the packet within the packet delivery deadline, then it becomes a potential forwarder. However, if there is more than one forwarder in a PFR, the protocol should identify which potential forwarder is better to utilize on average. That is why forwarding decisions will also be made based on forwarding probability. Forwarding probability reflects the the queuing delay of the potential forwarders. This probability depends on the average of one hop delay, τ_{av}, of m previously transmitted packets. The average delay is calculated by a sender and provided to the next forwarding nodes with the packet. The sender measures the one hop delay as the time between transmission and overhearing. Hence the average delay is given by,

$$\tau_{av} = \frac{\sum_{i=1}^{m} \tau_s^i}{m}, \tag{3.4}$$

where τ_s^i is the hop delay for ith packet measured by the sender. Then the forwarding probability, p, in possible forwarding nodes is given by,

$$p = \begin{cases} 1 - \frac{(\tau_{pr}+\tau_q+\tau_t)}{\tau_{av}} & \text{if } (\tau_{pr} + \tau_q + \tau_t) < \tau_{av}, \\ 0 & \text{otherwise.} \end{cases} \tag{3.5}$$

Hence, based on (3.5) a higher queuing delay will result in a lower probability of packet forwarding. Nodes make their forwarding decision based on p. If no nodes transmit the packet, the sender retransmits the packet, which alerts nodes outside of the previous PFR to participate in the next round by increasing their β. The adjustment of β is done locally and is explained in the following subsection.

3.2.3 VNP Handling

VNP is defined by a packet that reaches a node that has no next hop neighbor which can serve as a forwarding node. VNP can occur when a network is sparse or there are no nodes available because of battery depletion, or as in our case, the nodes cannot deliver the packet within their deadlines. The probability of experiencing VNP is a critical parameter for the protocols performance as it

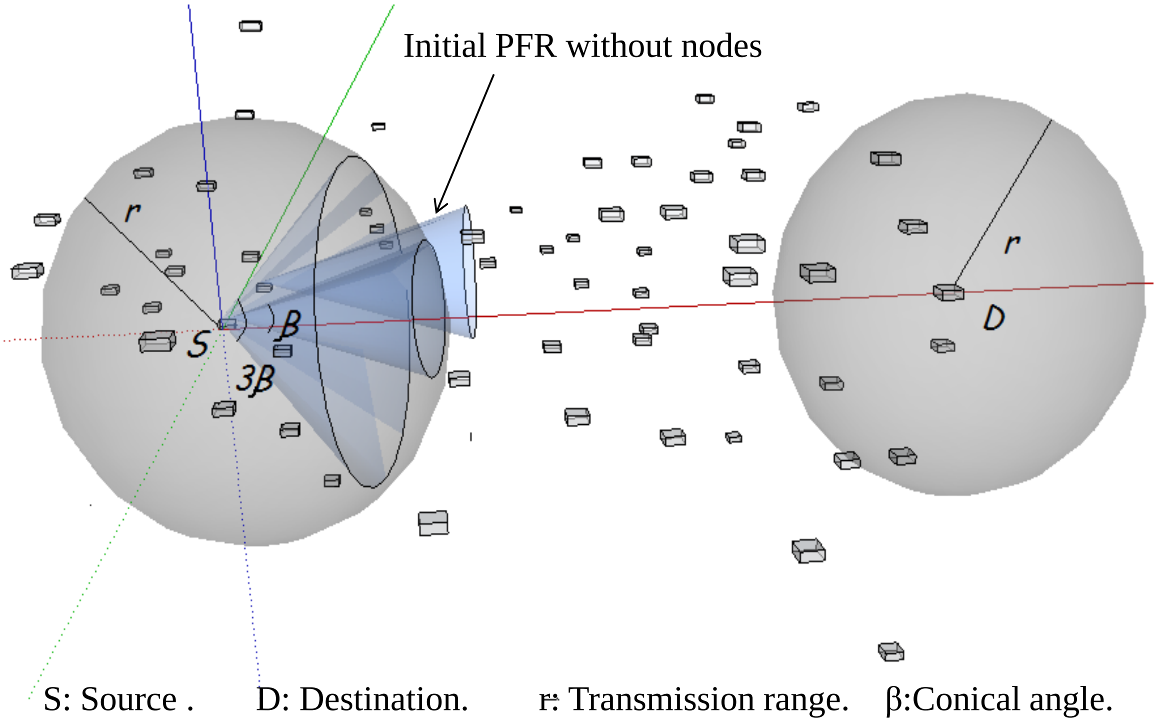


Figure 3.4. PFR with and without nodes.

raises the packet miss ratio, particularly for real-time applications. In general, VNP does not occur if there is at least one node in the PFR. The probability of having no node in the PFR is denoted by q, for a given β, is as follows,

$$q = \frac{V_{PFR}}{V_s}, \tag{3.6}$$

where V_{PFR} is the volume of the PFR, which is given by $[(\frac{2}{3}) \times \pi \times r^3 \times [1 - (\frac{1}{2}) \cos(\beta) \times \sin^2(\beta)]]$, V_s is the spherical transmission volume of a sender whose radius of transmission range is r and η_s is the average number of nodes in V_s. Fig. 3.5 shows the probability of having a void node, q in (3.6) and the probability of experiencing VNP in the simulation scenarios with different network deployments. These results provide significant information about how often 3DRTGP may experience void regions. Thus, VNP handling is very impor-

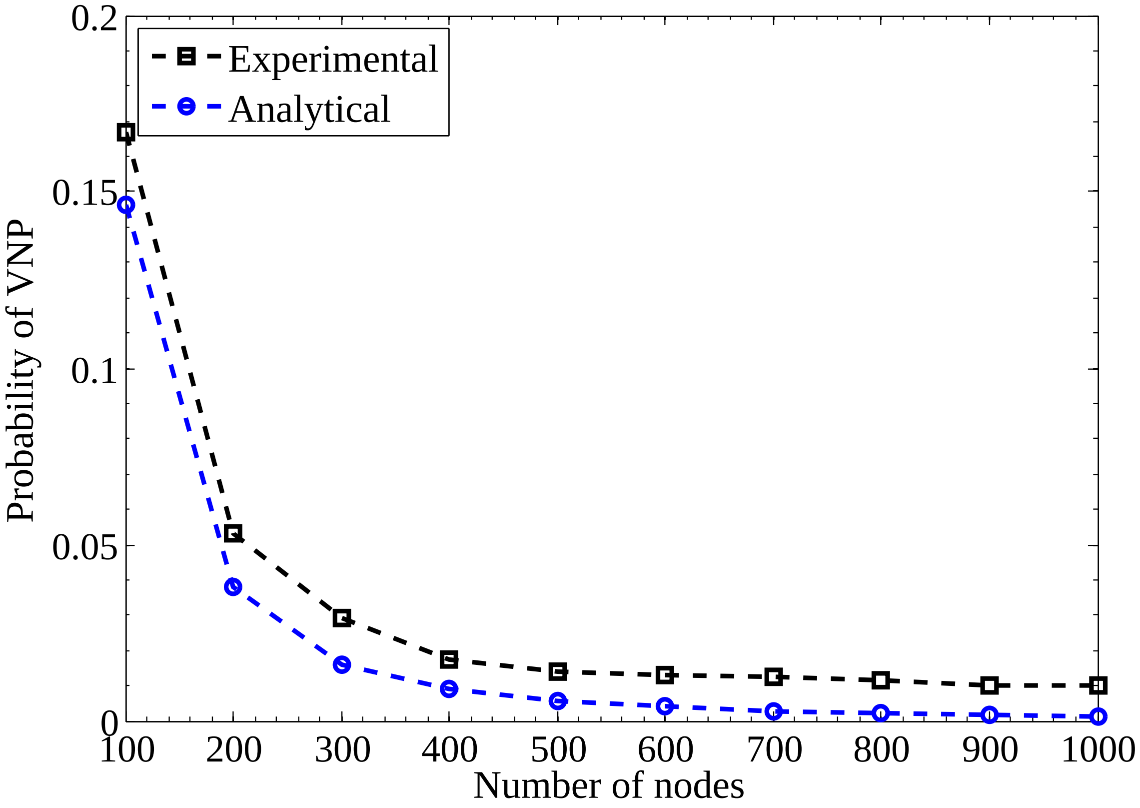


Figure 3.5. Probability of VNP: analytical and experimental calculated based on 3.1.

tant in 3DRTGP to provide reliable data delivery. The VNP handling function is triggered when a sender does not overhear the transmitted packet within a predefined waiting time, τ_w. The packet may not be forwarded because of the following two cases: *a*) the PFR does not have any node or *b*) nodes in the PFR are congested and cannot meet the delivery criteria. If there is a VNP, the sender has to rebroadcast the same packet. This time, the nodes that overhear this rebroadcast will double their β and check whether they are now located inside the newly formed PFR. This process will enable a new set of nodes in this wider PFR to participate in packet forwarding. Such PFR adaptation is done locally at each node and β is set to this new value at the nodes throughout the operation. If there is still no forwarding after this rebroadcast, then the sender waits for another τ_w duration before rebroadcasting again and the

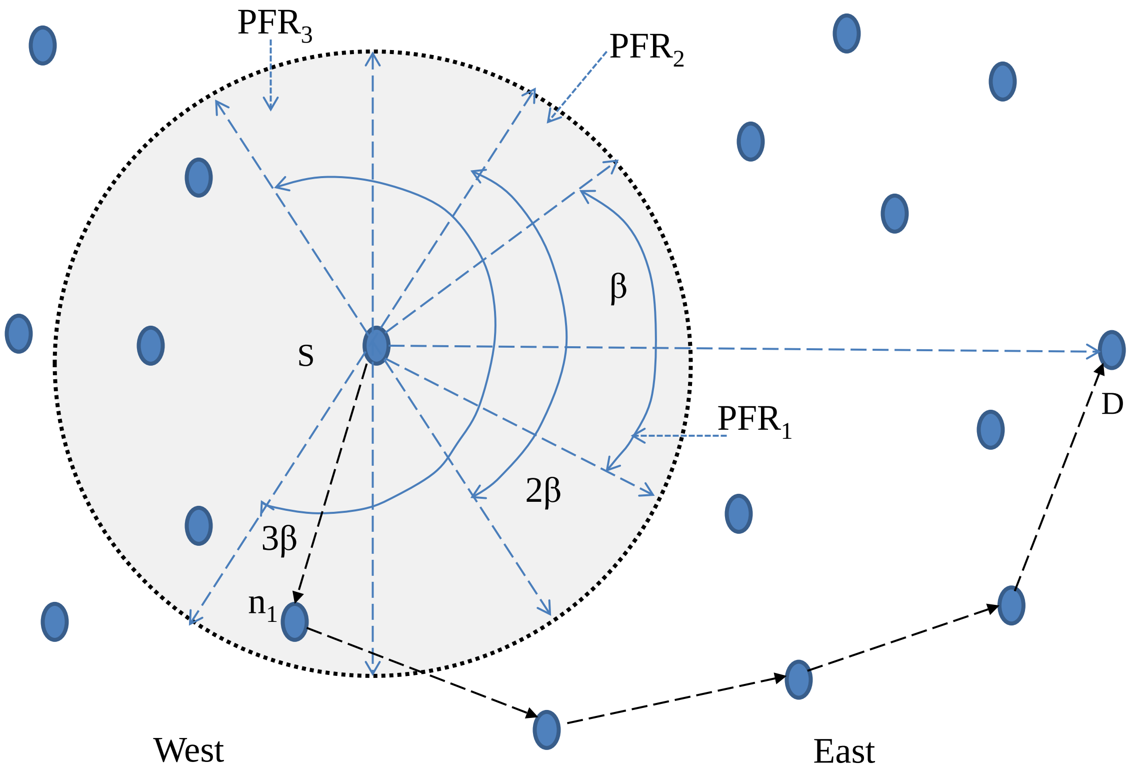


Figure 3.6. Illustration of VNP in 2D.

receiving nodes will extend their PFR to be even wider. This adaptive process continues until the packet is forwarded successfully by a forwarding node and resolves VNP as long as there is no network partitioning around the sender in the network. If β becomes large enough to contain the previous hop sender, then the previous hop sender assumes responsibility for the packet transmission. Fig. 3.6 illustrate the process of VNP handling in 2D.

The possible maximum number of retransmissions of a packet by a node, Q, can be given by,

$$Q = \lceil \frac{\log(360) - \log(\beta)}{\log(2)} \rceil, \tag{3.7}$$

where, $2^Q \times \beta < 360$. Equation (3.7) provides number attempts made by a node to recover from a VNP and this number is finite.

The PFR adaptation process is illustrated in Fig. 3.4 where the PFR with initial β has no forwarding node and thus, the node encounters the VNP. The PFR with 4β encompasses more than one node, which solves the VNP in the network. The process of increasing β in each node also helps to deal with congestion by exploring new forwarding nodes in a wider region.

3.2.4 Flooding Reduction

Flooding reduction is important to reduce the amount of retransmissions in WSNs and ad hoc networks. Generally, in protocols based on flooding there is an implosion due to the transmission of duplicated packets by many neighboring nodes. Such indiscriminate forwarding can cause collisions, congestion and battery depletion in WSNs [14]. In order to avoid this problem, the sender drops the previously broadcast packets by itself. Dropping the packets that have already been broadcast prevents packet looping.

3.3 RESULTS AND DISCUSSION

OMNeT++ discrete event network simulator with MIXIM framework [79] has been used to evaluate the performance of the proposed 3DRTGP protocol. In order to conduct a reliable performance analysis, a convergecast traffic pattern has been implemented with constant bit rate traffic. Simulation parameters while obtaining the results are given in Table 3.1. In order to evaluate the timing performance of the protocol under different traffic loads and network conditions, E2E delay and miss ratio are measured. E2E delay is the time taken for a packet to reach from the source to the destination node. In addition to E2E delay, miss ratio needs to be provided for real-time protocols to analyze

Table 3.1. SIMULATION PARAMETERS

Parameter	*Value*
MAC	IEEE802.15.4
Prorogation model	Log-normal Shadowing
Shadowing deviation (dB)	2.5
Data packet size	32 bytes
Terrain (*width*, *depth*, *height*)	500m, 500m, 200m
Number of nodes	100 to 1000 (randomly distributed)
Bandwidth	200Kb/s
Radio range	100m

the timing and reliability of the proposed protocol. Miss ratio is defined as the ratio between the number of packets that do not meet the deadline to the total number of transmitted packets. Each experiment was repeated 10 times with different network deployments to have statistically consistent results. The performance of 3DRTGP protocol is compared with ABLAR and 3D Greedy GRP. ABLAR uses a restricted forwarding region scheme to limit the number of forwarding nodes, which is in a sense similar to 3DRTGP. 3D Greedy is one of the commonly used baseline 3D GRPs for comparison. In our simulations, ABLAR is used with a greedy forwarding mechanism and 3 forwarding nodes in the transmission range of a sender. The simulation duration is five seconds for all the experiments. In the simulation studies, data packets are generated by a source node with a deadline of 250 milliseconds. This deadline was calculated based on our experiment where the average number of hopes is 7 and the average processing time in each hop is 0.014. We allow 0.150s in case if there is VNPs.

