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GAME THEORETIC ENERGY BALANCED ROUTING PROTOCOLS FOR
WIRELESS SENSOR NETWORKS

by

Mehmmood Abdulla Abd

A Dissertation

Submitted to the Faculty of Graduate Studies
through the Department of Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada

2015

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Game Theoretic Energy Balanced 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 Sarab F. Majed Alrubeaai and Brajendra K. Singh, under the supervision of Professor Dr. Kemal E. Tepe and Rachid Benlamri. In all cases, the key 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	Mehmmood A. Abd, Sarab F. Al Rubeaai, Brajendra K. Singh, Kemal E. Tepe, Rachid Benlamri, Global Game Theoretic Energy Balance Approach For Wireless Sensor Networks ,	Submitted
Part of Chapter 4	Mehmmood A. Abd, Sarab F. Al Rubeaai, Kemal E. Tepe, Rachid Benlamri, "Game Theoretic Energy Balancing Routing in Three Dimensional Wireless Sensor Networks", Accepted in Wireless Communications and Networking Conference (WCNC), 2014 IEEE	Accepted
Part of Chapter 3 and 5	Mehmmood A. Abd, Brajendra K. Singh, Sarab F. Al Rubeaai, Kemal E. Tepe, Rachid Benlamri, "Game Theoretic Energy Balanced (GTEB) Routing Protocol for Wireless Sensor Networks", Wireless Communications and Networking Conference (WCNC), 2014 IEEE , vol., no., pp.2564, 2569, 6-9 April 2014	Published

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A primary concern in the operation of Wireless Sensor Network (WSN) is the issue of balancing energy consumption and lifetime maximization. This dissertation addresses the problem of unbalanced energy consumption in WSNs by designing traffic load balancing geographical routing protocols. In order to provide energy balance; two decentralized, scalable and stable routing protocols are proposed: Game Theoretic Energy Balanced (GTEB) routing protocol for WSNs and three dimensional (3D) Game Theoretic Energy Balance (3D-GTEB) routing protocol for WSNs. GTEB were designed to fit with WSNs deployed in 2D space, while 3D-GTEB designed to work with WSNs deployed in 3D terrain.

Both protocols are built based on balancing energy consumption into region level and node level using different game theory in each level. In the first level, evolutionary game theory was used to balance the energy consumption in various packet forwarding sub-regions, while in the second level classical game theory was used to balance the energy consumption in forwarding sub-region nodes. 3D-GTEB benefits from utilizing the third coordinate of nodes' locations to achieve better and accurate routing decision with low network overhead.

The protocols were evaluated analytically and experimentally under realistic simulation environment. Thus, the results show not only combining evolutionary and

classical game theories are applicable to WSNs, but also they achieve significantly better performance in terms of energy usage, load spreading, and packet delivery ratio under different network scenarios when compared to the state-of-art protocols. Moreover, further investigation is made to evaluate the effectiveness of using game theories by comparing GTEB with three random test protocols. The results demonstrated that the GTEB and 3D-GTEB are prolonged the network lifetime from 33% to 85%, and provided better delivery ratio form 26% to 52% as compared with other three random test protocols and three similar state-of-art routing algorithms.

DEDICATION

to my

MOTHER and FATHER

with love

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I would like to thank my advisor Dr. Kemal E. Tepe for introducing me into 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 am grateful for all the time he dedicated to me and my work despite he has many other students they 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

N	Number of sensor nodes (players) in region/wedge k
C_i	Proportion of packet already forwarded by a node out of C_i
\dot{E}_i	Residual energy in node i
\bar{T}	No Transmission strategy
β	Normalization factor for the total energies in region/wedges
Δ	Collision energy cost
δ	Transmission energy cost
\dot{X}	Replicator dynamics
\dot{X}_k	Net change in the number of packets in region k
X^*	Equilibrium packet distribution vector
λ	Packet population of a sensor node
λ_k	Number of packets in region k
\mathcal{M}	Number of sensor nodes in WSN
\mathcal{N}	Set of players
\mathcal{S}	Set of strategies
\mathcal{S}_i	Set of strategies of node i
\mathcal{S}_{-i}	Set of strategies of opponent node $-i$
Ω	Volume of deployment terrain
ρ	Density of network
θ	Angle of forwarding region/wedge
\overrightarrow{SA}	Vector from sender S to the node A
\overrightarrow{SD}	Vector from sender S to the destination D
\overrightarrow{SO}	Vector from sender S to the polar of transmission sphere O

S	Sender sensor node
D	Destination sensor node
A	Sensor node A
O	Polar point of a node's transmission sphere
$3D$	Three dimensions
$GTEB$	Game theoretic energy balance
$2D$	Two dimensions
C_i	Ideal proportion of packet must be forwarded by node i
$E[U_i]$	Expected payoff for node i
E_{tr}	Receiving energy cost in Joule
E_{tx}	Transmission energy cost in Joule
E_i	Initial energy of node i in Joules
E_k	Residential energy in region k
$F_k(X)$	Fitness function of region k
GRP	Geographical routing protocol
H_k	Function of the number of players in region k
K	Number of forwarding region/wedge
n	Node n
O	The polar transmission sphere
P	Transition probability matrix
$p_{i,k}$	Node i forwarding probability in region k
q^*	Nash equilibrium strategy
R	Forwarding region
T	Transmission strategy
v	Reward value
u_i	Payoff function of node i
s_i	Strategy of node i
u_{-i}	Strategy of Opponent node i

B	Broadcasting strategy
\bar{B}	No Broadcasting strategy
B_k	Available resources in region k
BS	Base station
C	Proportion of packet in a region/wedge
CBR	Constant bit rate
CGT	Classical game theory
d	Depth of deployment space
dB	Decibel
EGT	Evolutionary game theory
FW	Forwarding wedge region
h	Hight of deployment space
J	Joule
kbps	Kilo bit per second
MANET	Mobile ad hoc networks
m	Meter
mW	milliwatt
NE	Nash equilibrium strategy
NLEB	Node level energy balance
PDR	Packet delivery ratio
QoS	Quality of service
RLEB	Region Level Energy Balance
RTT	Round trip time
RLEG	Region level evolutionary game
s	Any strategy
w	Width of deployment space
WLEB	Wedge level energy balance
WSN	Wireless sensor network
ESS	Evolutionary stable strategy

1.1 Introduction

Wireless Sensor Networks (WSNs) will be very prevalent technology in the near future due to their unique characteristics and to their great number of applications. WSNs consist of a large number of autonomous micro-sensors that are deployed in remote and inaccessible areas to monitor physical or environmental conditions. Although the sizes of sensors are very small, they have their own on-board processor, as well as communication, mobilizing, position finding, and storage capabilities. Sensor nodes have the ability to collect and route data, through one or multi hops, to other nodes, or external base stations. Coordination and cooperation among sensor nodes will provide essential network information collected from monitored physical phenomena. Base Station (BS) basically acts as a gateway between sensor network and end user by receiving the data from sensor nodes and forwarding it to the server hence, it is required to have more computational, energy, and communication resources than sensor nodes.

Routing data in WSNs very challenging task due to infrastructure-less communications and frequent topology changes. The main drawbacks of the WSNs are the limitation of storage capacity, bandwidth, communication range and power resources.

This chapter presents examples of WSNs applications, challenges in WSNs, problem statement, and contributions of this work.

1.1.1 Applications of wireless sensor networks (WSNs)

WSN applications can be classified into three categories based on sensing and reporting mechanisms [1, 2].

1. **Periodic reporting applications:** in these applications, the sensor nodes will sample the collected data periodically, store and transmit collected data to the base station. This type of scenario is commonly used in monitoring applications such as automatic irrigation systems [3], habitat surveillance [4], and military operations [5]. The main advantage of this category is that data generation rate and traffic volume is predictable.
2. **Event driven applications [6–8]:** In these applications each sensor has the ability to sense and evaluate the usefulness of information. If the detected information is useful the information will be transmitted to the base station for evaluation. The main property of this type of application is the randomness of event occurrence, which correlates with the time and place. Therefore, time and packet traffic load is unpredicted. The surveillance applications, disaster relief applications, intrusion detection applications, and patients monitoring applications are a few examples of such event driven applications.
3. **Query based applications [9]:** In these applications, the sensory data are regularly sampled and stored in sensor nodes. The base station sends request messages to the specific sensors to fetch the data directly. The main challenge in this category is that the data management process due to the limitation of the storage capacity of the sensors.

The following subsection will present a brief discussion of WSNs challenges.

1.1.2 Challenges in Wireless Sensor Network (WSNs)

The limitation in WSNs resources make it necessary to design new routing protocols that differ from regular routing protocols designed for other wireless communication systems. Some of the limitations in WSNs are as following:

1. **Energy restriction:** Wireless sensors are powered with a limited power supply such as batteries and capacitors. These limited energy resources have a direct impact on the network lifetime [10]. The network lifetime is the duration from the deployment time until the time when the first sensor runs out of energy. In unattended and remote environments, replacing or charging batteries is not cost effective and practical. Hence, good utilization of the limited power resources is important to prolong the network lifetime.

Geographical Routing Protocols (GRPs) due to their low network overhead can increase energy utilization and improve network lifetime. In this dissertation, I focused on energy balance challenge to prolong the network lifetime by evenly distributing traffic load in the network using GRP.

2. **Mobility:** Due to the sensor node's mobility, the topology of the network may change frequently, which may cause route failure, high collision rate, blockage routing information, and increase energy consumption [11]. Thus, network mobility must be addressed in a data propagation protocol design.
3. **Network deployment:** Network deployment is another challenge in WSNs, specially when a WSN deployed in remote or inaccessible areas. It is very difficult or even impossible to determine their location in advance. For example, sensors that are serving to monitor battlefields or disaster areas are usually randomly thrown from airplanes over areas of interest and these sensors must be able to determine their own locations, initiate their sensing, and communicate with their neighbors [12]. Therefore, any routing protocol design must be able to adapt with

random network deployment scenarios and various network densities.

4. **Scalability [13]:** Due to the increasing number of sensors in a network, the messages that must be routed to the base station increase. Therefore, data propagation protocol must be able to scale with changes in a network; such as changes in network density, network connectivity, and/or sensing operations. Decentralized and localized algorithms, where sensor nodes usually employ, are often used to satisfy the scalability requirements.
5. **Fault tolerance [14]:** WSNs are inherently prone to failure due to the low cost hardware and limitation of the energy supplies. A failure of a sensor node should not influence the overall functionality of the network. So in such cases, a network must have the ability to accommodate a new route to the base station. This may need actively rerouting packets through a more reliable part of the network that has more resources (available energy).
6. **Location dependent contention [15]:** The traffic load on a wireless channel varies with the number of sensor nodes that are present in a given region. The contention over the usage of a channel will increase with the increase in the number of sensor nodes. The high contention over the channel causes a large number of collisions and consequently inefficient utilization of energy and bandwidth. Therefore, any reliable data propagation protocol must have the property of preventing or minimizing high channel contention.
7. **Security [9, 16, 17]:** Normally, the traffic routing in the sensor network is connectionless, consequently making it highly susceptible to security threats. The shared wireless medium makes the network subject to various attacks such as denial service attacks. Therefore, WSNs require security solutions that fit with their wireless communication and limited resources.
8. **Quality of service [16, 18]:** The quality of service challenge varies depend-

ing on WSNs applications. For example, disaster field monitoring entails reliable minimum delay delivery of sensory information for ensuring fast response by a corresponding authority. In contrast, agricultural monitoring and animal-borne applications require balancing energy consumption in sensor nodes and long network lifetime to minimize maintenance effort and cost.

The main goal of this dissertation is to extend the network lifetime by distributing traffic load in WSNs. This goal is achieved by employing a decentralized, scalable and energy-balanced geographical routing protocol called GTEB and three dimensional routing protocol called 3D-GTEB. Both routing protocols utilize a combination of evolutionary and classical game theories.

1.2 Problem Statement

This dissertation provides solution to problems associated with GRPs to achieve global balanced energy consumption in order to extend the lifetime of network. These problems are discussed hereunder:

Problem 1. Unbalanced energy consumption: uneven energy dissipation in the Geographical Routing Protocols (GRPs) can result in premature network failures, which shorten the lifetime of the network, accelerate network partitioning, and generate energy hole problem [19–23]. Therefore, utilizing routing protocol for fair traffic load distribution among wide range of sensors is one of the key methods to prolong operations of the network.

Problem 2. Unbalanced traffic load and redundant transmission: GRPs forward the packets toward the destination based on one of the following techniques:

- A. Shortest path forwarding (SPF) approach [24–26]: Where, a packet travels from source to destination through the shortest straight path. That leads to an overuse of the nodes along this path. These overused nodes deplete their

energy faster than other nodes, which creates network partitions and failures. Hence, the traffic load must be spread on large number of sensor nodes to evenly deplete energy consumption and improve the network lifetime.

- B. Region Based Forwarding (RBF) approach [27–29]: A packet is broadcasted to a set of nodes located in the same region and all sensors transmit the received packet toward the destination. That causes redundant transmissions. These redundant transmissions can increase energy consumption. Therefore, a new innovative routing protocol is required to improve energy utilization to prolong the network lifetime.

Problem 3. 3D network deployment [30–32]: sensor networks are deployed in a 3D space. Utilizing 2D geographical routing protocols for 3D wireless networks may not provide an accurate solution and in some cases it is not possible such as Unmanned Aerial Vehicles (UAV) communication. Thus, there is a strong desire to use 3D GRP to improve accuracy and energy efficiency of the network. Therefore, by including third coordinate of nodes' position is decreased the number of dropped packets, while energy efficiency and the lifetime of the network is increased. For this reason, it is important to consider the third coordinate of nodes' location in order to avoid route description errors, transmission redundancies, and high packet miss ratio.

Problem 4. Energy hole problem [22, 33]: Energy hole problem is associated with GRPs due to over utilization of some nodes over other nodes. For instance, in case of SPF the nodes that are located along the straight line between source and destination will deplete their energy sooner than outer sub-regions nodes. Moreover, nodes near the sink will suffer from high traffic load and deplete their energy because these nodes send their own data as well as forwarding other nodes' data to the base station. This rapid energy depletion of some nodes generate energy holes problem, which can significantly reduce the life

span of the network.