3.3.1 E2E packet delay performance

E2E delay is commonly used to measure the timing performance of real-time protocols. In this experiment, the average E2E delay in 3DRTGP was compared

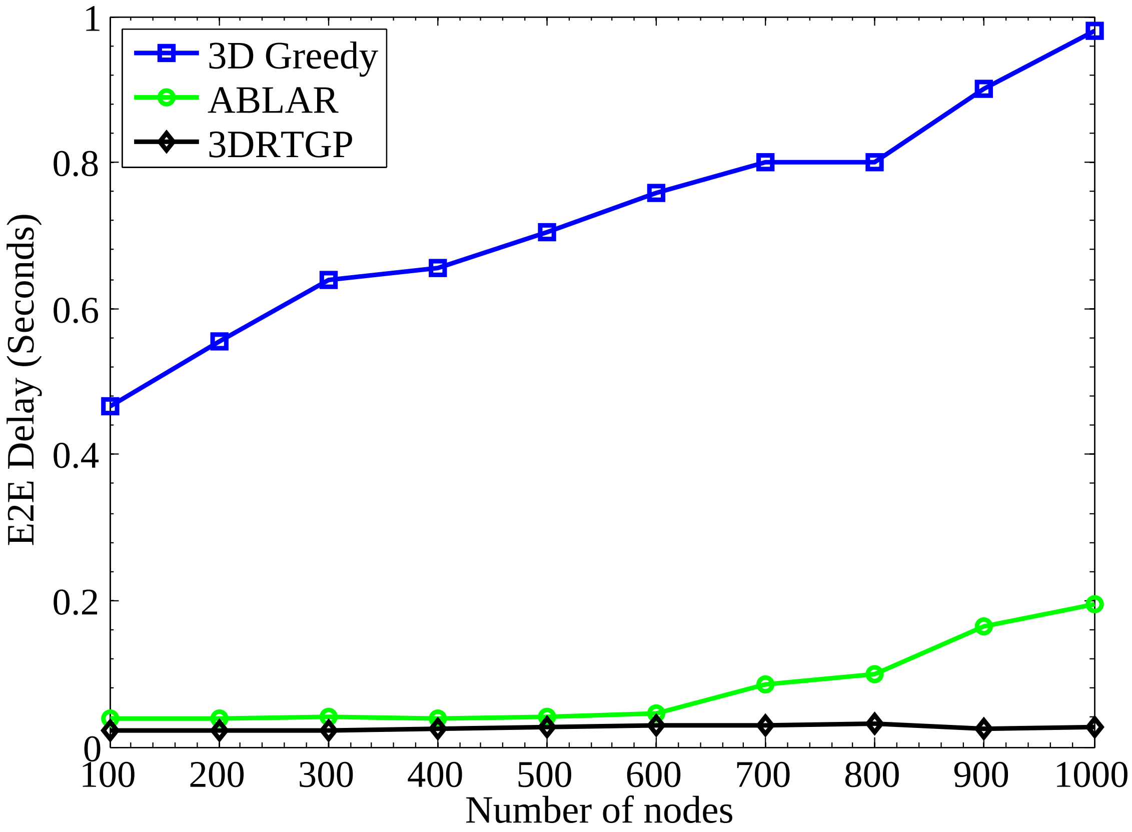


Figure 3.7. E2E packet delay versus number of nodes.

with ABLAR and 3D greedy. Fig. 3.7 presents the simulation results related to average E2E delay under different number of deployed nodes. However, the packet generation rate was kept constant at two packets per second. From this figure, we observe that E2E delay of 3DRTGP is better than other two protocols by 2% to 90% and do not decline with growing number of nodes. On the other hand, 3D Greedy performed the worst and ABLAR performed slightly worse than 3DRTGP until the number of nodes reaches 600, then its performance significantly suffered and deviated from 3DRTGP. The reason for consistent and better E2E is an indication of the effectiveness of adaptive PFR selection mechanism in 3DGRTP which decreases the number of forwarding nodes. However, ABLAR and 3D Greedy does not adapt well to the changing

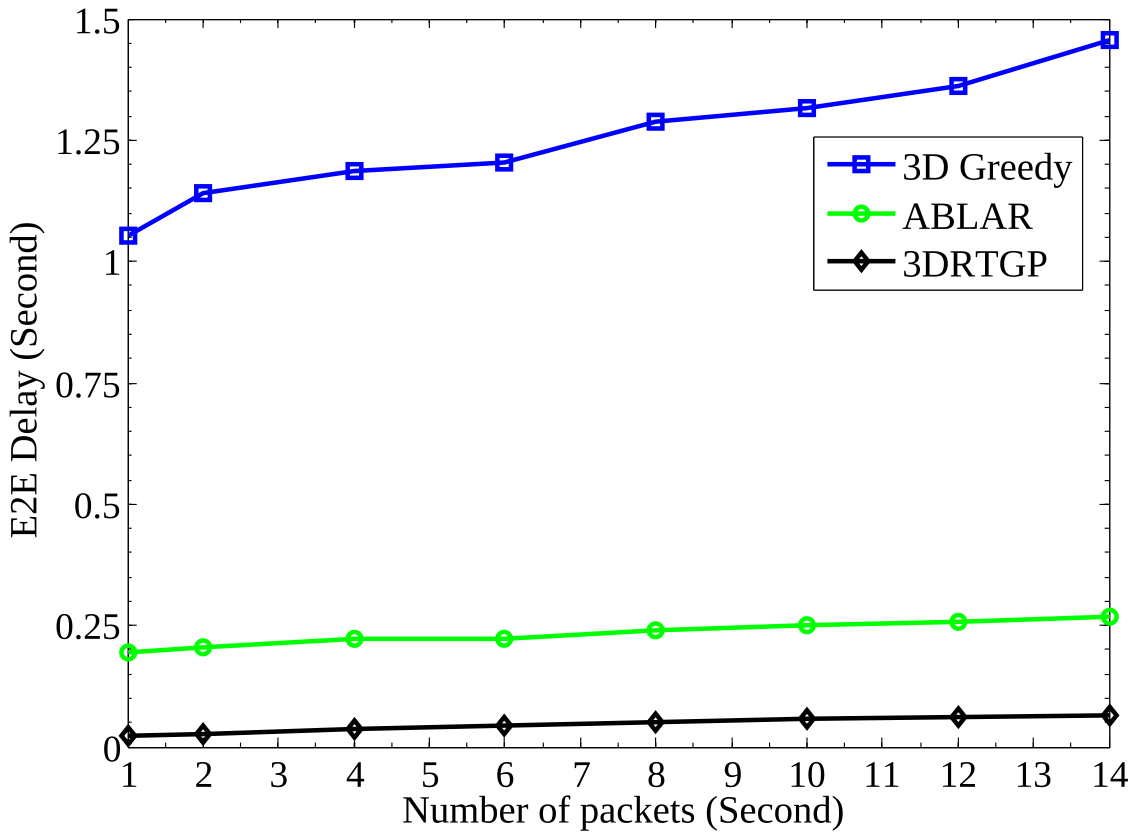


Figure 3.8. E2E packet delay versus traffic load.

number of nodes in the network, hence performing worse than the proposed protocol. This result indicates that 3DRTGP is scalable by adapting to the variation to network densities.

3.3.2 E2E packet delay with traffic load

These experiments were done to test the delay performance of the protocols under different network loads. The prime objective is to evaluate congestion avoidance capability of 3DRTGP. The network consists of 1000 nodes with four source nodes. Fig. 3.8 depicts one of the simulation performances of these experiments. The comparison shows that 3DRTGP outperforms 3D Greedy and

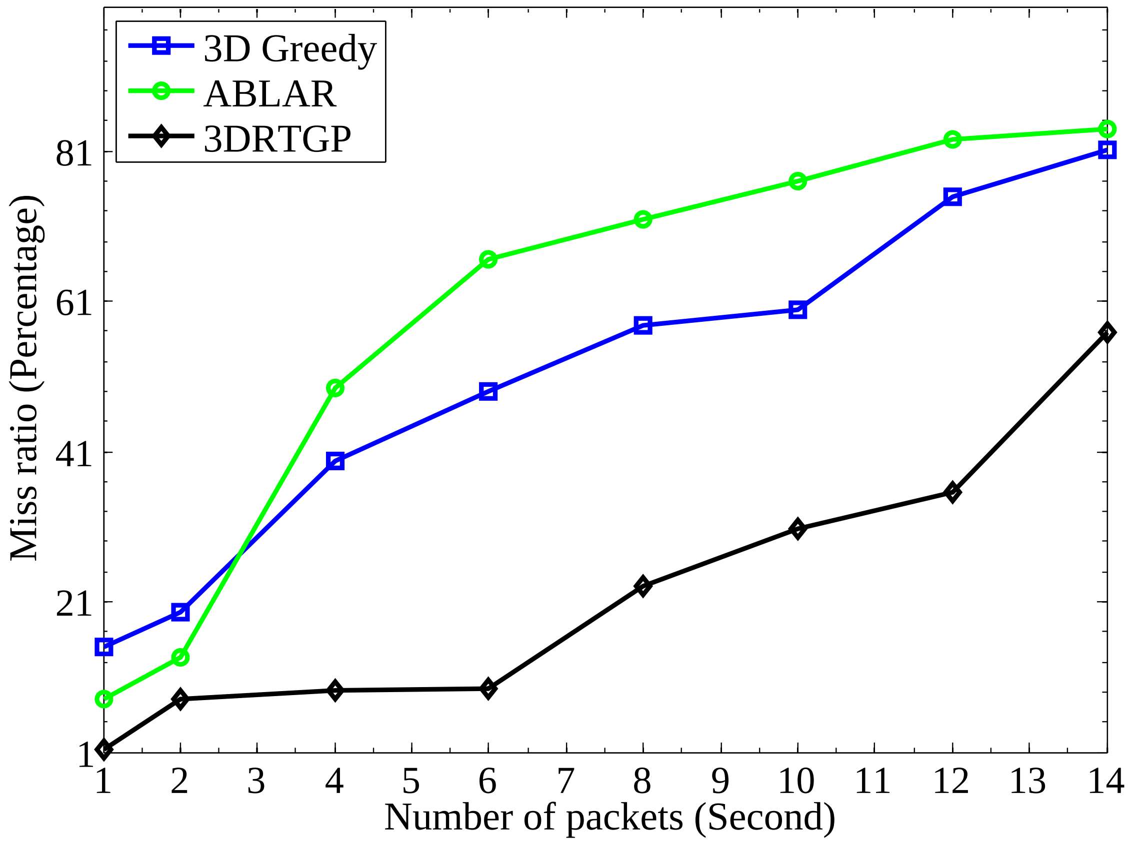


Figure 3.9. Packet miss ratio versus traffic load.

ABLAR by 40% to 90% because a potential forwarding node in 3DRTGP protocol considers the congestion by observing its queuing delay in its forwarding decision. By integrating queuing delay in packet forwarding probability, the packet will be directed to the less congested nodes.

3.3.3 Packet miss ratio with traffic load

Since miss ratio is an important parameter for any real-time protocol, experiments were performed to assess the real-time capabilities of the proposed protocol. Fig. 3.9 presents results of one of the experiment that compares miss ratio of 3DRTGP with other competing protocols. To test the impact of net-

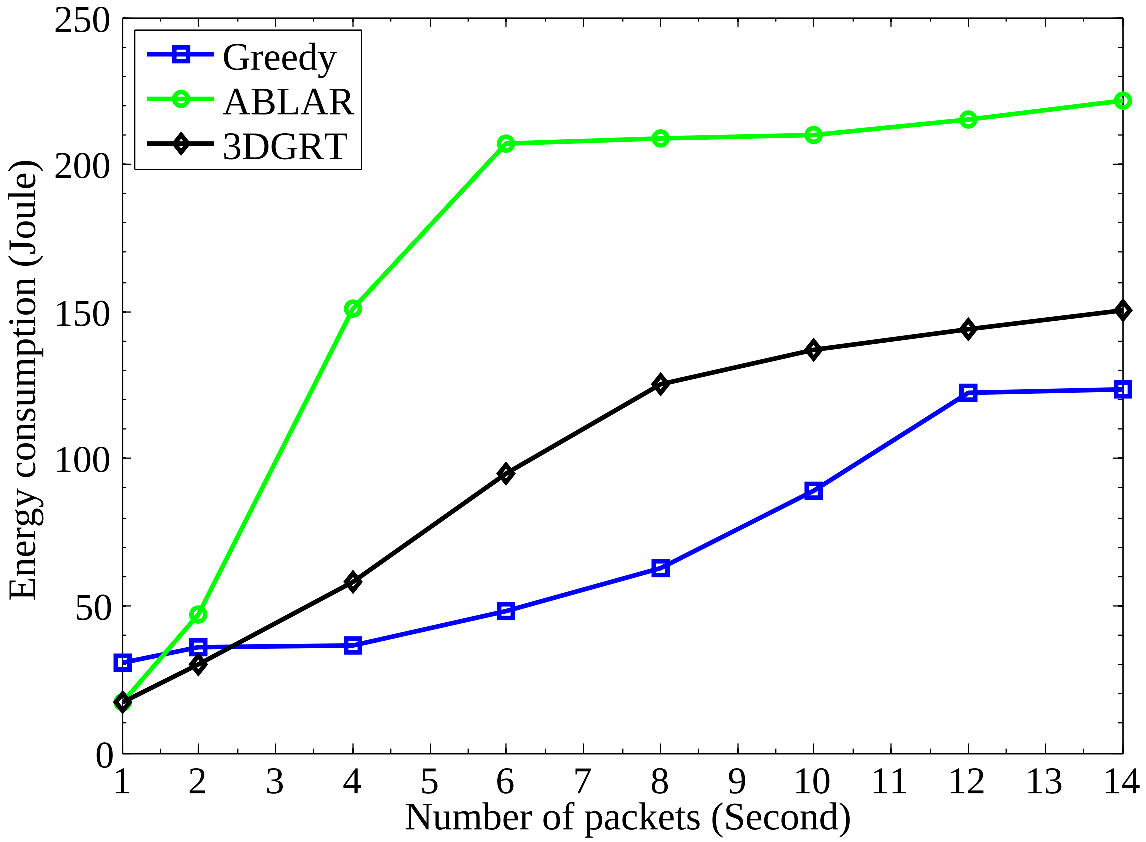


Figure 3.10. Energy consumption per packet versus traffic load.

work load on the miss ratio, the packet generation of four source nodes was varied while the number of nodes was fixed to 1000. In all the scenarios, while 3DRTGP provided the least miss ratio among all the protocols by 5% to 60%, the other protocols have a high miss ratio at low and moderate packet generation rates.In one scenario, where there was a large number of nodes and the traffic load was up to six packets per second, 3DRTGP performed better and was stable. However, the miss ratio in 3DRTGP is increased gradually with traffic load of seven or more packets per second but its performance is better than competing protocols. The better performance of 3DRTGP is attributed to the VNP handling mechanism, which allows the protocol to find alternative routes in case of congestion.

3.3.4 Energy per packet with traffic load

Although the objective of the 3DRTGP design is to provide real-time operation, energy per packet consumption is also of primary concern for WSNs. This is why we also compared the energy consumption of 3DRTGP with competing protocols. Fig. 3.10 shows that the energy consumption of 3DRTGP compared to competing protocols, ABLAR and 3D Greedy, with the same energy model. In general, 3DRTGP reduces energy consumption because it does not require beacon messages to collect neighbors' information. In our simulation study, it is observed that 3DRTGP consumes 31% less energy per packet than ABLAR and 26% more energy than the 3D Greedy protocol for a WSN with 1000 nodes. However, 3D Greedy has a much worse miss ratio during the same simulation studies.

3.4 Summary

In this part of the dissertation, it has been shown that it is possible to provide real-time capability to a 3D geographical routing protocols by controlling the number of forwarding nodes in the one hop transmission range of a sender. Additionally, it was found that the heuristic based approach can solve void node problem in WSN that is deployed in 3D space, which resulted in the 3DRTGP protocol presented in this chapter. 3DRTGP provides soft real-time guarantees with property of handling void node problem. The simulation studies show that 3DRTGP has a better E2E delay performance compared to competing protocols, namely ABLAR and 3D Greedy GRP. The proposed protocol provides 10 to 50% lower packet miss ratio than the 3D Greedy GRP and 5 to 60% lower than competing protocol ABLAR. 3DRTGP provides real-time operation without sacrificing energy consumption performance in WSNs.

CHAPTER 4

ENERGY-AWARE REAL-TIME ROUTING PROTOCOL FOR WIRELESS SENSOR NETWORKS

4.1 Introduction

Energy aware and real-time communications are critical issues in WSNs. This is because wireless sensors have limitations in terms of power supply, memory, and processing ability. Real-time communication is very important in many of WSNs applications. For example, in seismic monitoring [58] and fire fighting applications [5], appropriate actions must be made immediately as delay may cause devastating damage. In order to have such critical detected data to be delivered instantly and accurately, the energy in sensor nodes must be taken into account in routing decision.

Discarding the node's energy metric in real-time routing decision may cause repetitive selection of the same sensors. This repetitive selection leads to rapid network partition, generate void regions, and causes unreliable data delivery [35]. Moreover, ignoring the delay metric in sensor node in routing decision may force the transmitted packets to take a longer detour to reach their destination, which violates the real-time requirements [41, 62]. For these reasons both metrics must be considered to meet the time sensitive requirements and delay network partitioning.

In literature, power aware and real-time routings rely on the global information of network [21, 31, 60]. This sort of topological routings is inefficient because sensor nodes have to periodically update their routing tables. This periodical update increases the packet latency, network overhead and energy depletion. Fortunately, GRPs have low overhead as they do not require periodical route discovery or route maintenance [21, 44]. These characteristics make GRPs a good choice for designing a real-time protocol with power aware property.

However, one of the common assumptions is that WSN is deployed in 2D terrain [71]. This assumption does not fit with the actual real-life applications, which entail the network to be deployed in 3D space. Recent studies in [51,53,71] show that discarding third coordinate results in errors in finding a reliable route, increases energy depletion, and increases packet E2E delay due to overhead and redundant transmission.

In this chapter, the work in Chapter 3 is extended to design a real-time and power-aware routing protocol. This protocol is called: Energy-Aware Real-Time Routing Protocol for Wireless Sensor Networks (EART). This protocol is designed to provide a data delivery guarantee with a minimum energy usage based packet forwarding mechanism in form of spherical forwarding wedge (SFW). Therefore, the queuing delay in the potential forwarding node (PFN) and energy are an integrated in the protocol forwarding metric. The main contributions of in this work are:

1. Ensuring real-time data delivery.
2. Extending network lifetime.
3. Solving VNP in 3D WSN in a novel way.
4. Minimizing the networks overhead.

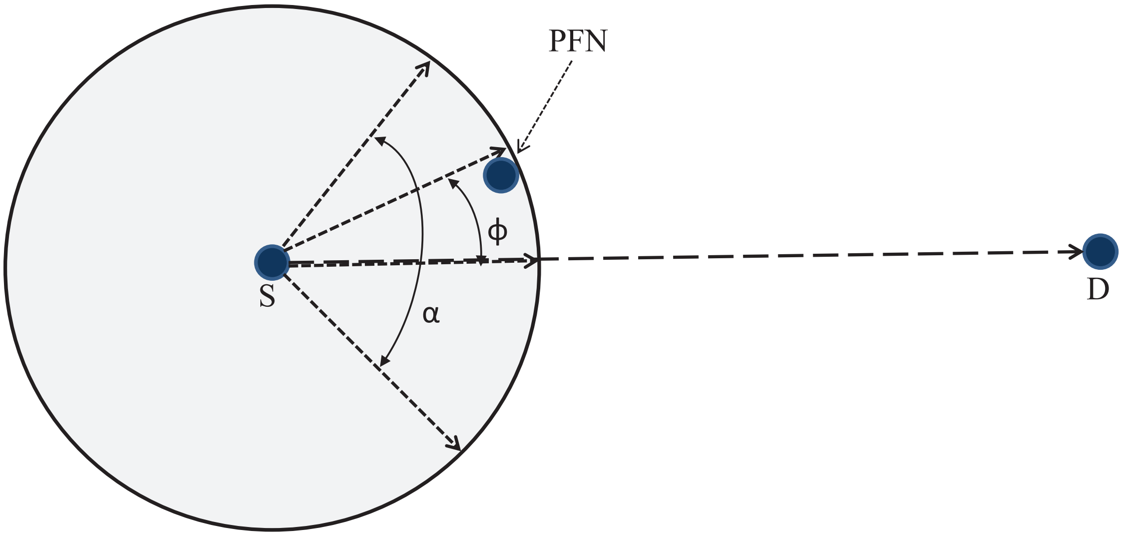


Figure 4.1. 2D projection of SFW, α, and, ϕ.

The rest of the chapter is organized as follows: Section 4.2 presents the problem statement and EART design. Section 4.3 states the results and discussions of the simulation experiments and Section 4.4 summarizes the chapter.

4.2 PROTOCOL DESIGN

A stationary WSN of, η, homogeneous sensor nodes deployed in three dimensional (3D) terrain of volume V is considered. It is assumed that every node can acquire its location information, (N_x, N_y, N_z), through an embedded GPS or any location service [18, 47]. At the deployment time all nodes are programmed to learn the destination's location, (D_x, D_y, D_z) and the network density, ρ. Nodes have the same, initial energy of E_0 Joules and spherical transmission range of, r. Every node can act as source to sense and report events, or relay to forward the reports of other nodes to the destination. The energy-aware and real-time protocol (EART) is designed to meet the real-time requirements and ensures that the network can operate for a long time. This protocol consists of three phases:

1. The first phase is spherical forwarding wedge (SFW) mechanism.
2. The second phase is forwarding probabilistic mechanism.
3. The third phase is detecting and solving VNP in 3D WSNs (3D-VNP).

In SFW, a node forwards a packet based on a region based forwarding technique through a SFW. Then one of the nodes that are located in the SFW will be probabilistically selected to forward the packet to the next hop neighbor. The selected forwarding node will become a sender and attach its location information, (S_x, S_y, S_z), to the transmitted packet so that the next hop nodes can identify if they are in SFW or not. In the probabilistic forwarding mechanism, three parameters are considered:

1. Intra-node queuing delay.
2. The residual energy in a potential forwarding node (PFN).
3. Expected residual energy in PFN's neighborhood.

The third phase deals with 3D-VNP where there is no node in the selected SFW, and tries to find another reliable route to deliver the packet to the destination.

4.2.1 Spherical forwarding wedge mechanism

This phase is utilized to reduce the number of forwarding nodes in 3D space as it considers a small volume of transmission range, and provides an accurate route description by considering the third coordinate of the nodes. Reducing the number of forwarding node has a significant effect on minimizing the redundant transmission, which causes more energy depletion and increases packet miss ratio. Fig. 4.3 illustrates 2D projection of SFW and potential forwarding node (PFN) in this wedge.

The angle that bounds the spherical forwarding region , α, is solely dependant on the network density, ρ. Based on the angle of the wedge and destination's location every node can check if it is in SFW of the previous hop sender or not. Then, it evaluates its forwarding eligibility by testing the following condition,

$$\phi = atan^2[\frac{(\overrightarrow{SN} \times \overrightarrow{SD}) \times (\overrightarrow{SD} \times \overrightarrow{SO}) \bullet \overrightarrow{SD}}{\|\overrightarrow{SD}\|}, (\overrightarrow{SA} \times \overrightarrow{SD}) \times (\overrightarrow{SD} \times \overrightarrow{SO})] \leq \alpha \tag{4.1}$$

where, ϕ, represents the angle between the plane that is defined by the vectors $\overrightarrow{SD}$ and $\overrightarrow{SO}$ and the plane that is defined by the vectors $\overrightarrow{SN}$ and $\overrightarrow{SO}$.

Once the condition in (4.1) satisfied the node will calculate its forwarding probability (as stated in next subsection). Otherwise it will keep the packet for a packet round trip time (RTT) for further processing to deal with VNP once it occurs.

4.2.2 Forwarding probabilistic mechanism

The objective of the forwarding probabilistic mechanism phase is to reduce the number of forwarding nodes in SFW and to identify a PFN with better link's quality and low queuing delay. Hence, every node in SFW calculates its forwarding probability, q, to determine its forwarding eligibility. This probability depends on two factors:

1. Energy metric, P_E,
2. Delay metric, P_τ which includes queuing delay in PFN, τ_q and average estimated delay in its neighborhood, τ_{av}.

The energy metric captures the energy in PFN, E_n, and the expected energy in its neighborhood, E_s. The node calculates its delay metric only if it has available energy more than the average energy in neighborhood, E_{av}, which is equals to, $\frac{E_s}{\eta_s}$. If that is not the case the the node will drop the received packet, where η_s is the number of neighboring nodes. The energy metric is given by,

$$P_E = \frac{E_n}{E_s}, \tag{4.2}$$

The node can calculate the energy in its neighborhood as follows: the initial total energy in neighborhood is, $E_s = \eta_s \times E_0$, then each time the node transmits a packet it deducts the receiving energy, E_{rx}, from all its neighborhood, E_s, $E_s - \eta_s \times E_{rx}$. Moreover, each time the sender hears a packet from one of the neighboring node the sender assumes that at least half of its neighbors will hear the packet and deducts the overhearing energy and one transmitting cost form, E_s, that is $E_s - (\frac{\eta_s}{2}) \times E_{rx} - E_{tx}$,where E_{tx} represents the transmission energy. The delay metric, P_τ, captures the packet's delay in the PFN in order to avoid the congested nodes, which is given by,

$$P_\tau = \begin{cases} 1 - (\frac{(\tau_{pr}+\tau_q+\tau_t)}{\tau_{av}}) & if\, (\frac{\|ND\|}{(\tau_{pr}+\tau_q+\tau_t)}) > (\frac{\|SD\|}{\tau_{av}}) \\ 0 & otherwise \end{cases} \tag{4.3}$$

The first term of the condition, $\frac{\|ND\|}{\tau_{pr}+\tau_q+\tau_t}$, represents the velocity in the PFN and the second term, $\frac{\|SD\|}{\tau_{av}}$, represents the average velocity in its neighborhood. Where, τ_q, $\tau_p r$ and τ_t represent queuing delay, processing delay and the required time to transmit a packet of z bits respectively. Average delay, τ_{av}, in neighborhood is computed based on packet RTT of m previously transmitted packets, which is, $\frac{\sum_m^{i=1} RTT_i}{m}$. The sender attaches, τ_{av}, to the transmitted packet so that all nodes in SWF can find their delay metric, which is given in (4.3).

Hence, the PFN forwards the received packet only if both metrics are satisfied otherwise the packet is dropped. The forwarding probability, q, is given as

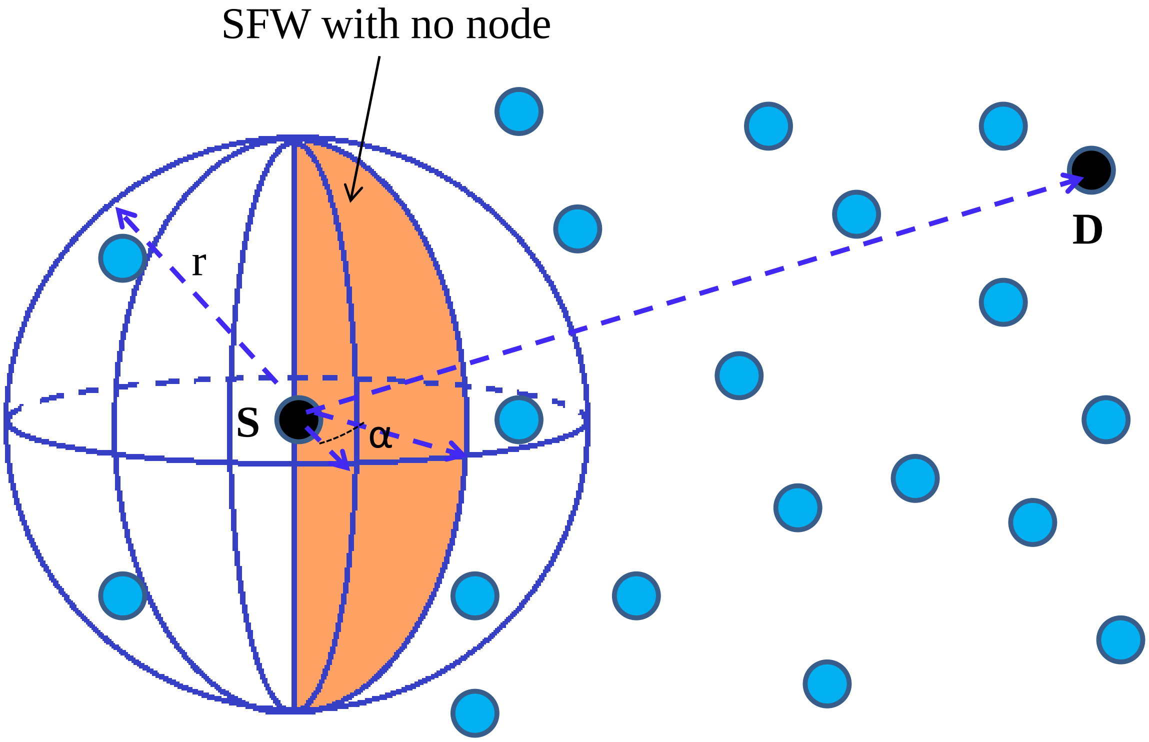


Figure 4.2. 3D shaded SFW with VNP.

follows,

$$q = \gamma \times P_\tau + (1 - \gamma) \times P_E) \tag{4.4}$$

The parameter, $\gamma \in [0, 1]$ is used to balance between the delay metric (4.3) and the energy metric (4.2) in the forwarding decision. For smaller, γ, the protocol tends to choose a node with better energy, while large, γ, the protocol tends to the node with low E2E delay.