In this work, GRPs will be used because they have lower network overhead than topological routing protocols because they do not require route discovery and route maintenance. Additionally, decentralized routing algorithms can be implemented in GRP efficiently where, each node makes its forwarding decision based on its local information only. These positive attributes of GRPs make them promising candidates for WSNs. In this dissertation, GRPs are designed to enhance the network lifetime by using game theory [26, 34].

In this dissertation, two novel decentralized, scalable and energy balanced routing protocols are proposed:

- A. Game theoretic energy balanced (GTEB) routing protocols for WSNs. GTEB is designed and implemented in WSN deployed in 2D space.
- B. Three dimensional game theoretic energy balanced (3D-GTEB) for WSNs. 3D-GTEB is designed and implemented in WSN deployed in 3D space.

The protocol operations are verified via a combination of evolutionary game theory (EGT) and classical game theory (CGT), an extensive simulation as well as analytical evaluations which have been conducted to verify their validity.

1.3 Contributions

The primary contributions of this dissertation are:

1. A novel energy balanced geographical routing protocol is proposed and extensively evaluated theoretically and in simulation, which is called: Game Theoretic Energy Balanced Routing Protocol (GTEB). GTEB protocol was designed based on a combination of evolutionary game theory (EGT) and classical game theory (CGT). GTEB was compared to two competing GRPs and to a probabilistic forwarding protocol. GTEB shows a promising performance compared to other two

competing protocols in terms of prolonging network lifetime, packet delivery rate, and energy consumption per packet. Moreover, GTEB is compared to three other advised geographical routing protocols which are designed to evaluate the reliability of GTEB in terms of region forwarding selection and forwarding node selection techniques.

2. Energy balance is achieved in the region level by balancing the traffic load over a set of packet forwarding regions around every sender and/or relay node between the source and destinations. In order to minimize the energy consumption per region and to delay the network partitioning at the region level, evolutionary game theory (EGT) was applied to balance the traffic load among these forwarding regions. Energy balance was achieved, in the node level, by distributing the traffic load evenly among the nodes in the forwarding region in order to delay network partitioning at the node level. The classical game theory (CGT) was used to balance the traffic load among a number of nodes in the forwarding region to minimizing the energy consumption per node. By combining region level energy balanced (RLEB) with node level energy balance (NLEB) the ultimate objective of this work, maximizing network lifetime, was achieved.
3. GTEB which is designed for 2D WSN was extended to 3D-GTEB to provide a solution to 3D WSN. The network lifetime, packet delivery ratio, and average energy consumption per packet were further improved by in-cooperating third coordinate of node locations.
4. The energy hole problem was solved by reflecting dynamic changes in the network by detecting the dynamic changes in the network conditions using evolutionary game theory.

The results were promising and the protocols exhibited exactly the desired properties: localized forwarding decision, flexible when an energy hole problem occurs,

optimal routing solution for minimizing energy consumption in sensor nodes, highly reliable (delivery rate), highly scalable, fits with any network size, and significantly extended network lifetime.

In RLEB, the analysis of the region level evolutionary game modeling has reached stable traffic load distribution over a set of forwarding regions using the concept of replicator dynamics. Such analysis was applied to 2D and 3D-forwarding regions. This work shows that if the traffic load distribution was disturbed, the traffic distribution would return to its original stable distribution. The analytical study in the NLEB proves that the effectiveness of using classical game theory in NLEB problem modeling and shows that all nodes play their role as a forwarder/or not at equilibrium satisfactory point. In summary, the routing protocol frameworks designed in this dissertation not only support the WSNs quality of services requirements, but also able to minimize energy consumption in sensor nodes, provide high reliability (delivery rate), and avoid energy hole problem.

1.4 Research Objectives

All problems that discussed in 1.2 are investigated and solved throughout this dissertation. In this work, network conditions and sensor node behavior were studied and it is found that designing a decentralized decision making routing algorithm can extend the network lifetime. The use of the EGT to balance the energy dissipation over the set of forwarding regions was proven, and also this study shows that the CGT can be used to balance the energy consumption in sensor nodes that are located in the same forwarding region. Therefore, to achieve such wide energy balance both EGT and CGT were combined in one protocol. The objectives of the research have achieved throughout five steps as following:

Step 1. In this phase, a routing algorithm for 2D WSN was developed to balance traffic load over a set of forwarding regions around the senders/relays. This

protocol was designed to make all forwarding regions consume their energy at the same time. The routing protocol is investigated in OMNeT++, and it was implemented using an evolutionary game.

Step 2. In this phase, the routing protocol in step 1 was enhanced by balancing the traffic load among nodes that were located in the same forwarding regions. This enhancement was investigated in OMNeT++, and it was implemented using a classical game.

Step 3. Both phases were combined together to form one game theoretical energy balance routing protocol; named GTEB. GTEB was evaluated based on an analytical analysis and compared to three state-of-art geographical routing protocols: RTLD [29], RPAR [35], and probabilistic forwarding protocols. This routing protocol was designed to fit with WSNs deployed in 2D space and is applicable to any network topology with various traffic loads.

The proposed protocol also evaluated with the three advised random forwarding protocols.

Step 4. In this step, a new 3D-GTEB routing protocol was designed by enhancing GTEB by including the third coordinates of node locations in the routing calculation. This protocol was investigated in OMNeT++, and evaluated by comparing the network lifetime and the packet delivery ratio in 3D-GTEB to GTEB.

Step 5. The stability in GTEB and 3D-GTEB was mathematically analyzed and the results proved that the protocols reach a stable state and all sensor nodes deplete their energy approximately at the same time.

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 Game Theoretic Energy Balanced (GTEB) Routing Protocol for Wireless Sensor Networks. Chapter 4 describes the design of Game Theoretic Energy Balancing Routing in Three Dimensional (3D-GETB) for Wireless Sensor Networks. 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.

2.1 Introduction

The process of establishing paths from a given sensor node to any base station through a single or multiple hop is called routing. Routing establishment is the main responsibility of the network layer of the communication protocol stack. Finding and maintaining routes in WSNs are not trivial tasks because energy restrictions and unreliability of the wireless medium cause unpredictable topological changes. Since WSNs applications require a large number of sensor nodes to be deployed in large geographical areas, thus the multi-hop communication approach is necessary. In multi-hop routing approach, nodes must not only generate and transmit the data which they sense, but also act as relays and forward the data of other nodes. However, when the nodes are deployed in harsh and inaccessible areas, usually they are deployed in a randomized way and the resulting topologies are non-uniform and unpredictable. In such case, it is important for the sensor nodes to have the ability to cooperate in order to determine their positions, learn about their neighbors, and explore the route to the base station. Thus, designing routing protocol that can adapt to topological changes and is able to fit to WSNs limited resources is essential to extend the network lifetime. Moreover, reliable routing protocols have various influences on

packet delivery ratio (PDR), quality of service (QoS), fault resistance, and energy dissipation fairness [26, 36, 37]. Therefore, WSNs require routing solutions that are light weighted, adaptive, scalable, and flexible.

2.2 Wireless Sensor Network Routing Metrics

The routing protocol metrics are used to express various objectives of the routing protocols with respect to the limited resources of WSNs. This section provides a brief overview of the routing protocol metrics that are related to this study:

- A. **Network lifetime:** The network lifetime is defined as the duration before any sensor node in the network becomes inoperative due to energy depletion [24, 38]. Thus, it is important to balance energy dissipation in wide range of sensor nodes to prevent premature network failure. In such balance, it has to ensure the average energy usage per node is the same in all sensors to prolong the network lifetime.
- B. **Average energy consumption per packet:** The average energy consumption per packet refers to the average amount of energy spent by all nodes to successfully deliver a packet to the destination [10, 39]. The goal of this metric is to minimize the total amount of energy dissipation for broadcasting a packet from the source node to the base station (sink). Average energy consumption per packet metric is the basic concept to evaluate the energy efficiency in routing protocols.
- C. **Packet delivery ratio:** The packet delivery ratio refers to the ratio of delivered packets to the base station out of the total number of generated packets by the sender node [40, 41]. The main objective of using this metric is to assess the network performance and protocol reliability.

2.3 Routing Protocol Classification

In literatures, a wide range of routing protocols has been proposed to solve multi-hop routing problem [36]. In general, the routing protocol algorithms can be classified into two categories: topological routing protocols and geographical routing protocols.

A. Topological Routing Protocols:

Topological routing protocols (TRPs) were designed on the basis of routing algorithms that engineered for mobile ad hoc networks (MANETs) [37, 42]. In the topological routing approach, a route is usually pre-defined among nodes and stored in a routing table before initiating a packet transmission, where every node has its own routing table [43]. The main advantage of this approach is that a route is readily available whenever a node requires sending a message to any other node. On the other hand, it is not adaptable to the dynamic changes in the network and has high network overhead due to the route discovery and route maintenance procedures, which were very costly in the energy constrained WSNs networks. In [37] a survey on multi-path routing and their challenges is presented.

B. Geographical Routing Protocols in WSNs:

Geographical routing protocols (GRPs) benefit from location knowledge of the sensor nodes to send data from any given node to the destination. This is done without the need to build up a routing table [26, 36]. Hence, the sender does not need to check the route availability or breakage as the packets travel from the sender to the destination they may take different routes depending on the network status. Furthermore, eliminating the reliance on topological information makes GRPs suitable to handle dynamic conditions that often present in WSNs. This makes geographical routings a valuable option to devise decentralized and scalable routing protocols which can balance energy utilization in WSNs. However, GRPs require location information. This information can be provided via Global

Positioning System (GPS) in outdoor deployments, and signal strength and time of arrival based location estimation techniques in indoor deployments [27]. Moreover, GRPs can be applied in WSNs deployed in two dimensional (2D) terrain or deployed in three dimensional (3D) terrain [44].

2.4 Energy Balanced in WSN

The main goal of energy balance in WSNs is to prolong network lifetime. Energy balance is commonly achieved through routing protocols by evenly distributing traffic load among nodes to ensure that the average energy expenditure in all nodes is the same [24, 45]. In GRP, there are two common energy balance routing techniques: route level energy balance [46, 47] and region level energy balance [23, 28, 48].

2.4.1 Route level energy balance

Route level energy balance is aiming to prolong the network lifetime by optimizing the energy usage in the sensor nodes that belong to a set of pre-defined routes. In this approach, a higher traffic load is observed around the line between the source and destination node [49, 50]. Additionally, more traffic will be passing through one hop nodes away from the destination causing quick energy depletion and early network partitioning. That is why, considering balancing energy in route level is not enough to achieve network wide energy balance.

2.4.2 Region level energy balance

In this approach, the energy balance can be achieved using region based forwarding techniques [22, 50]. The terrain of network is divided into a set of geographical regions and all the nodes that are located in those regions will forward the received packets causing redundant transmissions [27, 28, 40]. For that reason, the imbalance will still

exist in the region nodes in this approach. This imbalance can lead to premature network partitioning as some nodes in a forwarding region are used for packet forwarding more often.

Accordingly, both route level energy balance and region level energy were combined in this dissertation to achieve an effective and wide energy balance routing protocols.

2.5 Game Theory An Overview

Game theory is the study of the conflict and cooperation among a set of players. The players can be any kind of decision makers such as individuals, groups, firms, or combination of these. The concepts of game theory provide a method to formulate, analyze, and understand strategic interactions. In general, game theory can be classified into two classes of theories [51]. These classes are: classical game theory (CGT), and evolutionary game theory (EGT).

2.5.1 Classical game theory

Classical game theory (CGT) is a part of applied mathematics that describes and studies interactive decision making processes, this is where several players make their decisions based on the potential effect of the interest of other players [52, 53]. Game theory was firstly introduced by Von Neumann and Oskar Morgenstern in their work "*Theory of Games and Economic Behavior*", published in 1944 [54]. The classical game theory comprises two types of games: cooperative and non-cooperative games. In the cooperative game the player selects his/her strategies based on the coordination along with other the players in the game, while in non-cooperative games each player selects his/her strategies without any interference from other players. In this study, I considered non-cooperative game of N players with mixed strategies.

Normally, any a classical game comprises of three basic components:

1. **Players:** The decision makers in the modeled scenario are players and denoted by a finite set, $\mathcal{N} = \{1, \dots, N\}$, where $N \geq 2$. A player is said to be rational when he/she can choose an action in a way to magnify his/her own payoff.
2. **Strategies:** A strategy is one of the given possible actions of a player and each player has a finite set of K strategies denoted by $\mathcal{S}_i = \{s_1, s_2, \dots, s_K\}$, where \mathcal{S}_i represents the strategy space for player i .

The strategy is defined as pure strategy when the player plays one of his/her strategies without any probability and has no uncertainty about the payoff that result from playing any strategy. In contrast, when the player chooses one of his/her strategies with certain probability without knowing exact payoff that result from playing any strategy it is called mixed strategy. In this dissertation, I considered N -player non-cooperative game with mixed strategies.

3. **Payoff function:** The function that quantifies a player's preferences for a given strategy is called payoff function and is denoted by $U_n(s_i, s_{-i})$, where s_i represents the strategy that is selected by player i and s_{-i} represents strategies that are selected by other opponents. The received payoff by any player depends on the strategy he/she picked and the strategies which all the other players picked.

In a game, every player tries to maximize his/her payoff by choosing his/her own best response strategy to what other opponents choose. Such strategy is denoted by $s_i^* \in \mathcal{S}_i$ and opponent strategies are denoted by $s_{-i} \in \mathcal{S}_{-i}$. The best response strategy is mathematically defined as follows,

$$(\forall s_i \in \mathcal{S}_i) \quad u_i(s_i^*, s_{-i}) \geq u_i(s_i, s_{-i}). \quad (2.1)$$

When all players choose their best response strategies, the resulting strategy combination is called Nash equilibrium strategies [55]. Nash equilibrium is considered the

solution that satisfies all the players in the game. When the game reaches Nash equilibrium state no player can increase his/her payoff by deviating from current strategy unilaterally. Nash equilibrium condition is expressed as:

$$\forall i \in \mathcal{N}(\forall s_i \in \mathcal{S}_i) \quad u_i(s_i^*, s_{-i}^*) \geq u_i(s_i, s_{-i}^*) \quad (2.2)$$

It is worth mentioning that the condition in (2.2) is held in every N -player non-cooperative game whenever mixed strategies are allowed [52].