4.2.3 Void node problem detection and solution

3D-VNP is depicted in Fig. 4.2 where there is no node in the shaded wedge. The objective of this phase is to detect and recover from 3D-VNP once it occurs. This phase also can detect the congested regions and forward the packets to less

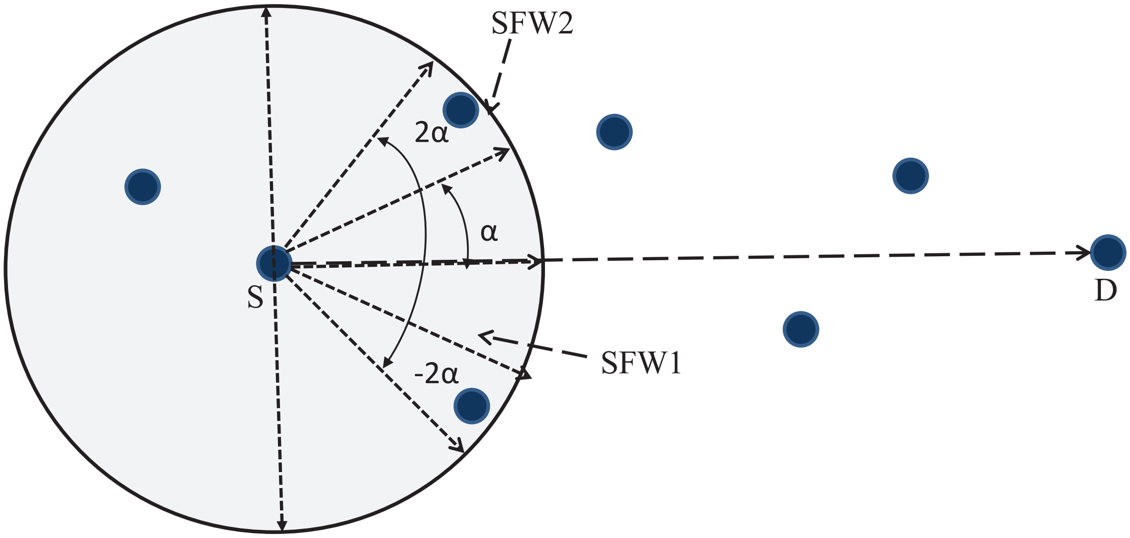


Figure 4.3. 2D projection of VNP solution in 3D WSNs.

congested areas. The sender senses VNP through overhearing of the transmitted packet. Thus, if the sender node does not overhear the transmitted packet it considers the selected SFW as void region or as congested region. Then, the sender retransmits the packet after RTT. All nodes located outside the first, SFW_1, and located in wedge SFW_2, which is bounded by dihedral angle α and $2 \times \alpha$ and wedge SFW_3, which bounded by $-\alpha$ and -2α will consider the forwarding task. This process is shown in Fig. 4.3. The process continues until the packet is forwarded successfully by one of the next hop neighbors.

4.3 RESULTS AND DISCUSSION

The evaluation of EART protocol has been conducted based on OMNeT++ with MIXIM framework [79]. The simulation parameters are in Table 3.1 and many to one traffic pattern was used with a constant bit rate (CBR). The network with 1000 nodes were uniformly and randomly deployed in a three dimensional terrain of 500 × 500 × 200 m^3 volume. The packets' deadline was set to 250 milliseconds (ms). The performance of the protocol was evaluated based on four metrics. These metrics are: *i*) *energy consumption per packet*, *ii*) *packet end-to-end (E2E) delay*, *iii*) *packet miss ratio, and iv*) *network lifetime.*

Energy consumption per packet is the average consumed energy in all of sensors for every successfully delivered packet to the destination. E2E delay is the time spent by a packet to travel from the source node to the destination node. The packet miss ratio is defined as the ratio of the packets that miss their deadlines out of the total number of transmitted packets. The network lifetime is defined as the duration of time between the network deployment time until a partitioning occurs.

These metrics have been used to evaluate the performance of EART against ABLAR [36] and 3DRTGP [80]. Both ABLAR and 3DRTGP use a restricted forwarding region mechanism to limit the number of potential forwarding nodes. However, none of them are able to capture the energy consumption in the network.

4.3.1 Average energy consumption per packet

In this set of experiments, the average energy consumption per packet in EART, ABLAR and 3DRTGP were compared in order to gain a clear perspective on the effect of integrating the energy and E2E in forwarding decision on the network performance. Fig. 4.4 shows the average energy consumption in EART in comparison with ABLAR and 3DRTGP where the traffic generation rate was varied from 1 to 14 packet/second. It shows that the average energy consumption per packet in EART is 10% to 60% better than the energy consumption in 3DRTGP and ABLAR. This good performance is due to considering the available energy in the potential forwarding node and its neighborhood. Although, the increase

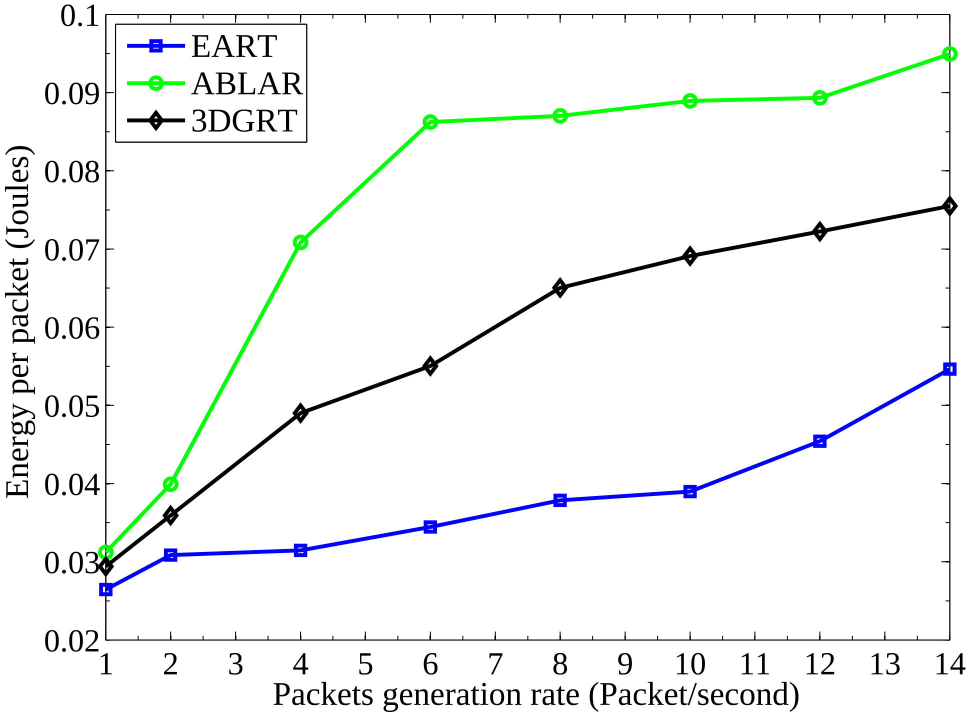


Figure 4.4. Energy consumption per packet versus packet generation rates.

in the traffic load causes more congestion and collision, EART could handle this problem by considering the delay metric in the forwarding decision. Hence, traffic can be deviated to other areas with less traffic load. On the other hand, 3DRTGP does not consider the available energy in the sensors, and for this reason it consumes more energy than EART. ABLAR depends on the periodical neighbor exchanging messages, which incurs sensor nodes more energy than in other protocols.

4.3.2 Network lifetime

This set of experiments was conducted to measure the network lifetime in EART in comparison with 3DRTGP and ABLAR. Fig. 4.5 shows that WSN operates for a longer time in EART than in 3DRTGP and ABLAR protocols by 63% to

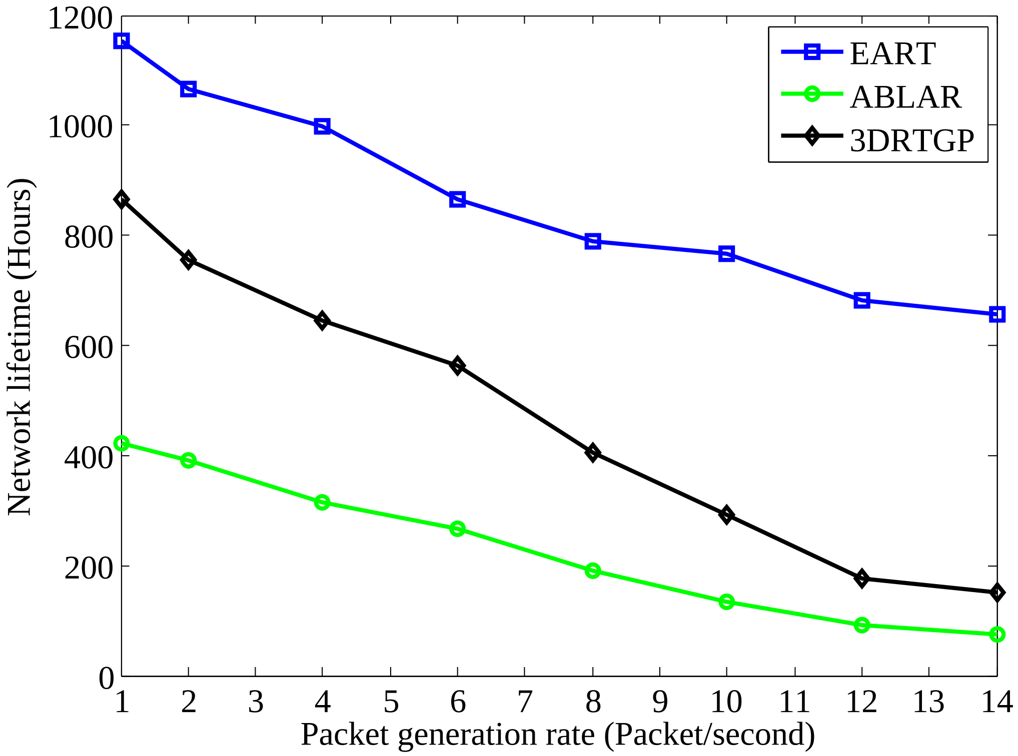


Figure 4.5. The effect of traffic load on the network lifetime.

77% respectively. This is because EART's forwarding decision is built on the basis of considering the available energy in potential forwarding node and its neighborhood. In Fig. 4.5, the trend of network lifetime in EART and 3DRTGP are the same with the increase of the traffic load, but combining the delay and energy in one metric in EART extends the network lifetime by balancing energy consumption among the sensor nodes. Moreover, 3D SFW allows more nodes to become forwarder candidates and increases the probability of selecting a better node in terms of E2E delay and remaining energy. However, 3DRTGP and ABLAR protocols not considered the available energy of sensors in their forwarding metrics.

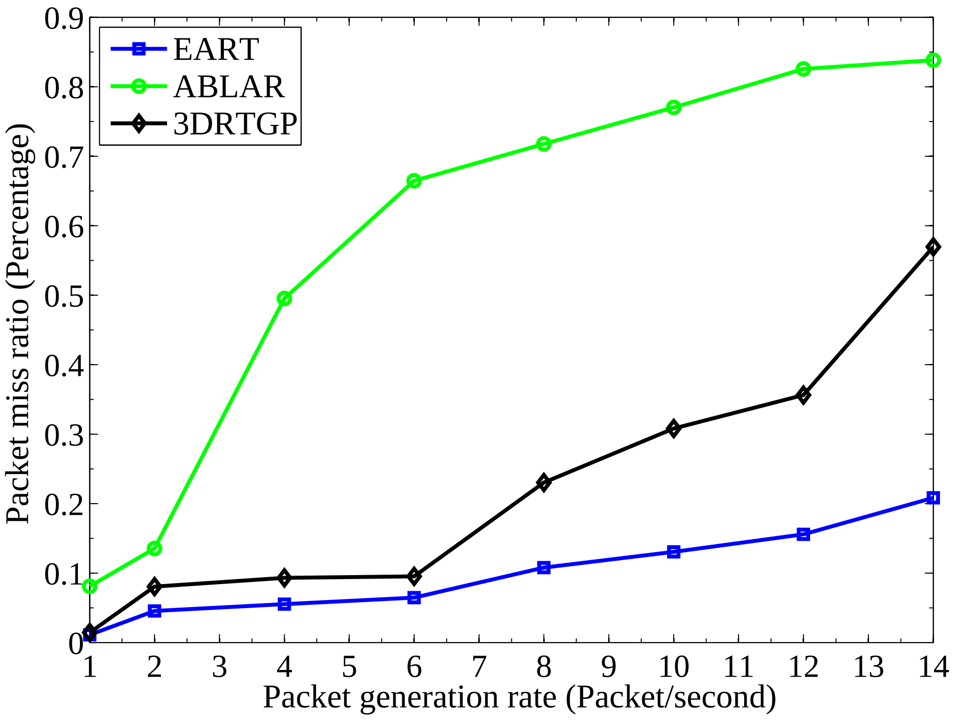


Figure 4.6. Packet miss ratio versus packet generation rates.

4.3.3 Packet miss ratio performance

The packet miss ratio is evaluated in this set of experiments to assess EART protocol's data delivery reliability. Fig. 4.6 shows the packet miss ratio with different packet generation rates. In order to test the impact of increasing the traffic load on packet miss ratio, the packet generation rates were varied from 1 to 14 packets per second, while the number of nodes was fixed to 1000. The figure shows that EART packet miss ratio is less than in 3DRTGP by 21% to 86% because the forwarding task is distributed fairly among the nodes in 3D SFW.

The SFW mechanism elevates the probability of choosing a better node that can deliver the packet before its deadline is expired. On the other hand, ABLAR suffers from high packet miss ratio at low and moderate packet generation rates

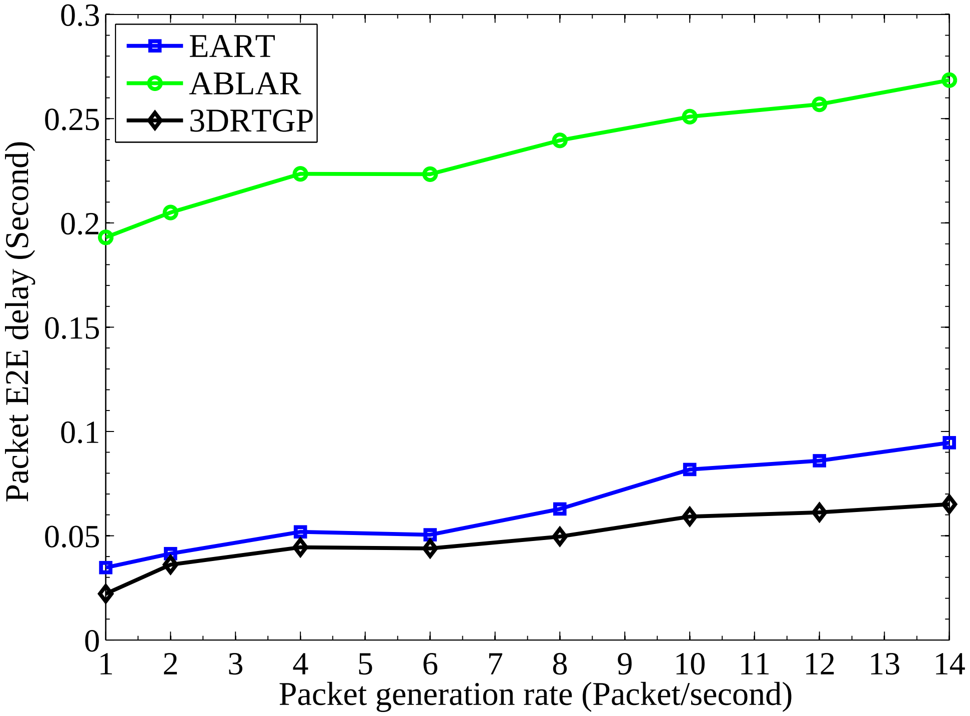


Figure 4.7. The effect of traffic load on E2E delay.

because of the periodical update of neighboring information.

4.3.4 Packet E2E delay performance

This set of experiments was performed to evaluate the congestion avoidance capability of EART and evaluate delay performance in the protocol under different traffic load. Fig. 4.7 presents packet E2E delay with various number of packet generation rates. The figure shows that the packet E2E delay in EART is less than E2E delay in ABLAR by 71% to 82%, while 3DRTGP is better than EART by 26% to 29%. 3DRTGP has slightly better E2E delay than EART because 3DRTGP always selects a node with low delay and without considering its remaining energy. However, EART takes into account the remaining energy in sensor nodes and queuing delay in its forwarding decision. This attribute reduces EART's flexibility and makes the packets take a longer route toward the destination. The experiment reveals that the packet travels through on average of 8 hops in EART and 6 hops in 3DRTGP. EART suffers such a high number of hops because nodes with high energy can be scattered on a large area, which results with longer routes and a larger number of hops.

4.4 Conclusion

In this chapter, energy-aware real-time geographical routing protocol, called EART, for WSN deployed in 3D is presented and evaluated. EART uses SFW that allows the protocol to control the number of nodes that participate in forwarding. In addition to that, EART selects the best forwarding node, which can meet the E2E delay with more available energy to perform the packet forwarding task. Another property of EART is detecting and solving void node problem (VPN) in 3D WSN. Simulation experiments show that the proposed protocol has better network lifetime, energy consumption per packet, and a more promising packet miss ratio than other competing protocols.

CHAPTER 5

PROTOCOL EVALUATION AND ANALYSIS

5.1 Introduction

This chapter presents an analytic study to aid the network designers to decide how to tune 3DRTGP for a given application requirements. The tuning procedure can be used to achieve an acceptable packet miss ratio and E2E delay. The analytical study considered two WSN's parameters, which are network density and packet deadlines. The finding shows that these two parameters have a significant impact on the network performance. Tuning the network density and packet deadlines have been investigated throughout this chapter.

The effect of PFR mechanism on the network performance is also analyzed. The validity of 3D-VNP solution, in 3DRTGP, was verified under different topologies and deadlines. A set of experiments were conducted and they proved the necessity of considering the third coordinate of sensor locations in routing protocol design. Thus, the location errors of sensor nodes and their impact on packet miss ratio and E2E delay was explored under three deployment scenarios. These scenarios were tested with 2D and 3D region based geographical routing protocols (RGRP).

In this chapter, tuning the protocol with network density are discussed in Section 5.2. The analysis of PFR size effect on the network performance is given in Section 5.3. 3D-VNP effect on 3DRTGP performance is stated in Section 5.4 and three dimensional routing protocols necessity is presented in Section 5.5. Finally, the chapter is summarized in Section 5.6.

5.2 Tuning deadlines and network density

In order to tune the network to meet the timing requirements of WSN applications, 3DRTGP was investigated under various network conditions using OMNeT++ with MiXiM framework [79]. The 3DRTGP performance was tuned and evaluated based on the network set up, which is given in Table 3.1. In this section the packet deadlines were tunned by network density based on a required packet miss ratio as probed in the following subsections.

5.2.1 Tuning deadlines with miss ratio

The aim of this set of experiments is to determine what the packet deadlines should be in order to obtain the desired minimum packet loss. Fig. 5.1 shows packet miss ratio versus packet deadlines in 3DRTGP, ABLAR and 3D Greedy. All these protocols were tested in a network of 1000 nodes with packet generation rate of four packet per second. In this figure, 3DRTGP has low packet miss ratio in comparison with other competing protocols. It is also estimates what the packet miss ratio would be for a given deadlines. For example, if an application requires 10% packet miss ratio, then the protocol can work with applications, which require 250 milliseconds (ms) or more delay. On the other hand, if the application deadline is set to 500 ms, then 3% of the packets will miss their deadlines.

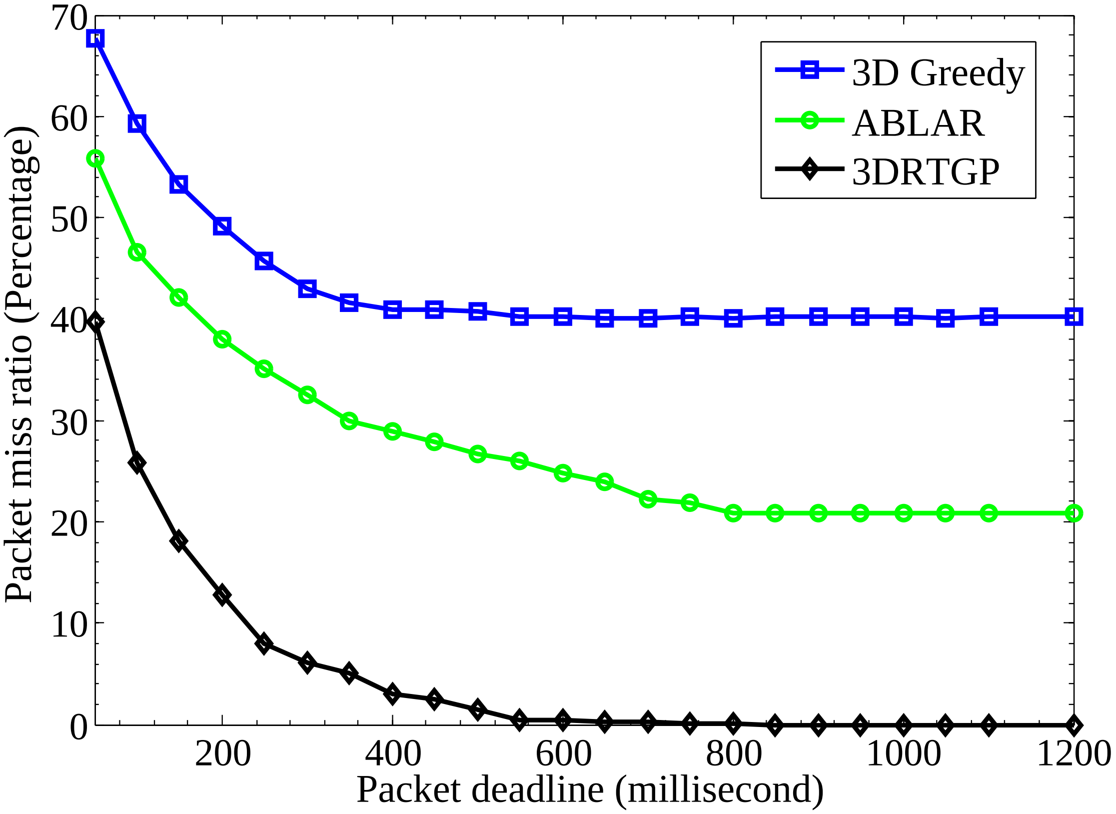


Figure 5.1. Tuning: Packet miss ratio versus packet deadlines.

5.2.2 Tuning network density with miss ratio

The objective of this set of experiments is to find out what the network density should be in order to keep the packet miss ratio within an acceptable limit. Fig. 5.2 shows the packet miss ratio versus packet deadlines with a various number of nodes with 3DRTGP only. The packet generation rate for the set of particular experiments was set to four packets per second. The figure demonstrates that there is a correlation between the packet miss ratio and the network densities for the proposed protocol. Moreover, this figure illustrates that a WSN with 3DRTGP can be tailored to meet the delay and miss ratio requirements of time sensitive applications. The packet miss ratio of dense network is lower

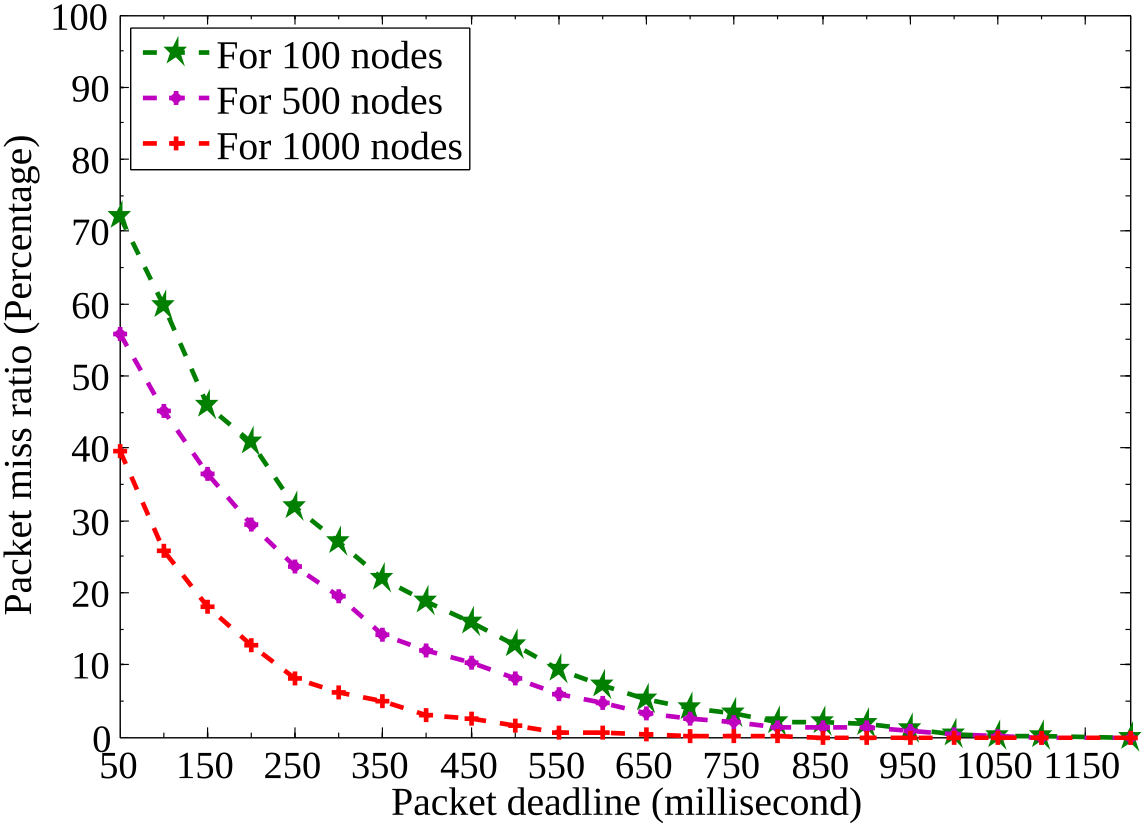


Figure 5.2. Tuning: Packet miss ratio versus deadlines with different densities.

than the miss ratio of sparse network. For example, if the miss ratio of 10 % and deadline of 450 ms are acceptable by the application, a WSN with 500 nodes in the volume can satisfy the requirement. However, if the miss ratio of 10 % and 250 ms deadlines are required, then the number of nodes in the volume must be increased to 1000 nodes. Decreasing the number of nodes in a network could populate the void regions. For this reason, the packets take longer detour and consequently the delay and miss ratio will be increased. It is interesting to see that with increased number of nodes, the adaptive PFR reduces the redundant transmissions and enables the network to meet its delay deadlines and miss ratio.