2.5.2 Evolutionary game theory

Evolutionary game theory (EGT) was originally developed by J. Maynard Smith and G.R Price [56] to study the evolutionary and animals conflict in nature. In particular, EGT is used to make reliable predications about population dynamics, where individuals in the populations are repeatedly engaged in strategic interactions. Evolutionary games are also useful to find the stable balance in the distribution of the proportions of population competing for resources in absence of a global view of the resources and the total size of population [56]. The proportion distribution of population λ over a set of different geographical regions is called the population state and denoted by, $X = [X_1, \dots, X_K]$, where $X_k = \frac{\lambda_k}{\lambda}$ and λ_k is the number of individuals that uses region k . A balance is achieved when an individual in a portion of population X receives the same fitness (payoff) in all geographical regions K . This balance evolves over time based on the resource consumption rate and the availability of residual resources at various regions. An evolutionary game consists of five main components:

1. **Player:** Any individual in the population is considered a player.
2. **Population:** The set of players that engage in strategic interactions are considered as population of players.

3. **Strategies:** The variations of selections from a set of K geographical regions by a player are considered as the set of strategies.
4. **Fitness function:** The function that quantifies the expected payoff that is received by the player when he/she plays one of his elementary strategies against the mean strategy of the population in the conflicting field is called fitness function.
5. **Replicator dynamics:** The set of differential equations that captures the inflow and outflow of players from one region to other regions represents Replicator dynamics.

In this study, the fitness function is defined as a decreasing function of population, which depends on the players' density that follows various strategies. On that account, the fitness function is expressed as follows,

$$F_k(X) = \mathcal{B}_k - H_k(X_k\lambda), \quad (2.3)$$

where, $F_k(X)$ represents the fitness function of the player when it uses region k and \mathcal{B} represents the available resources for the player in region R_k , and H_k is an increasing function of players' density in the conflict field.

The evolution of proportions of a population that adopt different strategies (regions) over time can be modeled through the replicator dynamics [57], which can be given as follows,

$$\dot{X}_k = X_k[F_k(X) - \bar{F}(X)], \quad (2.4)$$

where, $\dot{X} = [\dot{X}_1, \dots, \dot{X}_K]$ represents the vector of the players' distribution over all regions and $\bar{F}(X)$ represents the mean fitness for the population and given by:

$$\bar{F}(X) = \sum_{k=1}^K X_k F_k(X). \quad (2.5)$$

Ideally, such distribution would converge to a stable state, where the proportions do not change with time and even if they change, they would return to the stable state after a period of time. Such equilibrium proportion distribution is given by the vector, $X^* = [X_1^*, \dots, X_K^*]$.

At this moment the strategies that are followed by the players are called evolutionary stable strategies (ESSs), whenever the following conditions are hold:

- A. The fitness function for a player must be the same in all regions.
- B. The player cannot increase its fitness by moving to any other region.

These two conditions are robust and a refined version of the Nash equilibrium. The mathematical expressions of ESS is given hereunder:

$$XF(X^*) \leq X^*F(X^*) \quad (2.6a)$$

$$XF(X) \leq X^*F(X) \quad (2.6b)$$

Equation (2.6a), represents the Nash equilibrium condition and (2.6b), represents the evolutionary stability condition.

2.6 Literature Review

The research work in this dissertation is related to the energy balance in WSNs. The literatures reviewed throughout this dissertation is divided into the following three sub-sections.

2.6.1 Review of energy balance in 2D WSNs

Maximizing network lifetime can be achieved using different methods such as altering transmission power as in [23], designing power aware routing protocol as in [24], and distributing traffic load among least power routes as in [49,50]. Although each of these methods offers benefits, the most plausible is the load balancing. However, there is no globally applicable load balancing solution for extending the network lifetime in GRPs. This dissertation provides a globally applicable solution to extend network lifetime by balancing traffic load over regions and nodes, with scalable and distributed manner using GT and GRP.

GRPs are gaining popularity and are being employed for industrial applications such as advanced metering infrastructures for smart grids [26]. Geographical forwarding does not require routing overhead and every node is able to make its forwarding decision distributively and locally. GRPs have also been proposed to balance energy in the WSNs to prolong the network lifetime. Ahmed and Faisal [29] proposed a quadrant based directional forwarding scheme, called Real-time Load Balance Distribution protocol (RTLDD), which limits the forwarding task to a quadrant of the forwarding nodes. However, redundant transmissions in the selected quadrant may occur and some quadrants could be utilized more than others, depending on the location of the source. Jinnan et al. [23] presented heuristic routing scheme to solve the problem of uneven energy consumption around energy hole in GRPs. This scheme cannot be generalized to achieve load balancing in the entire network. Charilaos E.

et. al [21] presented a solution to the problem of condensing a traffic load around the base station (sink) by adjusting the transmission power of the nodes to by-pass these vulnerable nodes around sinks, and transmitting directly to the sink with certain probability. Although using a larger transmission power is more energy expensive, it helps extending the lifetime of the network. Petrioli et. al [22] presented ALBA-R localized and distributed GRP for balancing traffic load on nodes that are located around energy holes so that those nodes do not run out of energy too early. In our case, GTEB can detect the energy hole problem areas and does not forward any traffic toward such areas. Chipara et. al [35], suggested a real-time power aware routing protocol (RPAR) to find balance between end-to-end delay and energy consumption using transmission power adjustment. RPAR is compared to the proposed protocol in this dissertation.

2.6.2 Review of energy balance in 3D WSNs

As a part of this dissertation is related to the energy balance in 3D WSNs, therefore some of the related papers are discussed in this subsection. In order to overcome premature energy depletions in 3D WSNs different methods have been proposed [58,59]. For instance, proposals such as [30] and [31] offer to balance traffic load by mapping 2D network on a sphere and by routing packets on the surface of the sphere using virtual spherical coordinates. Particularly in [30], Circular Sailing Routing (CSR) is proposed to reduce congestion of the hot spots at the center of the network, which extended the lifetime of the whole network. Balanced energy consumption in a set of predefined routes was investigated in [60]. However, that approach requires a large number of routes to achieve a global load balance in order to provide a feasible solution [19]. Nonetheless, most of the available literatures offer solutions to 2D networks or assume the networks are 2D to reduce the complexity [60,61]. Realizing importance of 3D, a number of protocols are emerging in the literature for 3D WSNs [32].

Ellipsoid geographical 3D greedy-face based routing protocol was proposed to extend the network lifetime [44]. Greedy based routing algorithm, called ALFA+, was proposed to balance traffic load in a 3D network by forwarding packets toward regions that experience minimum traffic load [62].

2.6.3 Review of game theory in WSNs

A. Review of classical game theory in WSNs:

Game theory was proven to provide versatile solutions for dynamic and distributed networking problems [63]. CGT is used in GRPs for various problems related to the end-to-end delay optimization, task allocation, relay selection, and network congestion [64, 65]. Tekinay [66] had presented a survey for game theory applications in security and energy efficiency with different formulations of these problem based on the approach of game theory. Behzadan et al. [48] proposed a game theoretic heterogeneous balanced data routing (HBDR) algorithm for WSNs with tree topology. In this protocol, a hierarchical network is constructed using CGT to provide a load balanced tree that maximizes the lifetime of network.

Kamhoua et al. [67] proposed a GT based congestion avoidance mechanism for a GRP around the line between the source and destination. Naserian and Tepe [68] used game theoretic routing to reduce routing overhead by selecting forwarding nodes to provide connection without network partitioning. Neda et al. [65] applied forwarding task allocation problem to classical game in order to optimize energy consumption among sensor nodes to extend network lifetime. Huang et al. [69] proposed to use CGT in base stations for relay selection and transmission power allocation for the network.

B. Review of evolutionary game theory in WSNs:

EGT is emerging as an important tool to solve dynamic networking problems due to changes in energy state, channel state, and topology [70]. For example, Niyato and Hossain [71] used EGT to allocate bandwidth for the users based on the service cost of various wireless networks. Anastasopoulos et al. [72] employed an evolutionary game to optimize traffic routing over multi-path wireless back-haul networks experiencing rain attenuation. Khan et al. [63] applied EGT to fairly distribute users to various wireless access network technologies for bandwidth and cost. Altman et al. [70] designed EGT based routing protocol for WSNs to control congestion and reliability influenced by the wireless channel's characteristics. In [73], EGT is implemented to solve the packet forwarding problem when a network consists of heterogeneous nodes operated in networks with different authorities. This shows that the forwarding cooperation among authorities can evolve and provide stable communication. In this dissertation, load balancing based on available energy levels in the surrounding nodes was performed using EGT.

2.7 Summary

In this chapter the routing protocol definition, routing protocol metrics, routing algorithms classification, and the related techniques that are used to balance energy consumption in WSNs are discussed. It showed that geographical routing protocol provides a better energy solution than topological protocols. Introductions to the classical and evolutionary game theories were also provided. The literature review of energy balanced in 2D WSN, 3D WSN, and game theory in WSNs are presented. The combination of the two levels of game theories decision making will be presented in the next chapter as the core of the protocol design in this dissertation.

3.1 Introduction

Extending network lifetime and sensor functionality is crucial for successful utilization of wireless sensor networks (WSNs) in a number of challenging applications, where replacing or charging energy storage units (i.e. batteries) in the sensor devices is impractical or not cost effective. For example, ARGO project deploys thousands of floating sensors to gather hydro-graphic data from oceans and their energy supply cannot be replaced or recharged [74] after they are released to the environment. Prolonging sensors lifetime can significantly reduce the cost of ARGO project and help us to understand health of the oceans better. There are many similar large data gathering projects for which expansion of WSNs lifetime is extremely important. Different approaches have been used to extend the lifetime of sensor nodes. One prominent approach is to balance the WSN communication in the network in order to deplete energy at similar time or rate [21,29,49]. In these approaches, routing decisions play an important role in selecting candidate paths for balancing energy [20,33,38,50].

Geographical routing protocols (GRPs) seem to be more suitable for WSNs be-

cause they do not need routing tables, and therefore, do not require route discovery and route maintenance mechanisms which incur large overhead. However, GRPs require location information. This can be provided using Global Positioning System (GPS) in outdoor deployments, and signal strength and time of arrival based location estimation techniques in indoor deployments. Although these may increase the complexity of the GRPs for networks where nodes do not move, and data gathering applications where location of sinks are fixed, the benefits of simplicity of GRPs exceeds this extra complexity of obtaining location information. For this reason routing protocol for low power and lossy networks (RPL) as a GRP is adapted for smart grid applications [75]. One problem with GRPs, is that they do not have a global view of the network, including energy information at regions and nodes, and providing this information can incur large overhead and increase complexity. This issue is addressed by adopting distributed and relatively simple algorithms to balance energy in order to extend WSN lifetime.

This dissertation uses a game theoretic (GT) approach to build a viable load balancing solution to extend WSNs lifetime. GT offers interesting decision making mechanism in distributed and dynamic environment in absence of global view and certainty. For this reason GRP combined with GT was used in this work to take advantage of inherent benefits of this combination. In this work, the energy balance problem is solved at both region level and node level. In RLEB, the objective is to balance the energy consumption around a sender such that all sub-regions around the sender will participate fairly and deplete their energy approximately at the same time. After selecting the participating region, NLEB is required to select the most favorable forwarder node in this sub-region. Because of the objectives of RLEB and NLEB are different, RLEB employs evolutionary game theory (EGT), and NLEB employs classical game theory (CGT). EGT captures the dynamic energy changes in the sub-regions while CGT captures the selfish behavior of the nodes to preserve their

energy in the selected sub-region.

The main contribution of this dissertation is twofold. First, a new method is developed for extending the network lifetime by balancing traffic load at two levels, over regions and at the nodes in those regions. Second, the energy hole problem in WSN geographical routing is mitigated using EGT [23]. The energy hole problem occurs due to an uneven traffic load distribution. For instance nodes closer to the sink have to take heavier traffic load leading to deplete of their energy faster and partitioning of the network. In this dissertation, the energy hole problem is mitigated by using an evolutionary game.

In this chapter a description of the protocol with is presented in Section 3.2. Sub-section 3.2.1 provides a detailed region level energy balance while Sub-section 3.2.5 presents the detailed of node level energy balance of the proposed protocol. Section 3.3 presents the results and discussion. Finally, conclusions are drawn and further research is suggested in Section 3.4.

3.2 Protocol Description

The proposed game theoretic energy balanced (GTEB) routing protocol is designed to provide energy balance to randomly deploy multi-hop WSNs with \mathcal{M} homogeneous nodes with transmission range is r . Initial energy of a node is E Joules. The nodes know their locations and the location of the destination node (base station). In the network, any node can be a source and can report events periodically or when they occur. The problem of achieving network wide energy balance is broken down into the following two sub-problems:

A. RLEB at sub-regions.

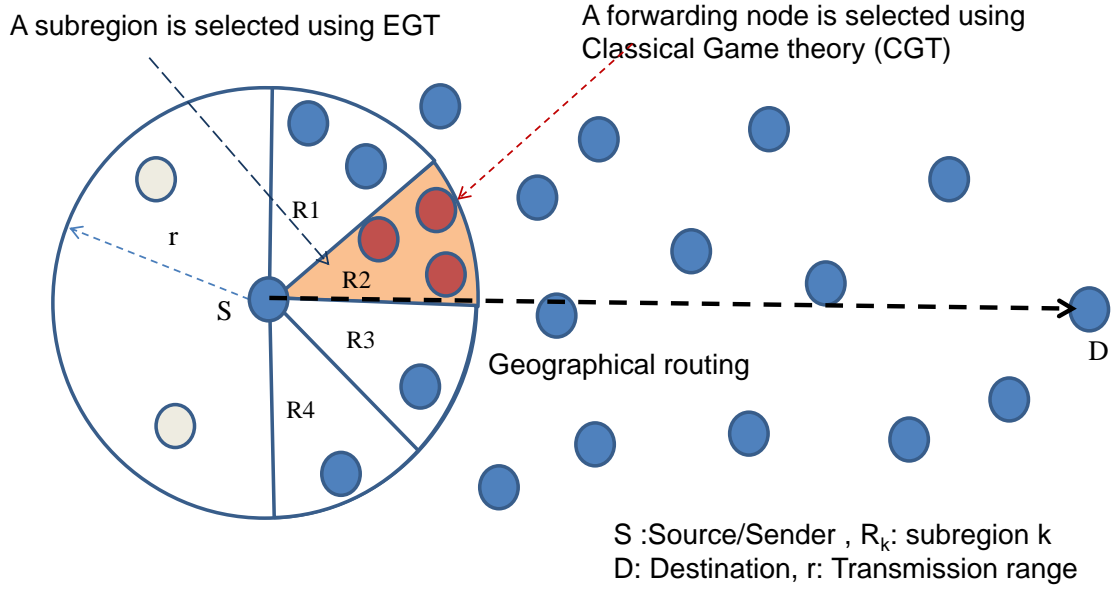


Figure 3.1. Subregion and node selection in the proposed protocol.

B. NLEB within the sub-region.

The energy balance at region level is achieved using EGT and the energy balance at node level will be achieved using CGT. The transmission range of a sender is divided into K forwarding sub-regions based on network density ρ . Figure 3.1 illustrates this scenario. In the figure, the selected sub-region is shaded and the selected forwarding node is shown.

Based on an EGT, a sender forwards a packet to one of its neighborhood with the following information:

1. Angle, θ , which is bounding the selected forwarding sub-region.
2. N_k , number of neighbors in this sub-region.
3. Sender's location (x, y) .
4. Proportion of packets, λ_k assigned to this sub-region.

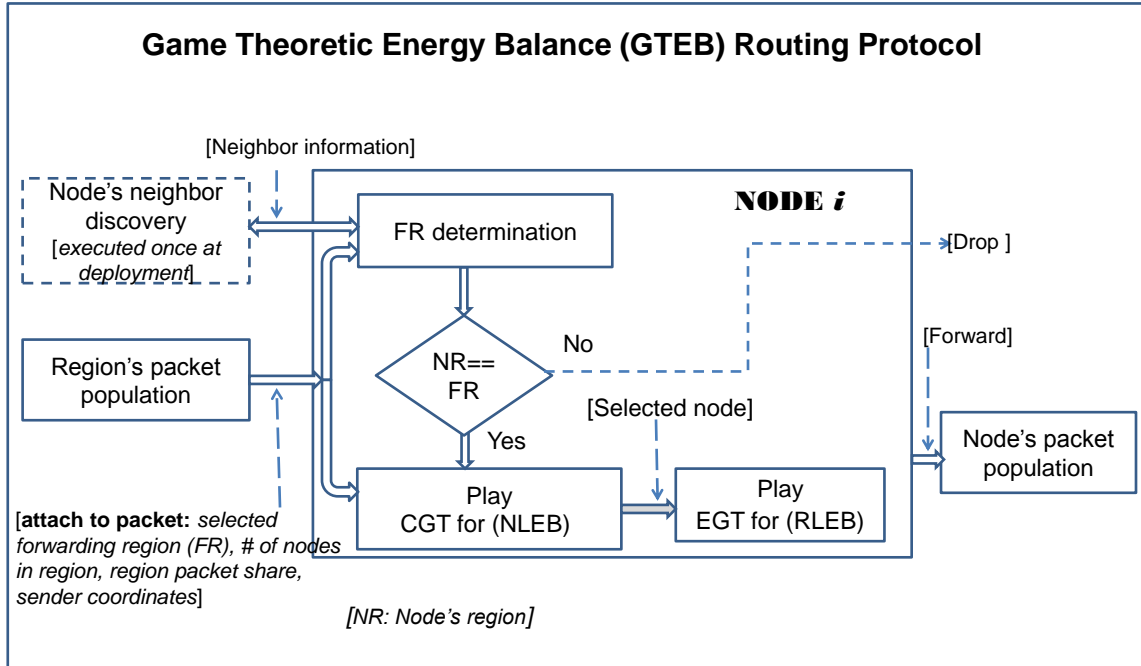


Figure 3.2. GTEB's functional diagram.

This information, provided by the packet, will allow surrounding nodes to identify whether they are in the forwarding sub-region. Then the nodes in the selected sub-region will play N -player non-cooperative classical game to identify which one will be potential forwarding node (PFN). One of the PFNs, in that sub-region who wins the game becomes a sender node, and its turn, plays it's own evolutionary game to select the next forwarding region in order to balance energy consumption in its own surrounding.

Figure 3.2 shows a schematic functional diagram of the distributed decision making processes in GTEB protocol. The node neighbor discovery function depicted in the figure is executed once at the deployment time of the network in order to allow nodes to learn the number of one hop neighbors. Other functions will be executed whenever a node receives a new packet from one of its neighbors. The node drops a received packet, if it is not located in the designated forwarding sub-region or if the packet has been forwarded before.

3.2.1 Region level energy balance (RLEB)

The objective of RLEB is to spread the forwarding task around the sender node fairly such that surrounding nodes deplete their energy at the same time. EGT is employed to achieve this objective. We assume total number of packets λ sent by a sender is S or any relay, which represents the total population of region level evolutionary game (RLEG). This population of packets is distributed to K sub-regions throughout the operation. Hence a sub-region k will forward λ_k packets and, consequently the total number of packets that are forwarded by all sub-regions is $\lambda = \sum_{k=1}^K \lambda_k$. The task of RLEG is to define the proportion of packets that can be forwarded by each sub-region in every game interval. Senders play the RLEG on behalf of the packet, and the set of strategies for the packet is the selection of sub-regions, which is denoted by $R = \{R_1, R_2, \dots, R_K\}$. Every packet has set of K strategies to play. The proportion of the packets forwarded through k th sub-region is specified by X_k , which is given by $\frac{\lambda_k}{\lambda}$. Thus, the packet population distribution vector X over all sub-regions is given by $X = [X_1, X_2, \dots, X_K]$. The goal of employing EGT is to find the stable packet proportions distribution of population in all sub-regions in order to make all regions consume their energy approximately at the same time. Such stable vector is called equilibrium packet proportions distribution vector or stable state X^* .

This vector can be obtained by modeling the energy balance problem into a set of differential equations, which will be the replicator dynamics of the RLEG. The most important part of evolutionary game is to design a fitness function that captures the energy consumption in the network. The fitness function will be used to identify switching probability from one region to another region. Both of these will be utilized to obtain replicator dynamics to find the equilibrium solution for the game. The fitness function $F_k(X)$ for a packet is expressed in term of gain and cost of utilizing a region for forwarding. The gain, E_k , represents the available remaining energy in the sub-region k . The cost of sending a packet through a sub-region depends on following

parameters:

1. Packet transmission and reception energies.
2. Number of nodes in that sub-region N_k .
3. Number of packets sent through this sub-region λ_k .

Consequently, the fitness function is given by

$$F_k(X) = E_k - [\lambda * X_k * (2 * N_k * E_{tr} + E_{tx})], \quad (3.1)$$

where E_{tr} and E_{tx} are the energy consumed by a node while receiving and transmitting a packet respectively. E_{tr} and E_{tx} are both dependent on the packet length of m bits, the transmission radius of d meters, and few hardware parameters. Then, energy consumption by a node for transmitting a packet can be expressed as

$$E_{tx}(m, d) = m * (e_{tc} + e_{ta} * d^\alpha), \quad (3.2)$$

where the energy spent by transmitter electronics is denoted by e_{tc} , and transmitter amplifier by e_{ta} . These are hardware dependent parameters related to the processing, sending the packets, and α is the path loss exponent whose value is larger than 2 in sensor networking applications.

The energy consumption by a node for receiving a packet is given by

$$E_{tr}(m) = m * e_{rc}, \quad (3.3)$$

where e_{rc} is the transceiver efficiency during the start-up time, which is ignored due to its dependence on the type of MAC protocol used.

All nodes located in the same sub-region (in transmission range of forwarding/sender node) will spend the receiving energy cost as they all receive the packets. After sub-region selection, one node only will be selected based on N -player non-cooperative

game to forward the packet in NLEB, and the forwarding node will spend the transmission cost. The values of transmission and receiving cost can be obtained from any sensor node's data-sheet. For example, the energy consumption for transmission and reception of an IRIS sensor node is 51 and 24 milliwatts, respectively [76]. During the protocol run time, packets forwarded in sub-region k will be further forwarding by next hop neighbor in a given game interval.

The fitness function in (3.1) expresses that a packet will be forwarded to a sub-region as long as the available energy in that sub-region E_k is more than energy threshold value given by

$$E_k/(\lambda * X_k) \geq (E_{tx} + E_{tr}), \quad (3.4)$$

which represents the required energy to receive and forward a packet. That is why the packet's share of energy will be decreased with the increase in the number of packets in a forwarding sub-region. Hence, a sub-region is considered dead if its residual energy drops below the energy threshold value.

3.2.2 Replicator Dynamics

The replicator dynamics provide packet population distribution over different sub-regions. Selection of a sub-region is considered a strategy for a packet. In every game interval, a sender decides the proportions of packets to be forwarded through various forwarding sub-regions based on their residual energies. The switching probability $P_{k,l}(X)$, from sub-region l to sub-region k is associated with region fitness values $F_l(X)$ and $F_k(X)$, respectively. This switching probability can be defined as,

$$P_{k,l}(X) = \begin{cases} \beta X_k [F_k(X) - F_l(X)] & \text{if } F_k(X) > F_l(X), k \neq l \\ 0 & \text{if } F_k(X) > F_l(X), k \neq l \\ 1 - \sum_{i \neq k, i \in K} \beta X_i [F_i(X) - F_k(X)] & \text{if } k = l, \end{cases} \quad (3.5)$$

where X_l is the proportion of packets in the sub-region l and β is the normalization factor for the total energy in all sub-regions and given by,

$$\beta = \frac{1}{\sum_{i=1}^K E_i}. \quad (3.6)$$

where E_i is the initial energy in node i . The rate of the change in the number of packets that forwarded through sub-region k represents the difference between the inflow and outflow packets. The expected number of inflow packets that might switch from another region to the region k is expressed as,

$$\sum_{l \neq k} X_l P_{k,l}(X), \quad (3.7)$$

and the expected number of outflow packets that might switch from region k to the other sub-regions is given by,

$$\sum_{l \neq k} X_k P_{l,k}(X). \quad (3.8)$$

The summation of all probabilities of switching from sub-region k to all other sub-regions including the sub-region itself must be one, which is reflected by the following equation,

$$P_{k,k}(X) + \sum_{l \neq k} P_{k,l}(X) = 1. \quad (3.9)$$

Accordingly, the differential equations of the replicator dynamics that captures the net change in the number of packets in game interval (unit time) in sub-region k , and can be given as follows,

$$\dot{X}_k = \sum_{l \neq k} X_l P_{k,l}(X) - \sum_{l \neq k} X_k P_{l,k}(X)$$

$$\dot{X}_k = \sum_{l \neq k} X_l P_{k,l}(X) - X_k \sum_{l \neq k} P_{l,k}(X)$$

$$\dot{X}_k = \sum_{l \neq k} X_l P_{k,l}(X) - X_k [1 - P_{k,k}(X)]$$

$$\dot{X}_k = \sum_{l \neq k} X_l P_{k,l}(X) + X_k P_{k,k}(X) - X_k$$

Hence, the replicator dynamics can be given by,

$$\dot{X}_k = \sum_{l=1}^K X_l P_{k,l}(X) - X_k \quad (3.10)$$

Using (3.5) the transition probability matrix P for a scenario with two sub-regions is provided by,

$$P(X) = \begin{bmatrix} 1 & \beta X_1 [F_1(X) - F_2(X)] \\ 0 & 1 - \beta X_1 [F_1(X) - F_2(X)] \end{bmatrix} \quad (3.11)$$

The change in packet proportions over all sub-regions for a sender is obtained substituting (3.11) in (3.10), can be written in a matrix form as follows,

$$\dot{X} = P(X)X - X. \quad (3.12)$$

When the number of inflow and outflow packets from all sub-regions are equals then the system is in the stability state.

3.2.3 Evolutionary equilibrium

RLEG reaches the equilibrium state when the rate of change in the proportions of packets in all sub-regions, \dot{X} becomes zero vector. At this state, the proportion of packets is represented by X^* . In order to find the equilibrium state, the solution of the set of system equations in (3.12) must be obtained as in below,

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 1 & \beta X_1 [F_1(X) - F_2(X)] \\ 0 & 1 - \beta X_1 [F_1(X) - F_2(X)] \end{bmatrix} \cdot \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} - \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (3.13)$$

Where,

$$X_1 > 0,$$

$$X_2 > 0$$

and

$$\sum_{k=1}^K X_k = 1 \quad (3.14)$$

According to Brouwer fixed point theorem [77], there will be at least one fixed point (Nash equilibrium) for any continuous function over a closed interval. In this work, the set of equations in (3.13) depend on the switching probability in (3.5). The switching probability is a continuous function of X on the closed interval $[0,1]$. Consequently, (3.13) have fixed points, which are denoted by X^* . From (3.13) and (3.14), the net changes in proportions of packets in the two sub-regions are given by

$$\dot{X}_1 = X_1 + \beta X_2 X_1 [F_1(X) - F_2(X)] - X_1 = 0 \quad (3.15)$$

$$\dot{X}_2 = X_2 - \beta X_2 X_1 [F_1(X) - F_2(X)] - X_2 = 0$$

Simplifying the above equation in (3.15) leads to:

$$\dot{X}_1 = \beta X_1 X_2 \cdot [F_1(X) - F_2(X)] = 0 \quad (3.16)$$

$$\dot{X}_2 = -\beta X_1 X_2 \cdot [F_1(X) - F_2(X)] = 0$$

By solving (3.13) and (3.14) using (3.1), setting $C_k = 2N_k E_{TR} - E_{TX}$, substitute $X_2 = 1 - X_1$ in (3.16) and $\beta X_1 X_2 > 0$ the equation (3.16) can be solved as follows,

$$(E_1 - \lambda C_1 X_1) - (E_2 - \lambda C_2 (1 - X_1)) = 0$$

$$E_1 - \lambda C_1 X_1 - E_2 + \lambda C_2 (1 - X_1) = 0$$

$$E_1 - \lambda C_1 X_1 - E_2 + \lambda C_2 - \lambda C_2 X_1 = 0$$

$$E_1 - E_2 - X_1 \lambda (C_1 + C_2) + \lambda C_2 = 0$$

$$X_1 = \frac{E_1 - E_2 + \lambda C_2}{\lambda (C_1 + C_2)} \quad (3.17)$$

Hence, the elements of equilibrium vector are specified by

$$X_1^* = \frac{E_1 - E_2 + \lambda C_2}{\lambda (C_1 + C_2)} \quad , \quad (3.18)$$

$$X_2^* = 1 - \frac{E_1 - E_2 + \lambda C_2}{\lambda (C_1 + C_2)}$$

At the equilibrium state, a packet's fitness will be the same in all sub-regions, that

is $F_1(X) = F_2(X) = \dots = F_k(X)$ and no packet can increase its fitness by moving to another sub-region (strategy).