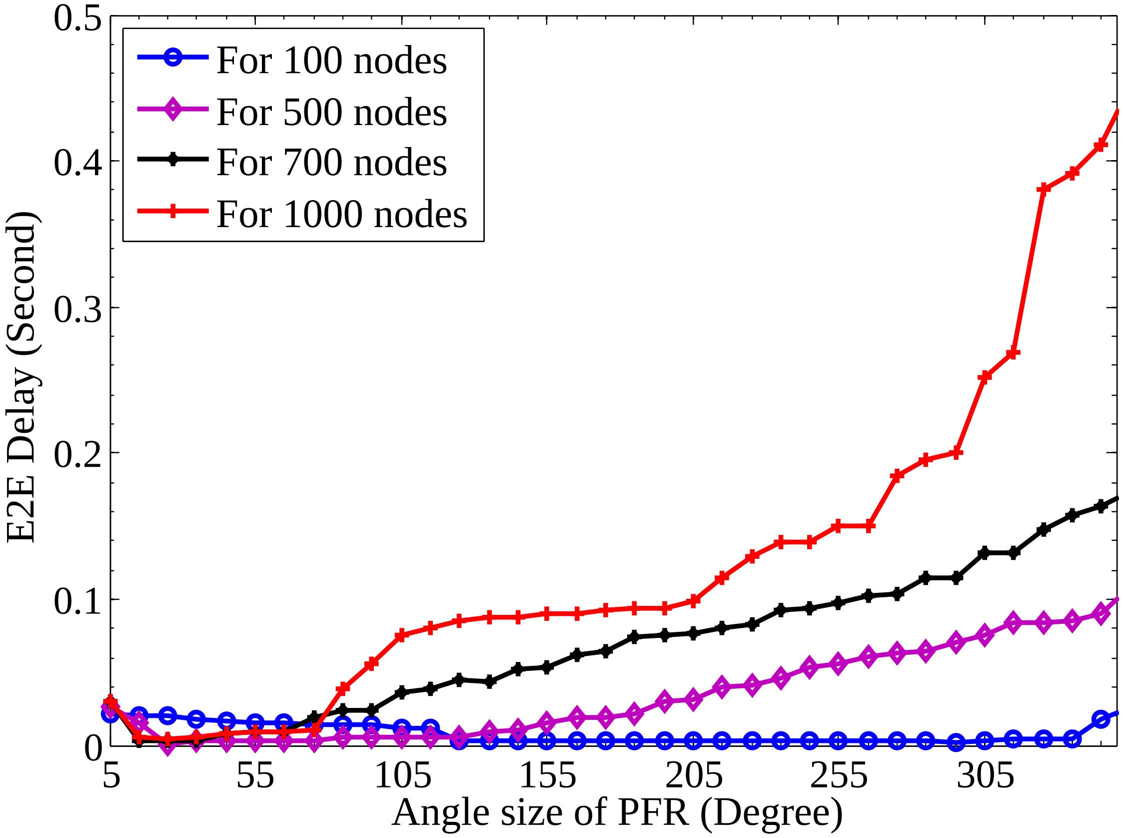


Figure 5.3. Tuning: Effect of PFR on packet E2E delay

5.3 Analysis of PFR size effect

This section presents the numerical analysis in aim of defining a proper PFR size based on the network density. The influences of PFR size on the packet E2E delay and miss ratio were investigated in the following subsections.

5.3.1 Effects of PFR on E2E delay

In real operation of 3DRTGP, the conical angle β of the PFR is a function of the network density at the time of deployment and is adjusted by nodes

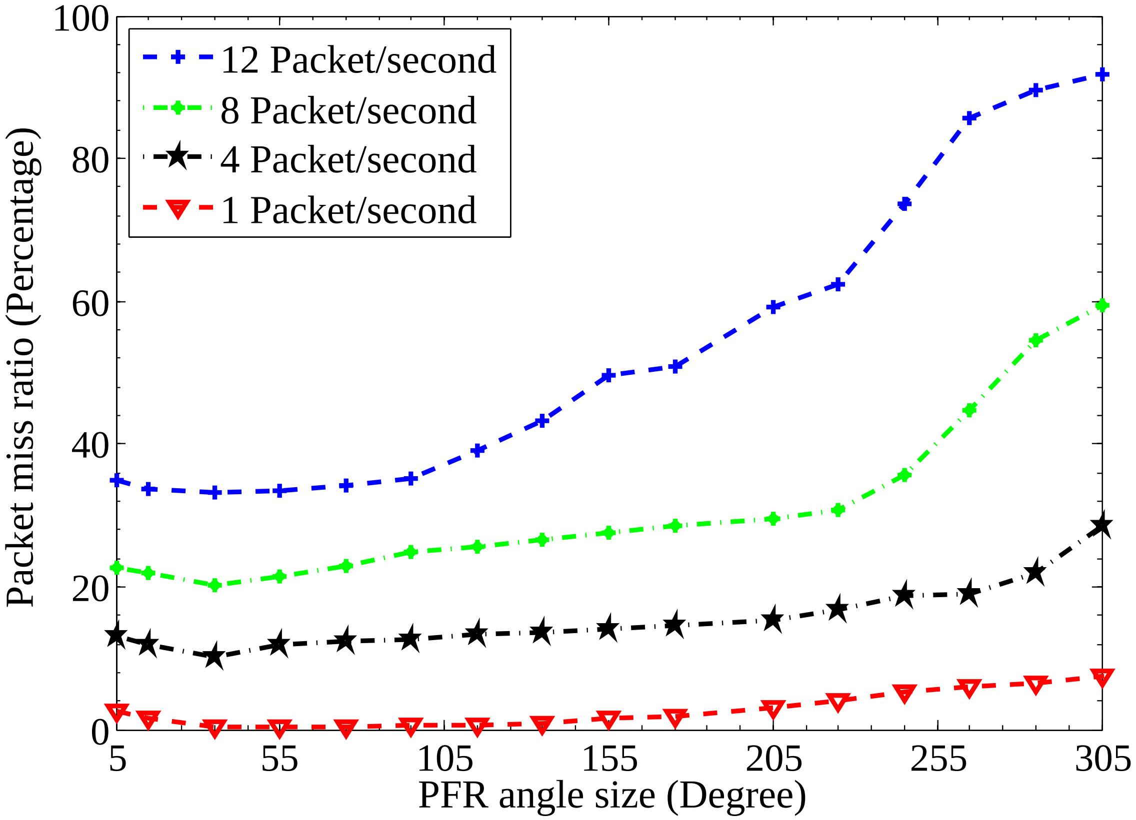


Figure 5.4. Tuning: Effect of PFR on packet miss ratio.

that experience VNP. However, in this experiment, β was varied to evaluate its impact on the protocol performance for various network densities and packet arrival rates. Fig. 5.3 plots packet E2E delay when β values vary from 0 to 360 degrees. E2E was higher when β was increased in a dense network because more nodes forwarded the packets, which increased the congestion because of the increase in the number of forwarding nodes and delay. Similarly, increasing β in a network also increases the miss ratio by increasing traffic load.

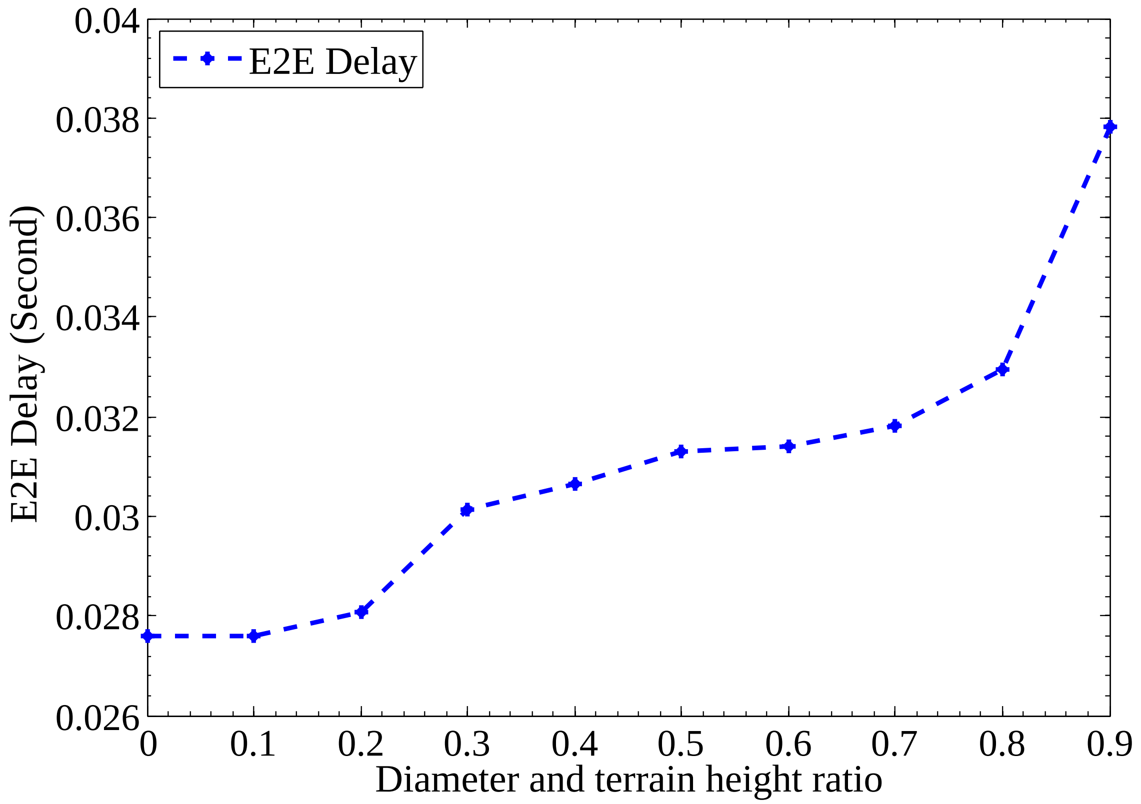


Figure 5.5. Tuning: Normalized void region size versus E2E delay

5.3.2 Effects of PFR on miss ratio

The influence of the PFR angle size is discussed in this subsection. Fig. 5.4 illustrates that the conical PFR angle, β, has a significant impact on miss ratio particularly when the traffic load is high, since more nodes try to forward packets in a larger cone. With the increase of the traffic in the conical angle more nodes will try to participate in forwarding and the congestion and collision increase, which will lead to more packets missing their deadlines. Therefore, selecting a suitable angle β that depends on the network density is essential to enhance the protocol performance.

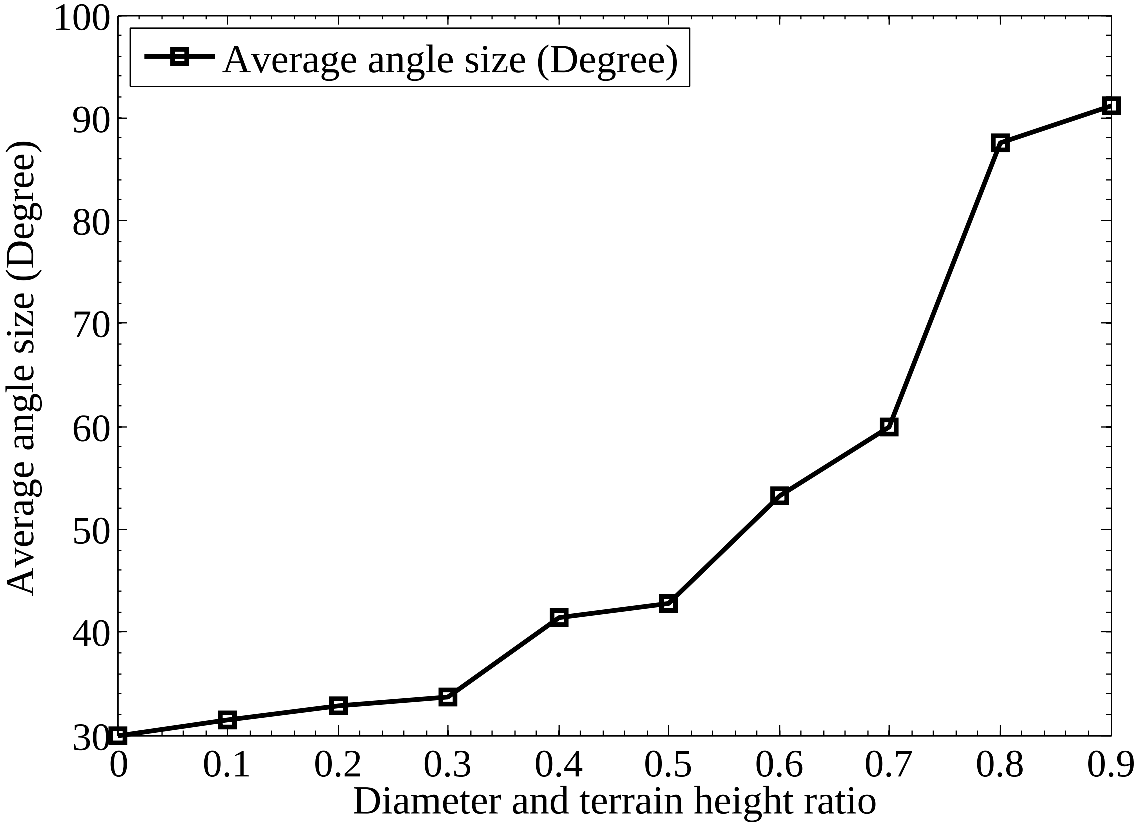


Figure 5.6. Tuning: Normalized void region size versus β.

5.4 Effect of VNP on 3DRTGP performance

In this section, a set of experiments were conducted to evaluate the influence of normalized void region size in a 3D terrain on the packet delay. The diameter of void regions is varied from 0 to 90 meters where the volume of the deployment terrain is $500 \times 500 \times 200\,m^3$. Fig. 5.5 shows the required packet E2E delay versus normalized void region size (ratio between diameter of void region and terrain height). The figure shows that with a large void region radius the packet E2E delay is increased because the packet may take a longer path to reach the destination. This experiment gives a clear indication about the effect of VNP on the packet E2E delay.

Fig. 5.6 shows average angle β versus normalized void region size. The average angle β is also enlarged with increasing void region radius since larger void region requires larger angles to find forwarders to circumvent the void region. However, in this experiment, when the packet deadline was ignored, the packet arrival rate was 100%, which is a clear indication that 3DRTGP is a reliable protocol and solves 3D VNP.

Table 5.1. SIMULATION PARAMETERS OF 2D-RGRP and 3D-RGRP TEST.