3.2.4 Stability analysis

In this section of analysis, the stability of the equilibrium state X^* is examined. To prove the population distribution stability, Equation (3.12) is linearized at X^* , whereas $F_1(X) = F_2(X)$, and Eigenvalues of Jacobian matrix $J(X_1, X_2)$ are obtained. Jacobian matrix for two forwarding sub-regions is given by

$$J(X_1, X_2) = \begin{bmatrix} \beta X_1 X_2 \frac{\partial F_1(X)}{\partial X_1} + \beta [F_1(X) - F_2(X)] X_2 & -\beta X_1 X_2 \frac{\partial F_2(X)}{\partial X_2} - [F_1(X) - F_2(X)] X_1 \\ -\beta X_1 X_2 \frac{\partial F_1(X)}{\partial X_1} - \beta [F_1(X) - F_2(X)] X_2 & \beta X_1 X_2 \frac{\partial F_2(X)}{\partial X_2} + \beta [F_1(X) - F_2(X)] X_2 \end{bmatrix} \quad (3.19)$$

Since $F_1(X) = F_2(X)$ at the equilibrium points X^* , Jacobian matrix of the system will be

$$J(X_1, X_2) = \begin{bmatrix} \beta X_1 X_2 \frac{\partial F_1(X)}{\partial X_1} & -\beta X_1 X_2 \frac{\partial F_2(X)}{\partial X_2} \\ -\beta X_1 X_2 \frac{\partial F_1(X)}{\partial X_1} & \beta X_1 X_2 \frac{\partial F_2(X)}{\partial X_2} \end{bmatrix} \quad (3.20)$$

Hence,

$$J(X_1, X_2) = \begin{bmatrix} -\beta \lambda C_1 X_1 X_2 & \beta \lambda C_2 X_1 X_2 \\ \beta \lambda C_1 X_1 X_2 & -\beta \lambda C_2 X_1 X_2 \end{bmatrix} \quad (3.21)$$

Eigenvalues γ of Jacobian matrix can be found by solving the following equation,

$$\det(J(X_1, X_2) - I\gamma) = 0 \quad (3.22)$$

where I is the identity matrix. The solution of (3.22) shows that Eigenvalues are $-\lambda C_1 \beta X_1 X_2 - \lambda C_2 \beta X_1 X_2$ and zero. Since the real part of Eigenvalue is negative, the ESSs condition is satisfied based on [78]. This proves that RLEB evolutionary game reach stable state. The region is considered dead when it does not have enough energy for transmission. Analysis and proof of the stability of X^* for K packet forwarding sub-regions are provides in appendix A.

Table 3.1. THE PAYOFF MATRIX OF N-PLAYER NON-COOPERATIVE GAME.

Player \mathcal{A}	$N - 1$ Players	$1 - (1 - q)^{N-1}$	$(1 - q)^{N-1}$
		T	\bar{T}
q	T	$-\delta - \Delta, -\delta - \Delta$	$v - \delta, 0$
$1 - q$	T	$0, v - \delta$	$0, 0$

3.2.5 Node level energy balance (NLEB)

The objective of NLEB game is to balance the energy consumption in a sub-region by selecting one forwarding node from N nodes in the sub-region k . This game is formulated as an N -player non-cooperative game of the following three components:

1. **Players:** The set of nodes in the same forwarding sub-region are consider as players and denoted by $\mathcal{N} = \{n_1, n_2, \dots, n_N\}$, where $N \geq 2$.

If there is only one node in a sub-region, then this node will forward the packet without playing any game.

2. **Strategies:** Each node has two mixed strategies, represented by a set $\mathcal{S} = \{T, \bar{T}\}$, where T represents transmission and \bar{T} represents no-transmission. Being a mixed strategy game, node \mathcal{A} plays one of available strategies against $N - 1$ opponent nodes. Other players play their strategies with their corresponding probabilities as shown in Table 3.1. Let the probability of transmission by a node is q , and no-transmission is $1 - q$, then the probability of transmission by at least another node is $1 - (1 - q)^{N-1}$; hence, the probability that all other nodes may not transmit is $(1 - q)^{N-1}$.

3. **Expected payoff:** the expected payoff for node i is denoted by $U_i(s)$, quantifies the award for node i when it plays one of its available strategy against other $N - 1$ players.

The matrix norm formulation that describes the game scenario is given in Table 3.1. In this game, if two or more nodes are playing transmission strategy simultaneously, all of the nodes will incur a collision cost of Δ and a transmission cost of δ , where Δ is greater than δ . If one node plays transmission strategy and other nodes play no-transmission strategy, the first node will receive reward value of v and incurs a transmission cost δ , v will be greater than δ . If no node plays transmission, then the payoff will be zero for all nodes.

The expected payoff calculated using Table 3.1 for a node n_i to forward a packet is given by

$$E[U_i] = q[(-\Delta - \delta)(1 - (1 - q)^{N-1}) + (v - \delta)(1 - q)^{N-1}] \quad (3.23)$$

Correspondingly, the expected payoff for no-transmission is zero. Therefore, equating $E[U_i]$ to zero will give probability q^* of mixed strategy Nash equilibrium as:

$$[(-\Delta - \delta)(1 - (1 - q)^{N-1}) + (v - \delta)(1 - q)^{N-1}] = 0$$

$$(-\Delta - \delta) - (-\Delta - \delta)(1 - q)^{N-1} + (v - \delta)(1 - q)^{N-1} = 0$$

$$-(-\Delta - \delta) = -(-\Delta - \delta)(1 - q)^{N-1} + (v - \delta)(1 - q)^{N-1}$$

$$(\Delta + \delta) = [(\Delta + \delta) + (v - \delta)](1 - q)^{N-1}$$

$$\frac{\Delta + \delta}{\Delta + v} = (1 - q)^{N-1}$$

$$(1 - q) = \left(\frac{\Delta + \delta}{\Delta + v}\right)^{\frac{1}{N-1}}$$

$$q^* = 1 - [(\delta + \Delta)/(\Delta + v)]^{\frac{1}{N-1}} \quad (3.24)$$

The number of player nodes in a region is N , the transmission cost $\delta = 51\text{milliwatts}$ and collision cost of $\Delta = 2 \times \delta$ are known and can be extracted from IRIS datasheet [76]. Each node uses its Nash equilibrium as a decision criteria to forward or drop the packet using its own forwarding probability in (3.26).

However, reducing the number of forwarding nodes may lead to network dis-connectivity. Nash equilibrium in equation (3.24) depends on the number of neighbors in forwarding sub-region N , and the reward value v . Hence, it is essential to determine the range of v and N , such that satisfy the following two conditions:

1. The number of players N must be greater than or equal to two [52].
2. The network connectivity is maintained with minimum routing overhead [79].

Previous studies in [80] and [79] showed that the required number of neighbors to maintain overall connectivity is at least four.

When the value of v is low, then the probability in (3.24) will be low, which might result in network dis-connectivity. However, for a high reward value that means the nodes have high their forwarding probability, and when $v \rightarrow \infty$ all nodes will forward the received packets causing redundant transmissions. For successfully forwarding a packet, the number of neighbors for each node should be on average of four, and the forwarding probability will be $0.9 \leq q \leq 0.99$. By using (3.24) with $\delta = 51\text{milliwatts}$ [76], where the a node transmits with 3dBm the value of v can be

calculated as follows,

$$(N - 1) \log q^* = \log\left(\frac{\Delta + \delta}{\Delta + v}\right)$$

$$\log(0.01) \leq \frac{1}{N - 1} \log\left(\frac{\Delta + \delta}{\Delta + v}\right) \leq \log(0.1)$$

$$-4 \leq \log\left(\frac{\Delta + \delta}{\Delta + v}\right) \leq -1$$

$$-4 \leq \log(\Delta + \delta) - \log(\Delta + v) \leq -1$$

$$-4 \leq \log(2\delta + \delta) - \log(2\delta + v) \leq -1$$

$$1 \leq \log(2\delta + v) - \log(3\delta) \leq 4$$

$$1 \leq \log\left(\frac{2\delta + v}{3\delta}\right) \leq 4$$

$$e^1 \leq \left(\frac{2\delta + v}{3\delta}\right) \leq e^4$$

$$2.7 \leq \left(\frac{2\delta + v}{3\delta}\right) \leq 10.8$$

$$8.15\delta \leq 2\delta + v \leq 32.16\delta$$

Table 3.2. NASH EQUILIBRIUM WITH DIFFERENT REWARD VALUE AND NUMBER OF NEIGHBORS

<i>Number of neighbors</i>	q^* with $v = 30.16\delta$	q^* with $v = 20\delta$	q^* with $v = 6.16\delta$
2	0.910045528	0.875	0.641157085
3	0.70007589	0.646446609	0.400965014
4	0.551935104	0.5	0.289384311
5	0.452346724	0.405396442	0.226026495
6	0.382261667	0.340246045	0.185331592
7	0.330623502	0.292893219	0.157019757
8	0.291116807	0.257002855	0.136196597
9	0.259964004	0.228894587	0.12024236
10	0.234790582	0.206299474	0.107630064
11	0.214036685	0.187747604	0.097410166
12	0.196638232	0.17224672	0.088961435
13	0.181845676	0.159103585	0.081860445
14	0.169116352	0.147819604	0.075808702
15	0.158047986	0.138027179	0.070589755
16	0.148336208	0.129449437	0.066042835
17	0.139746551	0.12187392	0.062046035
18	0.132095526	0.115134914	0.058505246
19	0.125237508	0.109101282	0.055346658
20	0.119055464	0.103667904	0.052511572
21	0.113454279	0.098749537	0.04995272

Hence, the value of v will be in the range of,

$$6.15\delta \leq v \leq 30.16\delta \tag{3.25}$$

In order to find the best value of v a set of experiments were conducted as depicted in Table 3.2. Figure 3.3 shows that Nash equilibrium forwarding probability versus the number of neighboring nodes in forwarding sub-region, when v is 30.16δ both above conditions are maintained.

Once the nodes in a selected forwarding region k receive a packet, those nodes will start N -player non-cooperative game, and each node i calculates its forwarding probability, p_{ik} , per equation (3.26) in order to make a forwarding decision. The

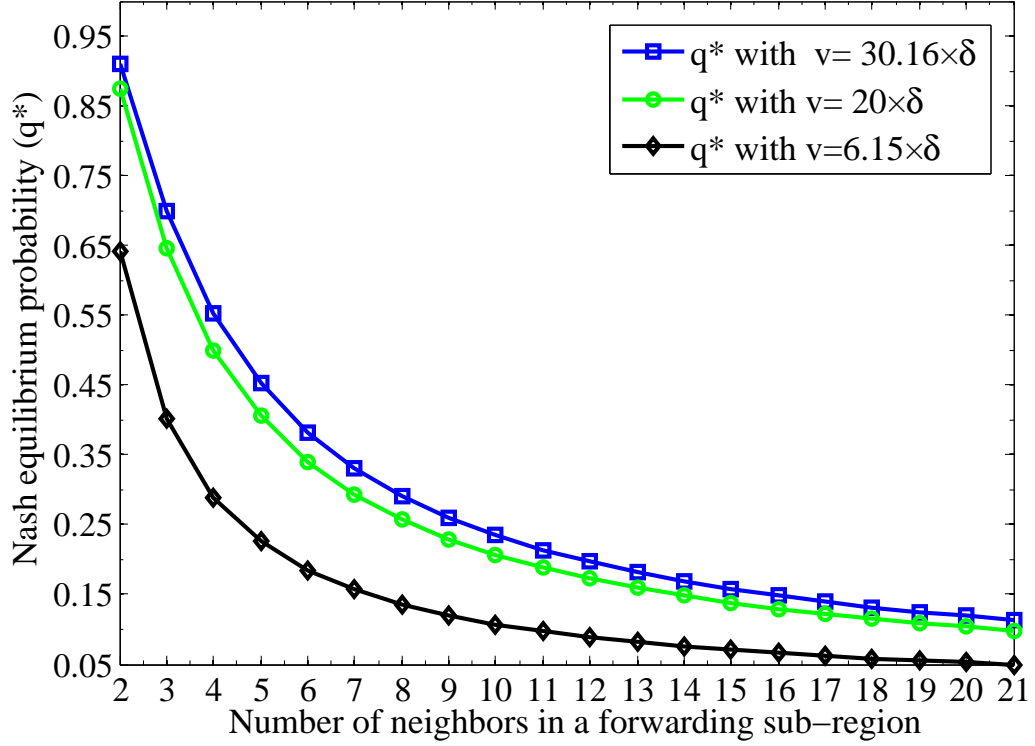


Figure 3.3. Nash equilibrium q^* versus changes in reward value v with different number of neighbors.

received packet will be forwarded only when the value of $p_{i,k}$ is less than the Nash equilibrium q^* in equation (3.24). This forwarding probability is calculated based on the following three factors:

1. The ideal share of packets that must be forwarded by every node in a selected forwarding region, $(\frac{C_i - \acute{C}_i}{C_i})$.
2. The ratio of the residual energy in a forwarding node, $(\frac{\acute{E}_i}{E_i})$.
3. The share of packets that is assigned to a selected forwarding sub-region by a sender, $(\frac{\lambda_k - \acute{\lambda}_k}{\lambda_k})$.

Hence the forwarding probability is given by

$$p_{i,k} = 1 - [(\frac{C_i - \acute{C}_i}{C_i})(\frac{\acute{E}_i}{E_i})(\frac{\lambda_k - \acute{\lambda}_k}{\lambda_k})], \quad (3.26)$$

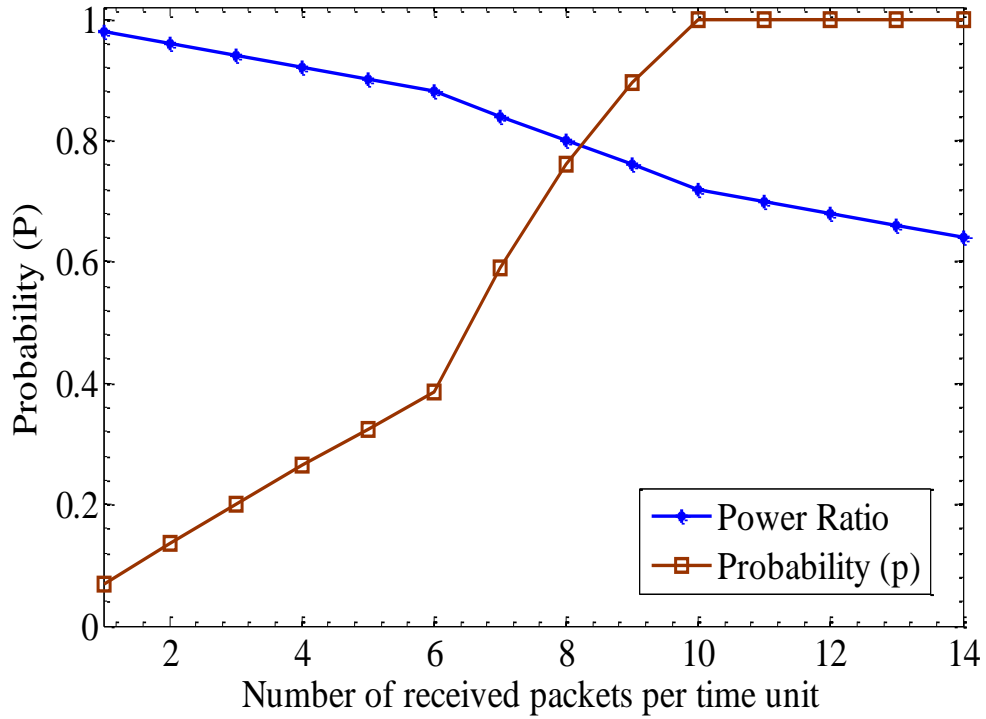


Figure 3.4. Forwarding probability versus number of forwarded packets and node's residual energy.

where C_i given by λ_k/N_k is the number of packets that must be ideally forwarded by the node i in the selected sub-region and \hat{C}_i is the number of packets that are already forwarded by node i . The residual energy of the node i , \hat{E}_i with initial energy E_i , $\hat{\lambda}_k$ is the number of packets out of a total number of packets, λ_k that have already been assigned to all nodes in the sub-region k . Any node, which decides to forward a packet based on the N -player non-cooperative forwarding game, will play its own evolutionary game to balance the energy in its surrounding sub-regions.

Figure 3.4 shows that the forwarding probability $p_{i,k}$ increases as the number of forwarded packets by the node increase. A node will not forward a packet when the forwarding probability is greater than its Nash equilibrium, and will wait for a round trip time (RTT) or until it overhears the forwarded packet by other nodes. If the node does not overhear the packet, it will gradually decrease its forwarding probability until

Table 3.3. SIMULATION PARAMETERS

<i>Parameter</i>	<i>Value</i>
MAC	IEEE802.15.4
Path loss exponent	Log-normal Shadowing
Shadowing deviation (dB)	2.5
Data packet size	128 bytes
Data rate	200 kbps
Initial energy	3.3J
Transmission power	1mW
Traffic type	CBR

the packet is forwarded either by the node itself or by any other node. A sensor node is considered dead when it does not have enough energy for transmission.

3.3 Results and Discussion

The performance of the proposed routing protocol, GTEB, has been evaluated using OMNET++4.2.2 network simulator with MiXiM framework [81]. The simulation parameters are given in Table 3.3. WSN was deployed in two-dimensional (2D) terrain of $100 \times 100m^2$ dimensions, in which 121 homogeneous sensor nodes were randomly deployed. A converge-cast traffic pattern with four sources was used and one destination node or base station. Although the data rate was large, when the number of sources and hops were increased, the available bandwidth (200 kbps) could be easily consumed. The performance of GTEB was analyzed based on three routing performance metrics. These metrics are :

1. The network lifetime.
2. Average energy consumption per packet.
3. Packet delivery ratio.

The performance of GTEB was evaluated in comparison with three other competing GRPs. These protocols are:

1. A real-time routing protocol with load distribution in wireless sensor networks (RTLTD) [29].
2. Real-time power-aware routing in sensor networks (RPAR) [35].
3. Probabilistic forwarding geographical routing protocols: This protocol is designed to verify if the proposed game theoretic approach was better than some simple probabilistic approach. In the probabilistic approach, an eligible forwarding node will forward a packet with a probability of 0.5, instead of using the Nash equilibrium.

This comparison was evaluation based on three scenarios: *i*) the first scenario concerns the lifetime of network with different network densities, while *ii*) the second scenario concerns the energy consumption per packet and finally *iii*) the third scenario concern the packet delivery ratio.

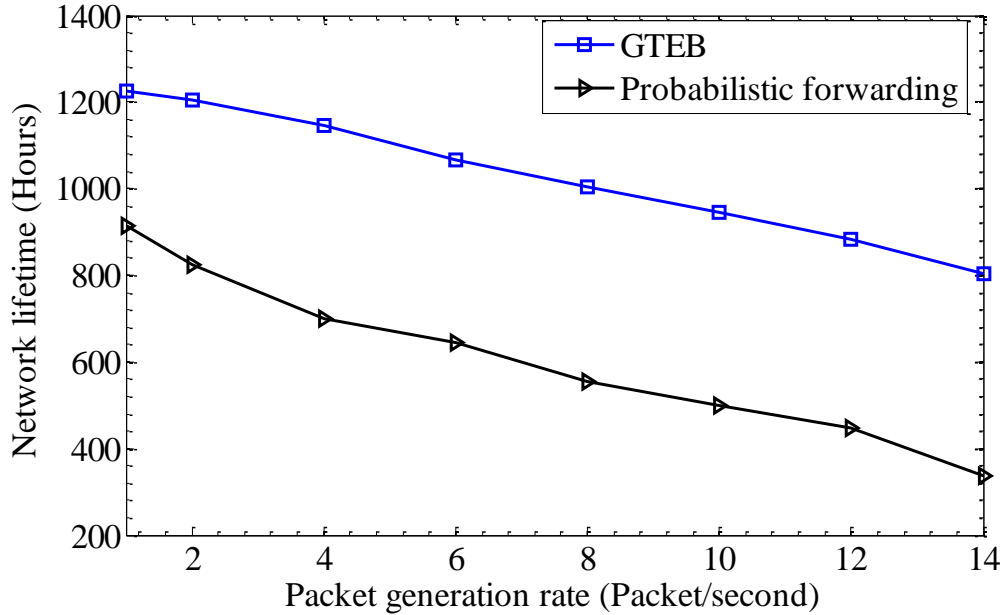


Figure 3.5. Network lifetime with different packet generation rates.

3.3.1 Network lifetime

This set of experiments was conducted to evaluate the effectiveness of packet forwarding probability mechanism, in GTEB, which depends on Nash equilibrium as a decision criteria. Moreover, the experiments evaluate the effect of two levels of game theories balancing technique on the lifetime of WSNs. Figure 3.5 represents a comparison of the lifetime of GTEB and probabilistic forwarding. This figure proves that using forwarding probability provided by Nash equilibrium condition and fitness function in game theoretic approaches allows better utilization of energy in each sensor network compared to the probabilistic forwarding protocol. GTEB integrates the accumulated energy in various sub-regions and the remaining energy in every individual node in sub-region in forwarding decision, while probabilistic forwarding protocol does not consider the energy factor in their forwarding decision and only forward based on a fixed probability. Another reason for the shorter network lifetime in probabilistic forwarding is that there could be more than one forwarding node in

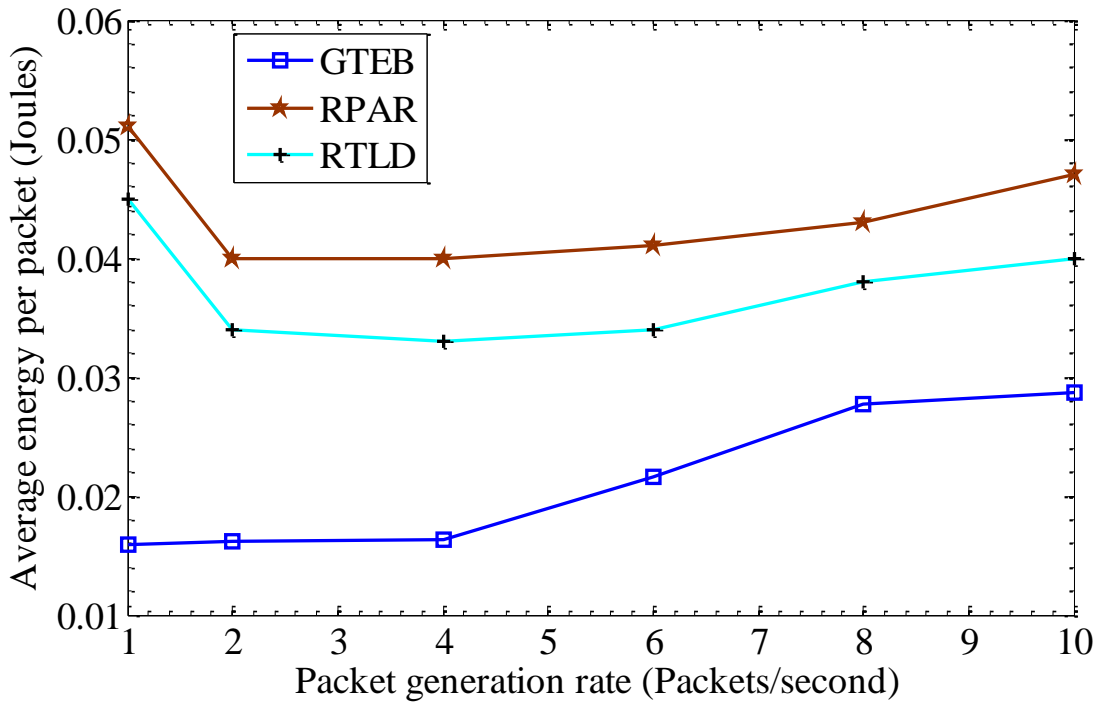


Figure 3.6. Average energy consumption per packet with different packet generation rates.

one hop neighborhood, which increases redundant broadcasts and increases energy consumption in the network. GTEB prolongs the network lifetime by approximately 33 to 58%, for packet generation rates of 1 to 14 packet per second, respectively when compared to the probabilistic forwarding protocol.

3.3.2 Energy consumption per packet

This experiments show the effectiveness of balancing energy in a set of forwarding sub-regions and in nodes in the sub-regions in GTEB and balancing energy consumption in regions only in RTLD protocol and in a set of pre-defined routes in RPAR protocol. The average energy consumption per packet for various packet generation rates is depicted in Figure 3.6. This figure shows that GTEB consumes 20 to 40% less energy as compared to the other protocols examined in this experiment. This less energy

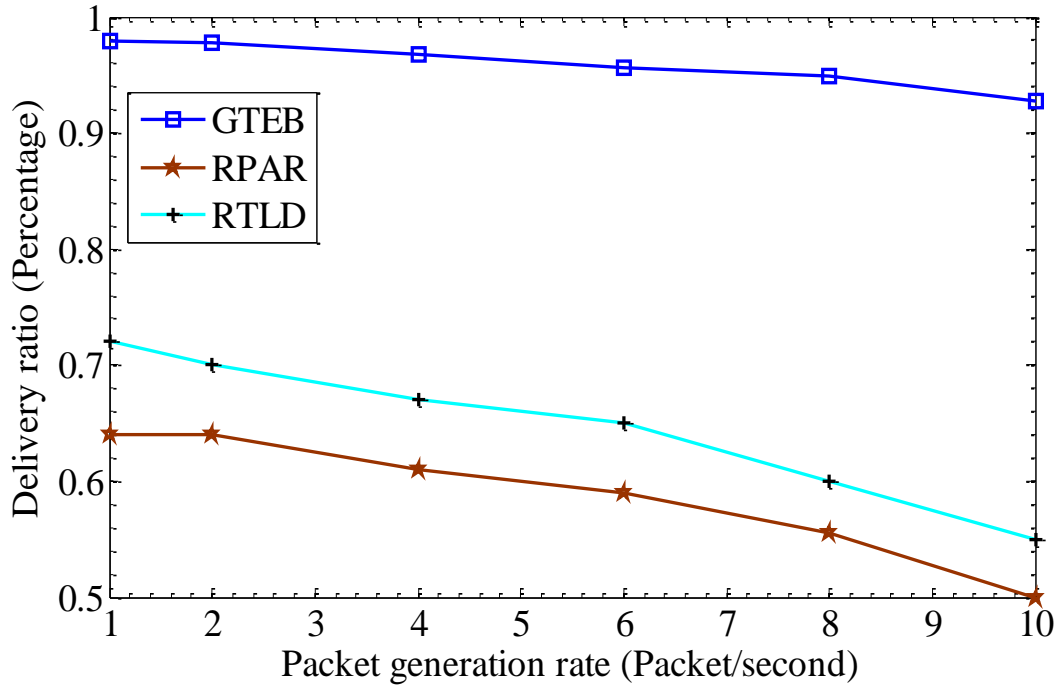


Figure 3.7. Packet delivery ratio with different packet generation rates.

consumption in GTEB in comparison to RTLD and RPAR is because GTEBs game theoretic forwarding decision making mechanism reduces redundant transmission and spread traffic load over large number of sensor nodes. Also, GTEB has no explicit exchange of control messages for exchanging neighbor information, which is generally a requirement in other GRPs.

3.3.3 Packet delivery ratio

The packet delivery ratio was measured with packet generation rate of 1 to 10 packet per second in this set of experiments. Figure 3.7 presents the results of this experiment. GTEB provides 25 to 30% higher packet delivery ratio than the other GRPs compared in this simulation study. The reason for the higher delivery ratio in GTEB is that it reduces redundant transmissions and avoids congested areas using its energy balanced forwarding mechanism.

3.4 Summary

In this research, it was observed that game theory is an efficient tool, which can be used to balance energy consumption. It is also observed that the combination of two different types of games are crucial to achieve a network wide energy balance. In particular, evolutionary games are useful to model the phenomenon in which every node tries to spread a population of data packets to achieve energy balance in its neighborhood without a defined global energy profile. Additionally, it was shown that classical games are necessary to avoid redundant transmissions among a finite number of nodes in a contention domain. The simulation study demonstrates that a game theoretic approach provides longer network lifetime, lower average energy per packet, and higher packet delivery ratio than other comparable protocols. Of particular note, the proposed protocol increases the network lifetime by 33% to 58% when compared to a probabilistic forwarding based on GRP. In a practical WSN deployment, GTEB can improve both operation time and cost.