Number of neighbors	*Number of nodes in 2D terrain*	*Number of nodes in 2D terrain*
10	80	120
15	120	180
20	160	240
25	200	300
30	240	360
35	280	420

5.5 Three dimensional routing necessity

The necessity of considering three dimensional routing protocols in the real-time operations was tested hereunder. Two region based geographical routing protocols were designed and labeled as:

A. Two dimensional region based geographical routing protocol (2D-RGRP).

B. Three dimensional region based geographical routing protocol (3D-RGRP).

2D-RGRP forwarding mechanism is shown in Fig. 5.7.The routing protocol was designed to be implemented in WSN, which is deployed in 2D space. In this protocol a sender node forwards a packet through an angular region of 45 degree. This angular region is formed around an imaginary line that connects the sender and destination nodes. 2D-RGRP protocol was tested under two scenarios: 2D-RGRP implemented on WSN deployed in 2D terrain and 2D-RGRP implemented and deployed in 3D terrain. Fig. 5.8 depicts the forwarding mechanism in 3D-RGRP. This 3D region based geographical protocol was designed to be implemented in a WSN that is deployed in 3D terrain. The sender in this protocol forwards a packet toward the destination node through a conical forwarding region apex angle of 45 degrees. This apex angle is formed around

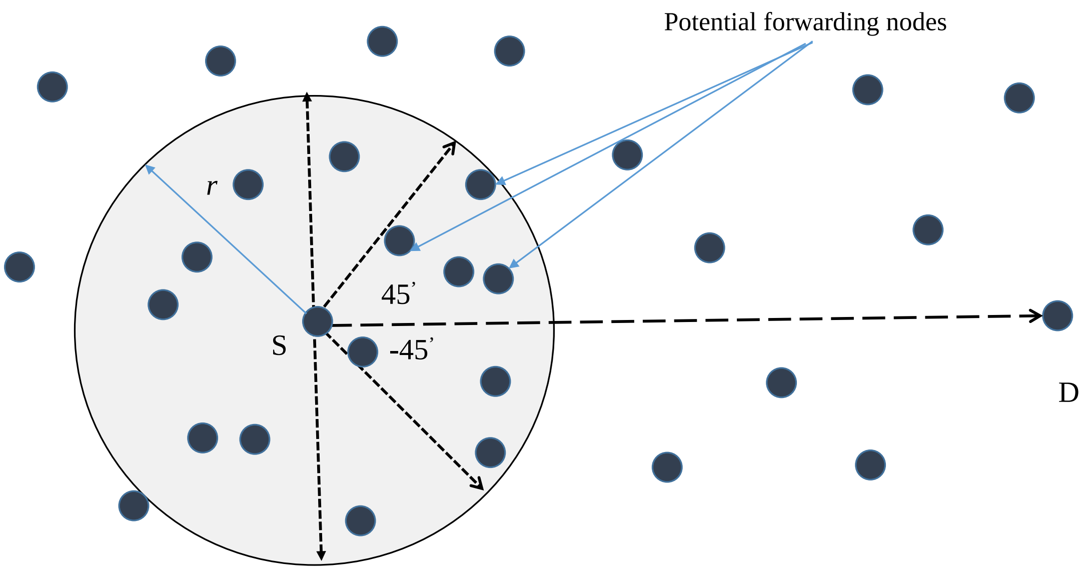


Figure 5.7. 2D-RGRP forwarding mechanism.

an imaginary line that connects the sender and destination nodes. 3D-RGRP protocol tested under one scenario where a WSN is deployed in 3D space.

The performance of 2D-RGRP and 3D-RGRP were tested with the same network density and the transmission range of sensor nodes was set to 100 meters. The number of nodes that must be deployed in any sender's transmission range in 2D terrain is specified by

$$\eta = \frac{\eta_c}{A_c} \times A \tag{5.1}$$

. Where η_c is the number of nodes in any circular transmission range of any sender node, A_c is the sender's transmission range area and A is the entire area of 2D deployment terrain. The number of nodes that must be deployed in any sender's transmission range of in 3D terrain is given by

$$\eta = \frac{\eta_s}{V_s} \times V_s \tag{5.2}$$

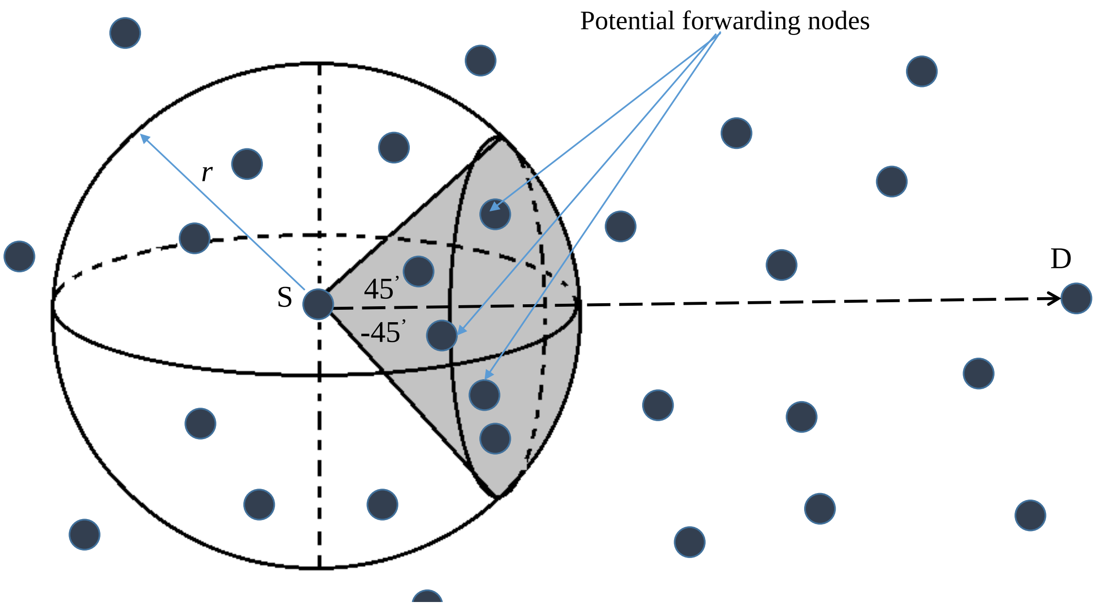


Figure 5.8. 3D-RGRP forwarding mechanism.

. Based on (2Ddensity) and (3Ddensity) the number of neighboring nodes of a sender node and the corresponding the number of nodes in the terrain are given in simulation Table 5.1. The size of 2D terrain is $500 \times 500\ m^2$ and the size of 3D terrain is $500 \times 500 \times 200\ m^3$. The objective of this experiment is to analyze the effect of nodes' location errors in implementation of three test cases. These test cases are :

A. 2D-RGRP implemented in 2D-WSN.

B. 2D-RGRP implemented in 3D-WSN.

C. 3D-RGRP implemented in 3D-WSN.

The performance of 2D-RGRP and 3D-RGRP are evaluated based on two metrics, which are packet miss ratio and packet E2E delay.

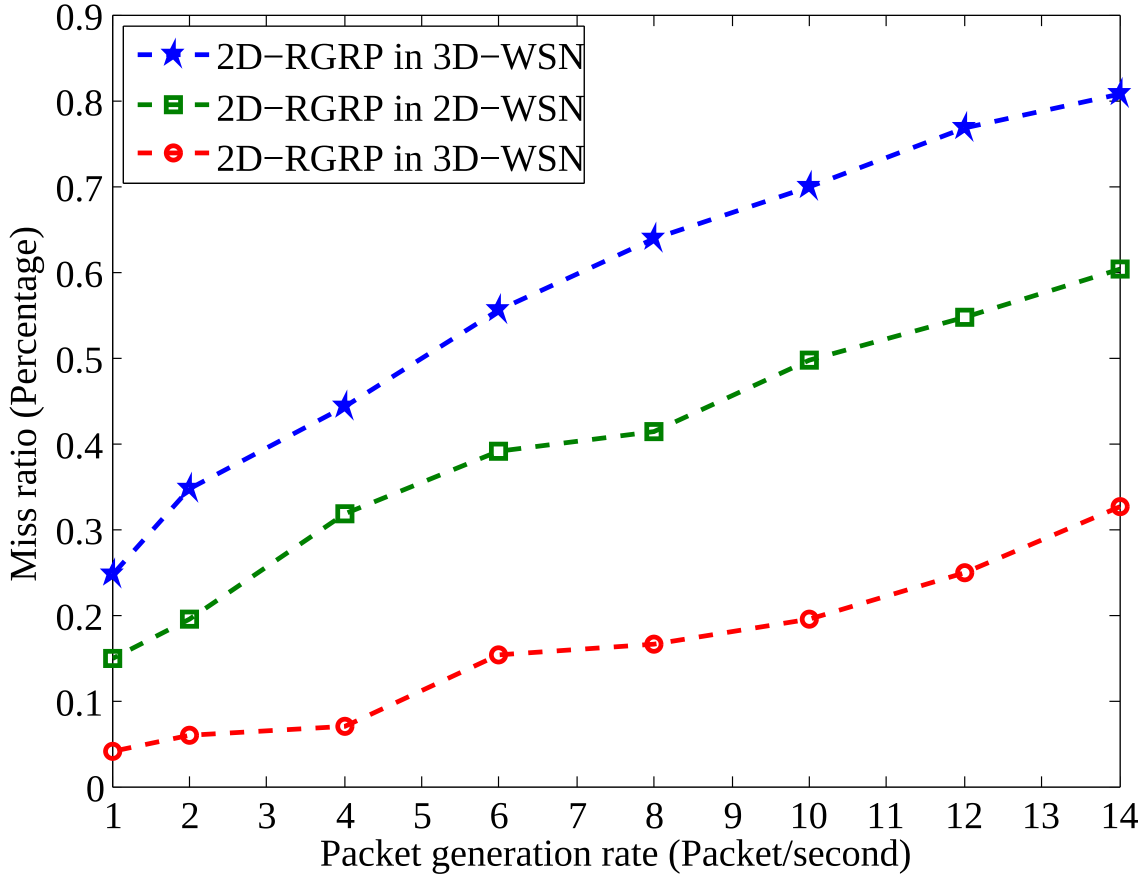


Figure 5.9. Packet miss ratio in 3D-RGRP versus 2D-RGRP protocols.

5.5.1 Discarding third coordinate impact on miss ratio

This section discusses the effect of discarding the third coordinate of sensor node location on the packet miss ratio when the network density is fixed. Fig. 5.9 shows packet miss ratio versus various packet generation rates. This comparison study of packet miss ratio in 2D-RGRP and 3D-RGRP routing protocols have been implemented on the same network size. The size of 2D network is 280 nodes and 420 nodes for 3D network. The figure shows that packet miss ratio of 3D-RGRP implementation in 3D-WSN is better than in other implementation test cases by 59% to 84%. This is due to considering the third coordinate of

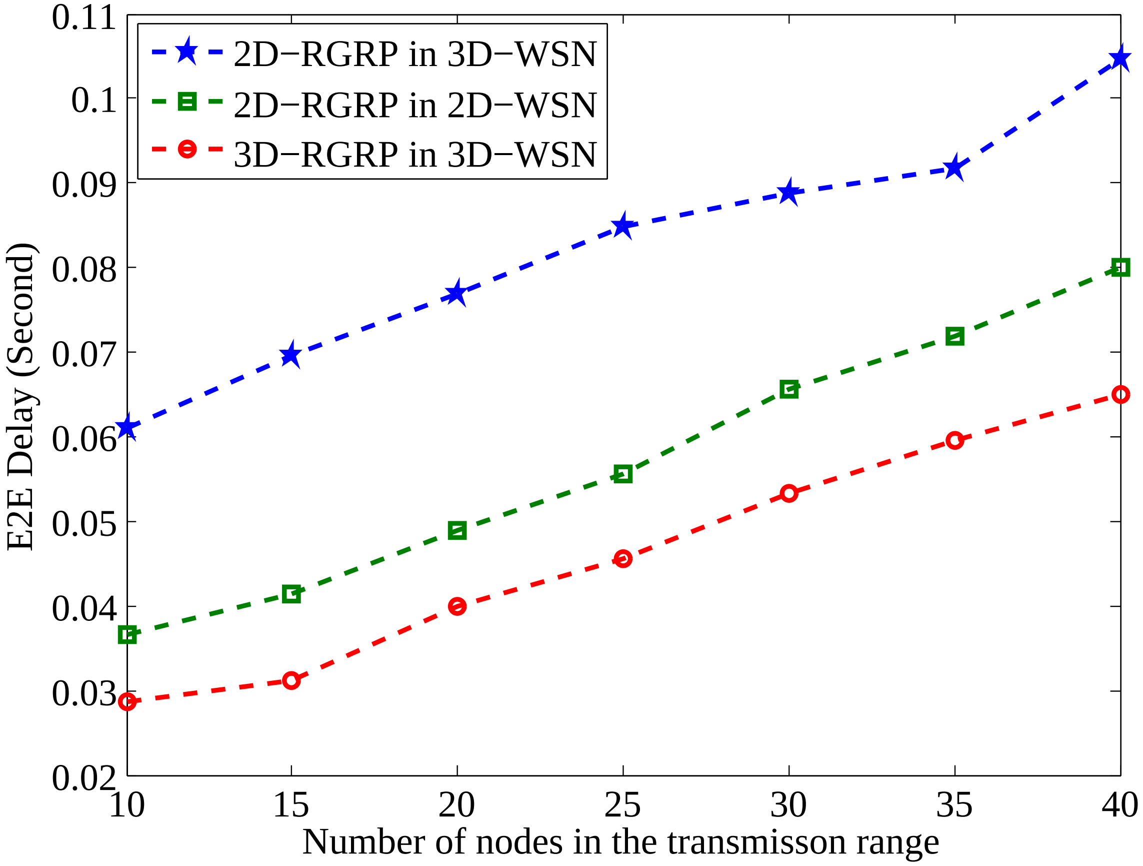


Figure 5.10. Packet E2E delay in 3D-RGRP versus 2D-RGRP protocols.

sensors in the routing decision. Considering the third coordinate reduces the number of forwarding nodes and make routing calculation more accurate. 2D-RGRP implementation in 2D-WSN has high packet miss ratio due to route miss calculation and more forwarding nodes.

5.5.2 Discarding third coordinate impact on E2E delay

This section discusses the effect of discarding the third coordinate of sensor node location on the packet E2E delay with various network densities. Fig. 5.10 shows packet E2E delay versus network densities. In this experiment the packet generation rate was 2 packet/second. It is clear that the packet E2E in 3D-RGRP is less than in other two implementation test cases by 14% to 46%. This is because discarding the third coordinate makes more nodes participate in packet forwarding as a result of projection of all nodes into 2D surface. As a result, the congestion becomes higher and increases E2E delay.

5.5.3 Terrain dimensions effect on network performance

Here the importance of terrain dimensions was tested when the number of nodes in the network is fixed. Fig. 5.11 shows the effect terrain dimensions on the packet E2E delay versus different packet generation rates. These three test cases were compared with each other. 3D-RGRP implemented in 3D WSN has lower packet E2E delay by 39% to 61% because the number of participating nodes in packet forwarding is in the less than other test cases. However, 2D-RGRP implemented in 2D WSN has high packet E2E delay because more nodes are participating in packet forwarding, which causes collision and congestion. In the case of 2D-RGRP implemented in 3D WSN, the packet may take a longer detour to the destination due to the miss calculation of nodes' locations.