4.1 Introduction

Energy balance in WSNs is very important issue for extending the network lifetime, since nodes are generally powered with limited energy sources. The process of replacing or recharging these energy sources is very difficult, and even can be impossible after they are distributed. Balancing energy usage is one of the key methods to prolong operation of the networks. That is why many energy balancing protocols have been proposed in the literature. However one of the commonly made assumptions is that the network is deployed in two dimensional (2D) space. In many real-life applications however, WSNs are actually deployed in three dimensional (3D) space [32]. For example, sensors used to monitor the giant redwoods in California are deployed at various heights on the trees [82]. Another example of 3D deployment of WSNs is drone or unmanned aerial vehicle networks [83]. In such cases, discarding third coordinate results in errors in finding the most desirable route and causes inefficient energy usage due to overhead and redundancies [32]. Accordingly, considering the third dimension in routing decisions is an important factor to improve energy efficiency and energy balance in WSNs.

In addition to energy balance, reducing protocol overhead associated with route discovery and maintenance messaging can further improve network lifetime. Fortunately, geographical routing protocols (GRPs) eliminate overhead associated with route discovery or route maintenance [26] at an expense of location information. Providing location information to nodes and destination location to packets are easier in a number of scenarios than route discovery and maintenance. That is why GRPs are emerging as a valuable option for WSN routing problems. However, there still redundancies in GRPs, which may increase energy consumption such as region based forwarding techniques used in some GRPs [28,84]. For this reason, designing a simple efficient GRP is essential to balance energy consumption to prolong the lifetime of WSNs. Another drawback associated with GRPs is the lack of global information in the nodes. That is why there is a need for a highly decentralized yet efficient protocols to optimize network resources. Game theory can be employed in network protocols to provide decentralized, scalable, and stable solutions. Game theory can capture the selfish behavior of nodes and dynamic energy changes in different regions of the network and can allow GRPs to achieve desired energy balance in the network. Additionally, game theory offers an intelligent decision making mechanism in distributed and dynamic environment under uncertainty. For these reasons, game theoretic energy balance routing protocol was proposed to extend the network lifetime [64,85,86].

In this chapter, unbalanced energy consumption problem in 3D WSN is modeled using two different game levels (sub-problems) which are:

1. Wedge level energy balance (WLEB). An evolutionary game theory (EGT) is applied to evenly distribute traffic load among a set of forwarding wedges (FWs) such that surrounding nodes of the sender will deplete their energy approximately at the same time.
2. Node level energy balance (NLEB). A classical game theory (CGT) is applied to balance energy consumption in sensor nodes in the selected wedge such that

all nodes deplete their energy approximately at the same time in that wedge.

The third coordinate of nodes “locations” was included using the above two different game levels. This coordinate will provide an accurate route description which enable more reliable energy balance solution to 3D network. The main contributions of this chapter are:

1. Two levels game theoretic decision making are employed to extend the network lifetime by balancing traffic load and reducing redundant transmissions in the network.
2. The approach is designed to work with WSN deployed in 3D space.
3. The energy hole problems, commonly associated with geographical routing, is solved by reflecting dynamic changes in the network.
4. By including the third coordinate, the redundant transmissions will be reduced as the forwarding nodes are limited by the the 3D space.

A description of the routing protocol with evolutionary game model for wedge level energy balance and N -player non-cooperative game model for node level energy balance will be discussed in Section 4.2. Section 4.3 presents the results and discussion. Finally, the conclusion is presented in the summary Section 4.4.

4.2 Protocol Description

A network of M homogeneous wireless sensors is considered to be deployed in 3D terrain of volume Ω , which is a rectangular prism with dimensions $w \times h \times d$ (m^3). It is assumed that the position information is aquaired using either embedded GPS receiver or other techniques such as signal strength or location services. By using a single hop neighborhood exchange, each node can learn the location information of its neighbors at the deployment time. The nodes have a spherical transmission range

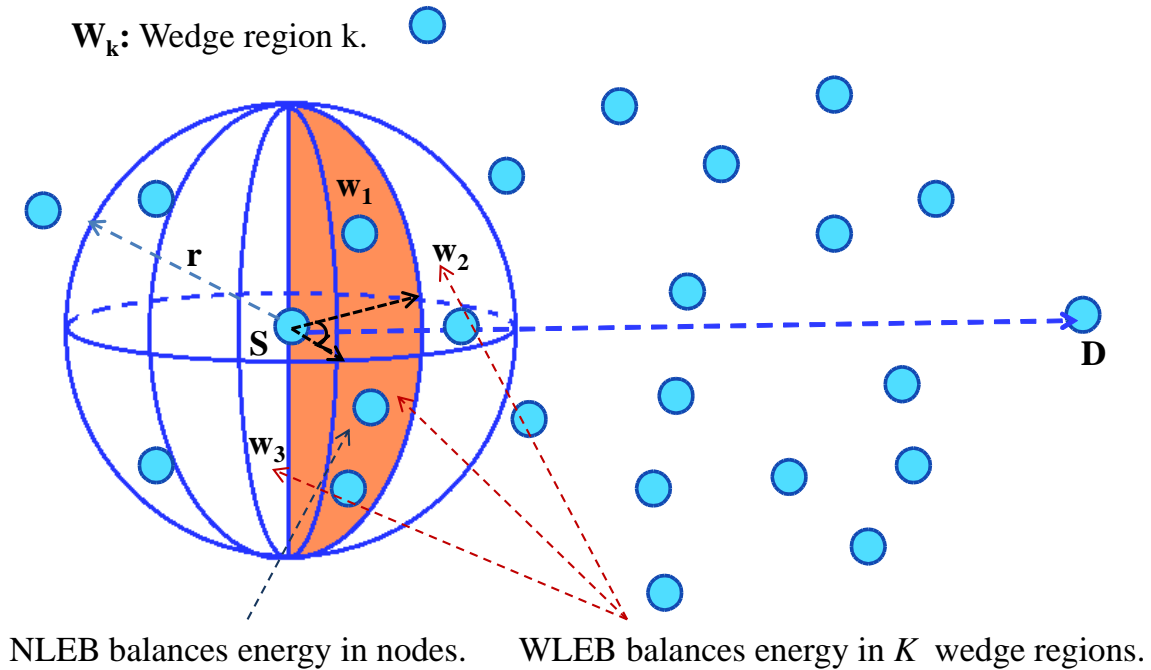


Figure 4.1. Illustration of 3D-GTEB scenario.

of radius r and initial energy E Joules. In this network, any node can be considered as a source, and reports events periodically or after a triggering mechanism, or the nodes can be act as a relay to forward the reports of othe sensors. The problem of extending lifetime of WSN is achieved through traffic load balance by breaking down the problem into the obve two sub-problems WLEB and NLEB.

Similar to the 2D WSNs approach described in Chapter 2, the energy balance in WLEB is modeled as an evolutionary game and in the NLEB is modeled as N -player non-cooperative game. In WLEB, evolutionary game was applied to capture the dynamic energy changes in the forwarding wedges and prevents traffic condensing to a certain region. In NLEB, N -player non-cooperative game was applied to capture the selfish behavior of the sensor nodes when they are trying to preserve their energy, by not forwarding, and motivate them to participate in the forwarding process.

The spherical transmission range r of a sensor node is divided into K forwarding wedges (FWs) based on the network's density. Figure 4.1 illustrates the selected forwarding wedge (FW) "the shaded part in the figure". One of the nodes in this wedge

will perform the forwarding task based on the N -player non-cooperative game. In WLEB, every sender/forwarder located in the selected FW will try to fairly distribute the generated-or-received traffic over its own FWs. Such traffic distribution were achieved using an evolutionary game based on the residual energy in these wedges. The sender or relay in those wedges will attaches the information of the following parameters to each transmitted packet:

1. The angle, θ , that bounds a selected FW .
2. The number of neighbor nodes N in this wedge.
3. The location of sender which is represented by three coordinates (x, y, z) .
4. The proportion of packets, λ_k assigned to k th FW.

Those parameters then utilized by the wedges nodes to identify if they are in the selected FW or not, using the following criteria,

$$\arctan 2[(\vec{SA} \times SD) \times (SD \times SO) \cdot \frac{\vec{SD}}{\|SD\|}, (SA \times SD) \times (\vec{SD} \times \vec{SO})] \in \theta \quad (4.1)$$

where SA represents the vector from sender S to the node A , SD is the vector from sender to the destination D , and SO is the vector from the sender to the polar of transmission sphere O .

The node drops the received packet, if the node is not in the designated FW or if the packet has already been forwarded. Then the nodes in the selected FW will play N -player non-cooperative game to determine the optimal node that is capable to forward the received packet. One of the nodes will win the game and become a new sender. Then, the the sender node will play it's own evolutionary game to distribute it's traffic load (population) over its surrounding wedges in order to balance the energy consumption among its neighborhood. However, every node executes a

neighbor discovery procedure at the deployment time to acquire the number of its neighbors to identify how many nodes are in each wedge which will also be used in the next stage to determine the number of players in the next game. Then, a sender runs the WLEB game of the protocol, which balances the energy consumption in the FWs.

4.2.1 Wedge level energy balance (WLEB)

WLEB was modeled as a dynamic evolutionary game, in which the transmission range of a sensor node is divided into a set of K FWs. These FWs have different number of nodes N . Hence, the available energy in these wedges are different. For any particular time interval, each node can be used as a generator or a receiver of a packet population λ (except the source and destination nodes). In order to extend the network lifetime and to prevent network traffic from condensing into a particular region, those nodes will evenly distribute the packet populations among its surrounding neighborhood nodes. Since the evolutionary game can capture the energy dynamic changes in different FWs, it was utilized to achieve a well distributed traffic loads over the FWs. The variation of wedges energy informations are acquired based on the proportion of packets $X_k = \lambda_k/\lambda$ which are forwarded through these wedges, where λ_k is the number of packets forwarded through a wedge k . The evolution of changes in the proportions of packets, $X = [X_1, \dots, X_K]$, among FWs was calculated according to the fitness function (payoff) as long as the fitness for all packets in all wedges are unequal. When these proportions become stable and do not change with time the system reaches the equilibrium state or stability. For this evolutionary game the equilibrium vector $X^* = [X_1^*, \dots, X_K^*]$ is considered as a proper solution for the wedge level evolutionary game. This vector was used as a gauge to determine the identical fitness (payoff) for a packet in all FWs. In this study the main components of WLEB evolutionary game can be described as follows:

1. **Player:** A packet is considered as a player while the sender plays the game on behalf of the packets.
2. **Population:** The packets that are generated or received by a node are considered as a population of players λ .
3. **Strategies:** The variation of FWs selection are considered as a packet strategies which is denoted by: $\mathcal{S} = [W_1, W_2, \dots, W_K]$.
4. **Fitness function:** The amount of energy assigned to each packet when it is forwarded through a certain wedge is quantified by the fitness function, where the fitness function represents a packet's satisfaction of energy usage in any region and is defined in term of gain and cost.

In this game the net fitness for the packet that is forwarded through wedge k is given by equation (3.1). In order to obtain the equilibrium packet distribution vector X^* the sender node evolves variation of packet proportions by switching these packets among different FWs based on the residual energy in these wedges. Replicator dynamics uses switching probability in equation (3.5) to determine the changes in inflow $\sum_{l \neq k} X_l P_{k,l}(X)$ and outflow $\sum_{l \neq k} X_k P_{l,k}(X)$ of packets from one FW to another.

When the difference between the expected inflow of the packets and the expected number of outflow of the packets through a wedge become equal, the system is said to be at the stable state. This state of stability is reflected in the concept of replicator dynamics which is given in equation (3.12).

The evolutionary equilibrium of the game is given in Subsection 3.2.3 and the stability analysis which is given in Subsection 3.2.4 are also applicable on this WLEB evolutionary game for 3D forwarding wedges. However, the number of nodes in 3D FW is different than in 2D forwarding sub-region because of discarding third dimensional coordinate in 2D WSN. The wedge is considered dead when it does not have enough energy for transmission.

4.2.2 Node level energy balance (NLEB)

The objective of NLEB game is to balance the energy consumption in nodes in a FW by making all nodes fairly participate in forwarding task. In this phase of 3D-GTEB, the problem of forwarding packets through a certain FW is modeled as N -player non-cooperative game. The N -player non-cooperative game is utilized to capture the selfish behavior of the sensor nodes in WSN since every node tries not to participate in forwarding in aim of preserve its energy.

This game modeling tries to motivate nodes to cooperate and participate in forwarding tasks fairly based on the Nash equilibrium (NE). NE is considered as the optimal solution for the game where all players are satisfied. The normal form game formulation which is denoted by, $G = \{N_k, S, U_{i,i \in N_k}\}$ is given in Table 3.1.

NLEB N -player non-cooperative game consists of three main components:

1. **Players:** A set of N_k nodes in the same FW is considered as players and $N_k \geq 2$.
2. **Strategies:** Each player has a set of two mixed-strategies, $S = [B, \bar{B}]$, where B and \bar{B} represents broadcasting and no broadcasting respectively. A node plays strategy B with a probability q , and plays strategy \bar{B} with probability $1 - q$.
3. **Expected payoff:** The expected payoff function $U_i(s)$ quantifies the award for node i when it plays one of its available strategies against other $N - 1$ opponents.

Once nodes in a selected FW receive a packet, they start N -player non-cooperative game. Then each node calculates its own expected payoff per equation (3.23) and determines its NE strategy, q_i^* based on the payoff matrix given in Table 3.1. The NES for node i in Equation (3.24). As q_i^* depends on the reward value v , a set of experiments were conducted to determine v . The value of 30.16δ was found to satisfy the network connectivity requirement [79] and a number of players to formulate a game [52]. Based on NE strategy given in Equation (3.24), a node makes its

forwarding decision if its forwarding probability, $p_{i,k}$, is less than q_i^* . The forwarding probability, $p_{i,k}$, of node i in Equation 3.26 which is calculated based on the following three factors:

1. The ideal share of packets, which must be forwarded by every node in a selected forwarding region, $(\frac{C_i - \dot{C}_i}{C_i})$.
2. The ratio of the residual energy in a node to its initial energy, $(\frac{\dot{E}_i}{E_i})$.
3. The share of packets which is assigned to a selected FW by the sender, $(\frac{\lambda_k - \dot{\lambda}_k}{\lambda_k})$.