5.6 Summary

This chapter provides design guidelines for WSNs which may employ the proposed protocol. The protocol is unique since it resolves VNP in WSNs that is deployed in 3D space and offers an adaptive conical PFR approach to limit the number of forwarding nodes. 3DRTGP selects nodes from less congested regions of the network to achieve soft real-time operation. The simulation results verified that 3DRTGP ultimately solves 3D-VNP. The effect of 3D-VNP and PFR of the protocol performance were analyzed and shown that 3DRTGP

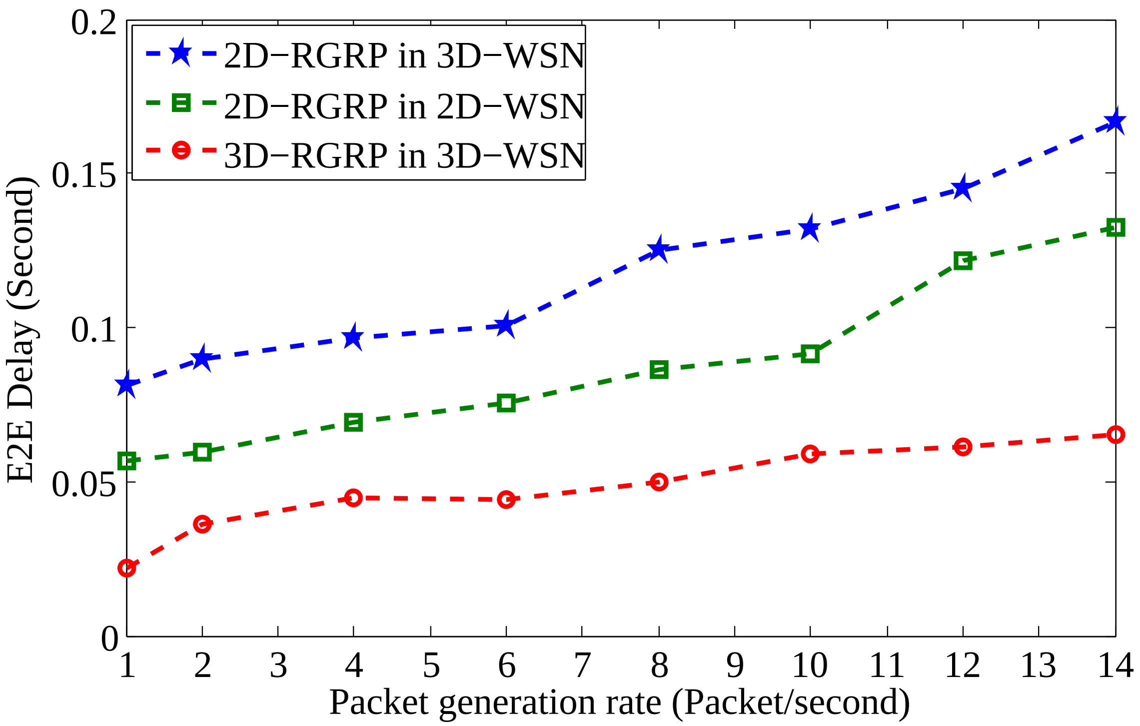


Figure 5.11. The effect of terrain dimensions on the packet E2E delay.

can fit with different WSN topologies and densities. The effect of discarding third coordinates of node locations on the network performance was also investigated and this showed that there is a significant impact on the performance of geographical routing protocol in real-time operations.

CHAPTER 6

CONCLUSION

6.1 Contributions

This dissertation has presented two adaptive and scalable soft real-time GRPs. These two protocols utilize the location information of sensor nodes to eliminate the need to exchange neighboring information overhead, routing table construction and maintenance. These protocols, which are called 3DRTGP and EART, support the real-time requirements in WSNs with better utilization of energy resources. The problem of void node in 3D WSNs has been solved using two different heuristic approaches. In 3DRTGP, 3D-VNP is solved using adaptive PFR while in EART 3D-VNP is solved using adaptive SFW. In both cases 3D-VNP solution have been performed locally without exchanging neighboring information.

The effectiveness and validity of both proposed protocols have been investigated through extensive simulation experiments. The provided results confirm that 3DRTGP and EART have successfully met the real-time application requirements in WSN. Moreover, extensive numerical simulation confirms the correctness of 3D-VNP solutions and can be successfully implemented in many WSN applications scenarios.

The dissertation also provides detailed study of tuning parameters that can be set to make the protocol fit with time sensitive applications. The effect of discarding the third coordinate in sensor node locations is investigated through a set of experiments. These experiments support the necessity of considering the three dimensional coordinates for accurate routing calculation. The results show that ignoring third coordinate in routing calculation has significant impact on the network performance. Three test scenario of region based routing protocols, which are 2D-RGRP implemented in 2D-WSN, 2D-RGRP implemented in 3D-WSN, and 3D-RGRP implemented in 3D-WSN, are designed and their results compared with each other to verify the effect of location errors on the network performance.

6.2 Future Work

The current versions of 3DRTGP and EART do not consider the mobility of sensor nodes in WSNs. However, a majority of mobile systems employ GPS devices, which can provide the location information of sensor nodes in real-time and the location of destination node can be pre-programmed in all sensors before the network is deployed in the targeted terrain. With these provisions, 3DRTGP and EART can be easily utilized by mobile networks, such as UAV networks. Mobile versions of the protocols will be investigated in future studies.

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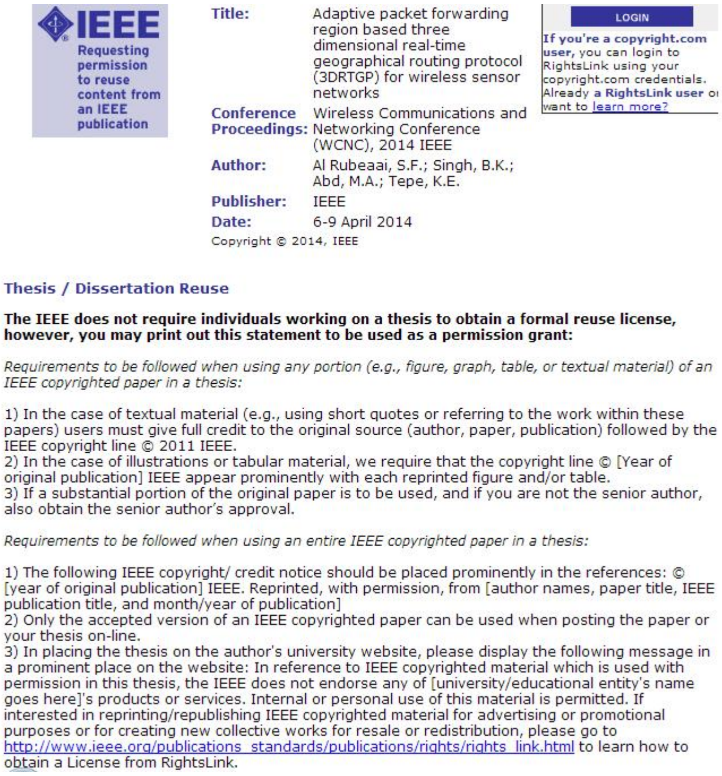

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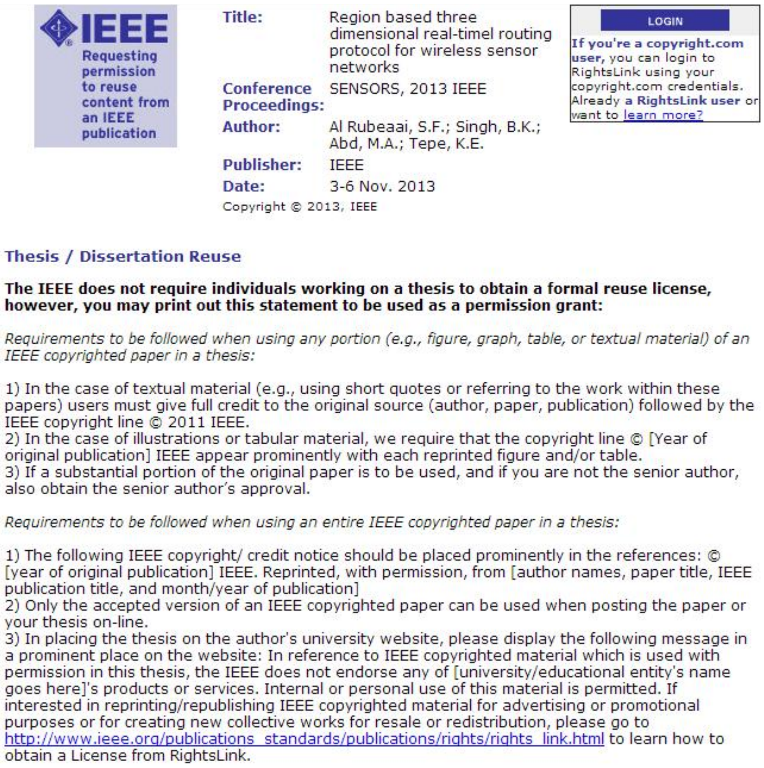

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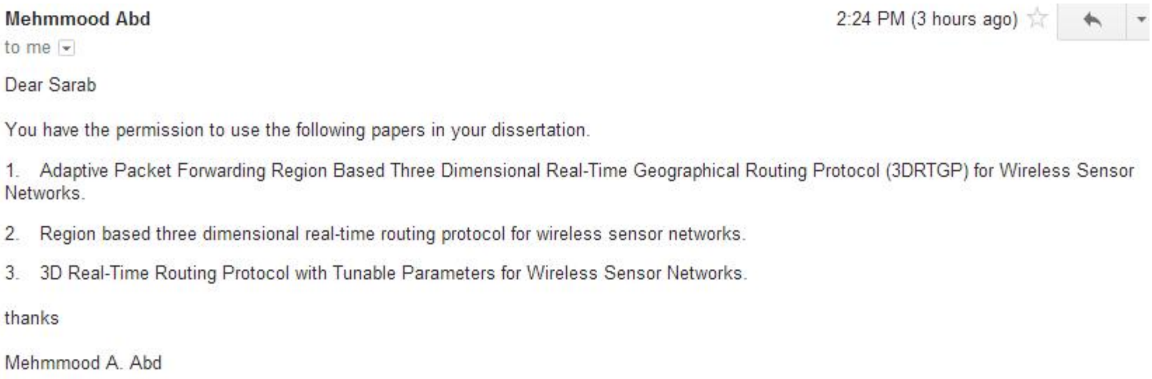

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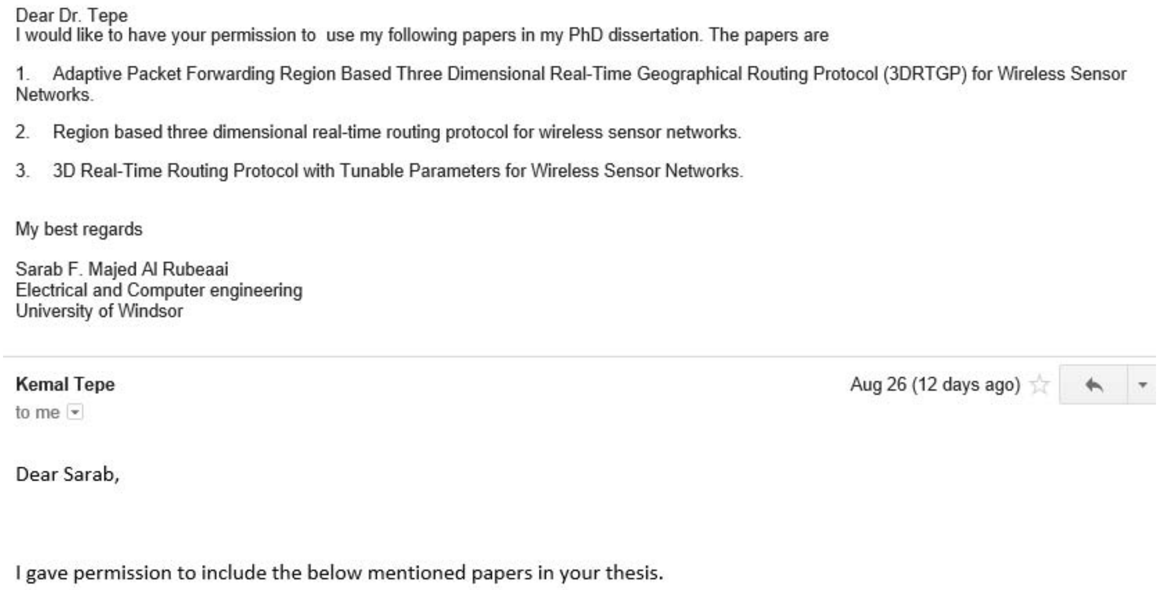

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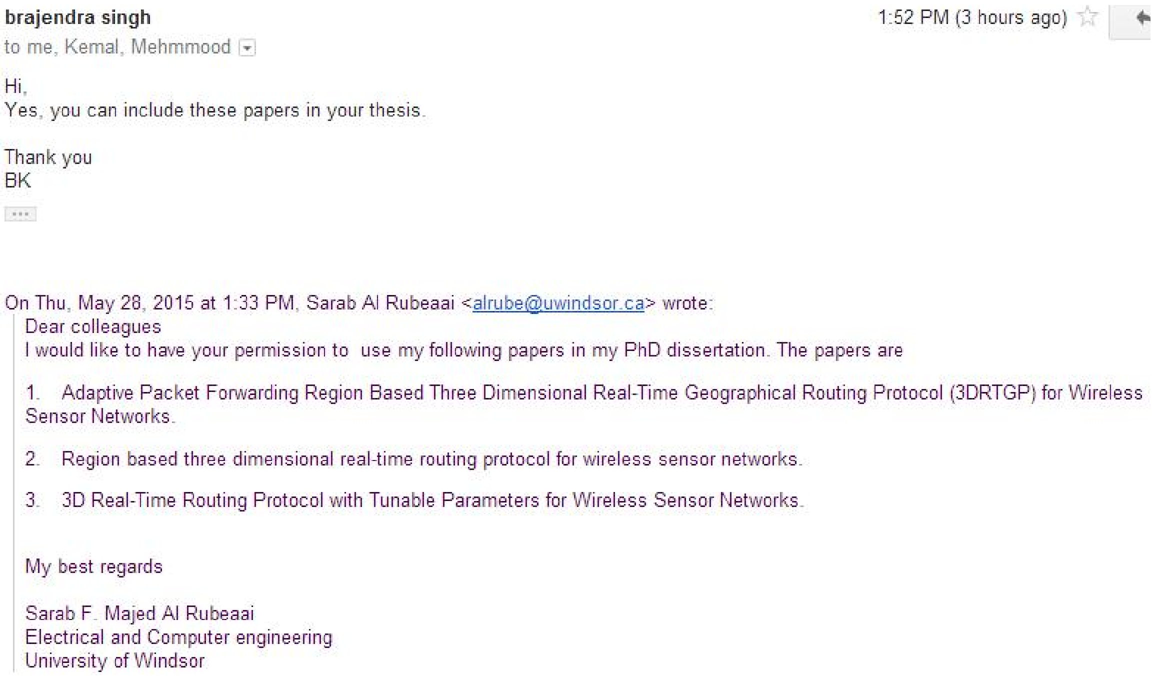

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