Then, the node compares its own $p_{i,k}$ with q_i^* and it forwards if $p_{i,k} \leq q_i^*$ otherwise waits for round trip time (RTT) of a packet and drops it if it does not overhear the packet. However, a sensor node is considered dead when it does not have enough energy for transmission.

4.3 Results and Discussion

In this section, a set of experiments have been conducted to evaluate the performance of 3D-GTEB. OMNeT++ 4.2.2 with MiXiM framework was used to simulate the network. The simulation parameters used to configure WSN scenario are given in Table 3.3. The sensors in the network were randomly deployed in a 3D space with dimensions of $100 \times 100 \times 100 m^3$. In this network, four sensor nodes were considered as sources and they can report to the base station. converge-cast traffic pattern was used. The transmission power, in sensor nodes, was set to achieve successful delivery to nodes within a distance equal to the chosen transmission range. In this study, a WSN with M sensor nodes, where the number of sensors is varied from 120 to 520 nodes, was considered. All results have been acquired by averaging the outcomes of 10 simulation runs with different network topologies. The performance of 3D-GTEB was investigated based on three metrics:

1. Network lifetime.
2. Average energy consumption per packet.
3. Packet delivery ratio.

The performance of 3D-GTEB protocol was evaluated in comparison with 2D-GTEB in three scenarios. These scenarios are:

1. The first scenario concerns the lifetime of network with moderately network density of 120 sensor nodes with various packet generation rates (PGR).
2. The second scenario concerns the lifetime of network with various network densities, where the number of sensors varied from 120 to 520 sensors and generation rate of two packets per second. On the other hand, 2D-GTEB network was deployed in 2D terrain of $100 \times 100 m^2$.
3. The third scenario concerns the packet delivery ratio with different packet generation rates.

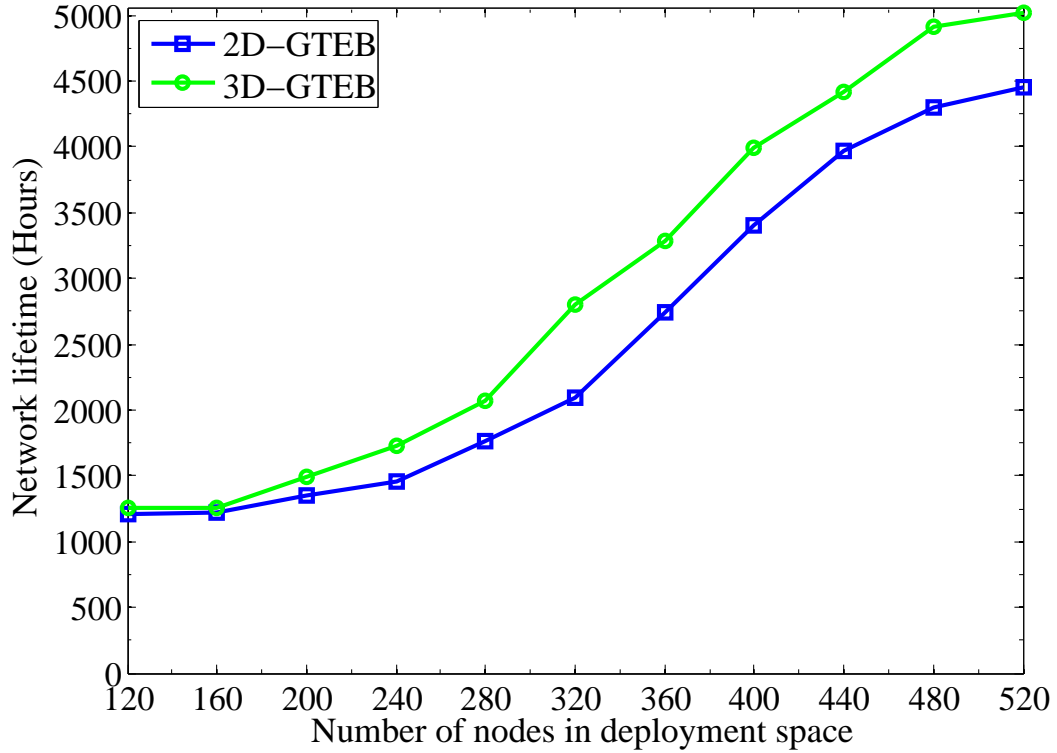


Figure 4.2. Network lifetime versus different densities.

4.3.1 Network lifetime

In this experiment, 3D-GTEB was compared with 2D-GTEB routing protocol to evaluate the effect of considering the third dimension on the network performance. The experiment was conducted based on packet generation of two packets per second with varied number of sensors from 120 to 520 nodes. Figure 4.2 presents the network lifetime of both protocols versus the various number of sensors. In 3D-GTEB, the network lifetime was prolonged longer by 2% to 25% in comparison with 2D-GTEB. This performance of network in 3D-GTEB is due to considering the third dimension by nodes in forwarding decision. Although the increase in the network density causes more redundant transmissions, 3D-GTEB limits the number of participated nodes better than 2D-GTEB.

Figure 4.3 shows the network lifetime versus various packet generation rates, which

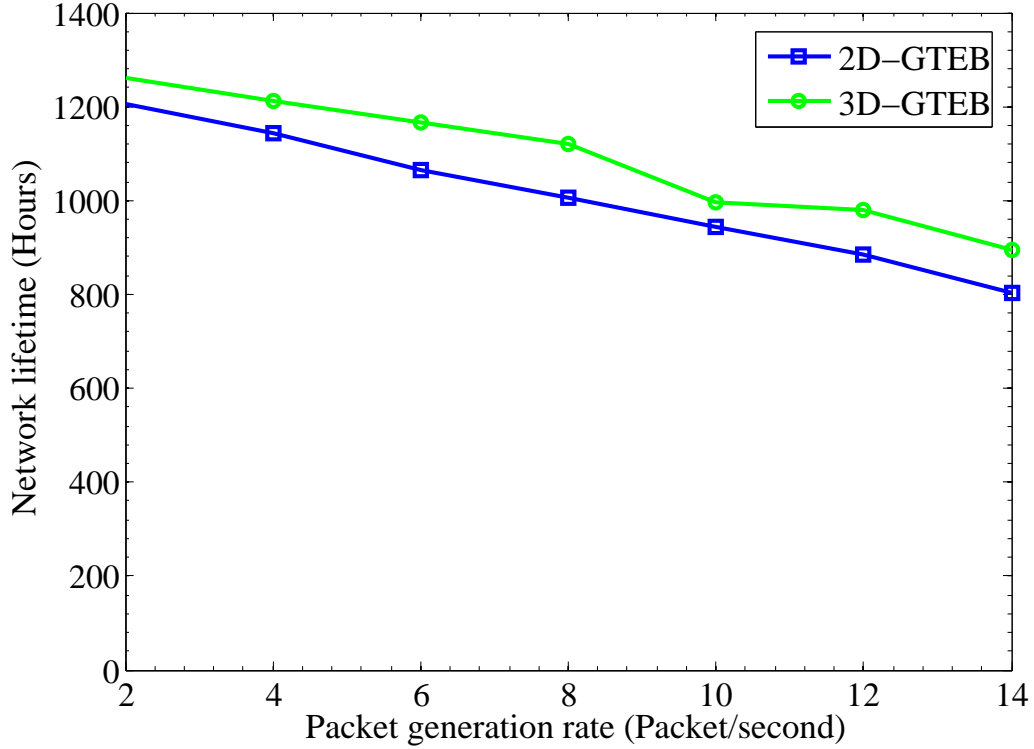


Figure 4.3. Network lifetime versus different packet generation rates.

varies between 1 to 14 packets per second. The lifetime provided by 3D-GTEB is longer than 2D-GTEB even with increased traffic loads.

4.3.2 Average energy consumption per packet

This set of experiments concerns about the performance of 3D-GTEB in term of average energy required to successfully deliver a packet with increase in the number of sensor nodes in the network. Figure 4.4 depicts the average energy consumption per packet versus different number of deployed sensors. In this experiment the obtained results are collected based on a network with different number of nodes and packet generation rate of two packets per second. The figure shows that a packet requires less energy per packet in 3D-GTEB than in 2D-GTEB by 4% to 21%. This is because 3D-GTEB utilizes less number of sensors to forward the packet.

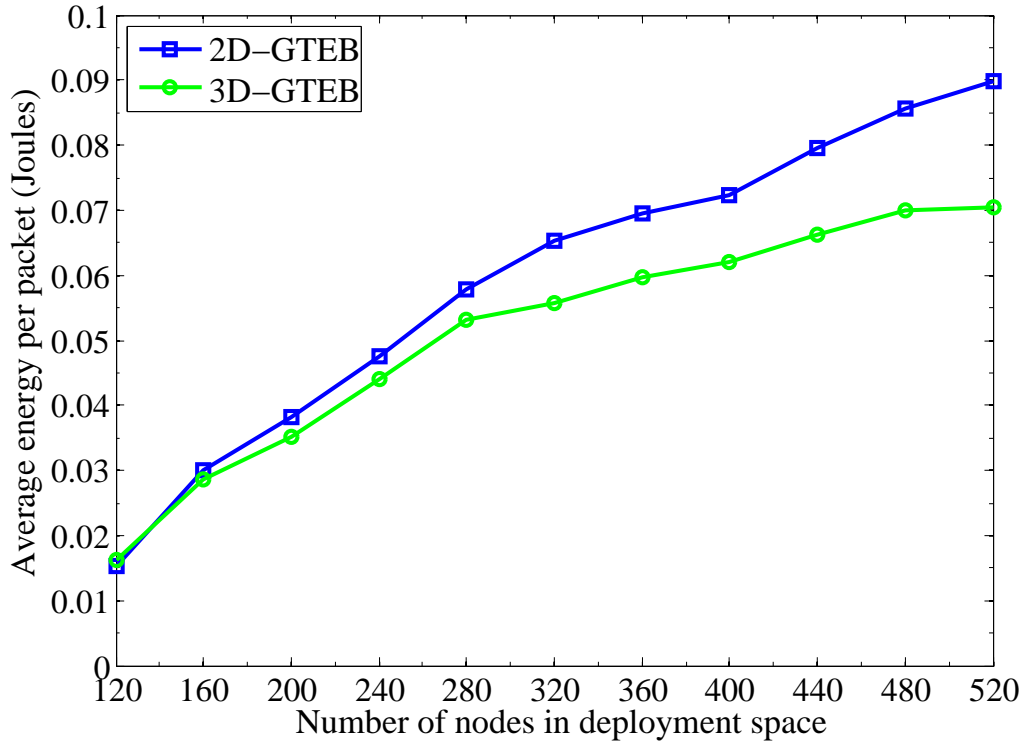


Figure 4.4. Energy per packet versus different densities.

Figure 4.5 shows the energy consumption per packet versus different packet generation rate. The figure shows the impact of the increase in traffic load in the network on the average energy consumed per packet. Despite of this traffic increase 3D-GTEB performance is better than 2D-GTEB because less number of nodes in 3D space may be located in the same forwarding region in comparison with 2D space. In 2D-GTEB deployment, the node density in forwarding region is high because all nodes are distributed on flat surface while in 3D-GTEB the nodes are distributed in 3D space. Therefore, in 2D space the packet passes through more nodes in comparison with 3D space, causing longer queuing delay and higher congestion.

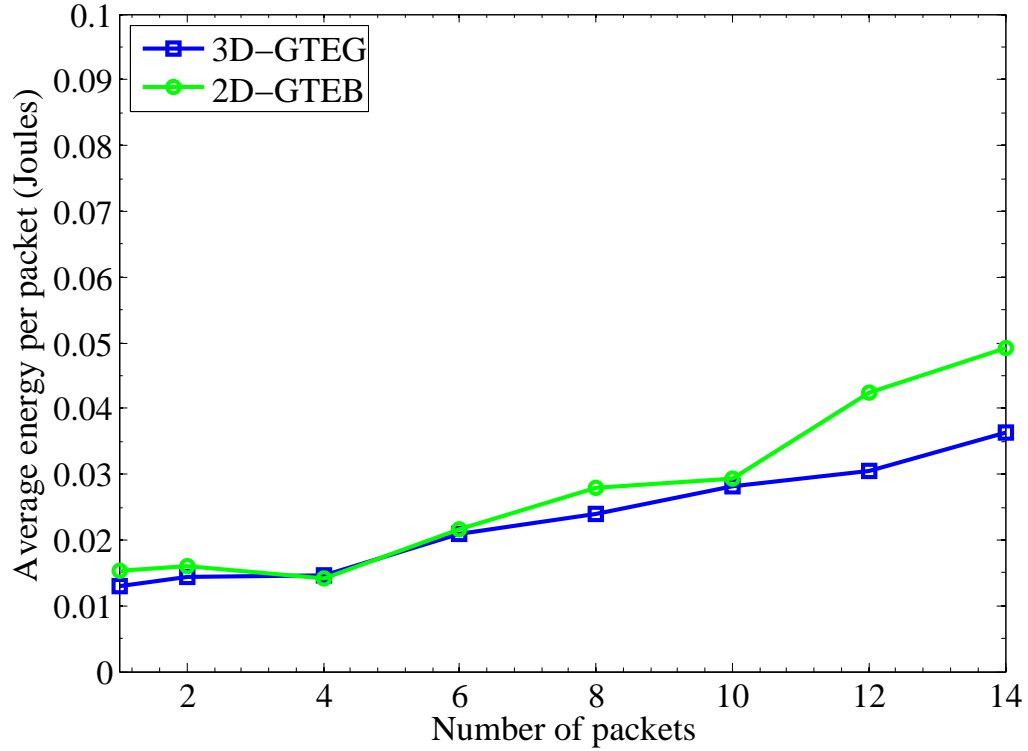


Figure 4.5. Energy per packet versus different packet generation rates.

4.3.3 Packet delivery ratio

In this set of experiments the packet delivery ratio is evaluated based on packet generation rate of two packet per seconds and the different network densities. In both protocol the deal-line was set to be 0.250 second. Figure 4.6 depicts the packet delivery ratio versus different number of sensor nodes. The figure shows the delivery ratio of 3D-GETB increase with the increase in the number of sensor nodes in the deployment area. This is because, more nodes are required to be deployed to fill 3D space in comparison with 2D space and with less number leads to to dis-connectivity or sparse network.

This increase in empty regions makes more packet miss their deadlines. However, when more nodes deployed in 3D terrain the delivery ratio increase due to considering third dimension in routing decision, while in 2D more nodes will forward packets even

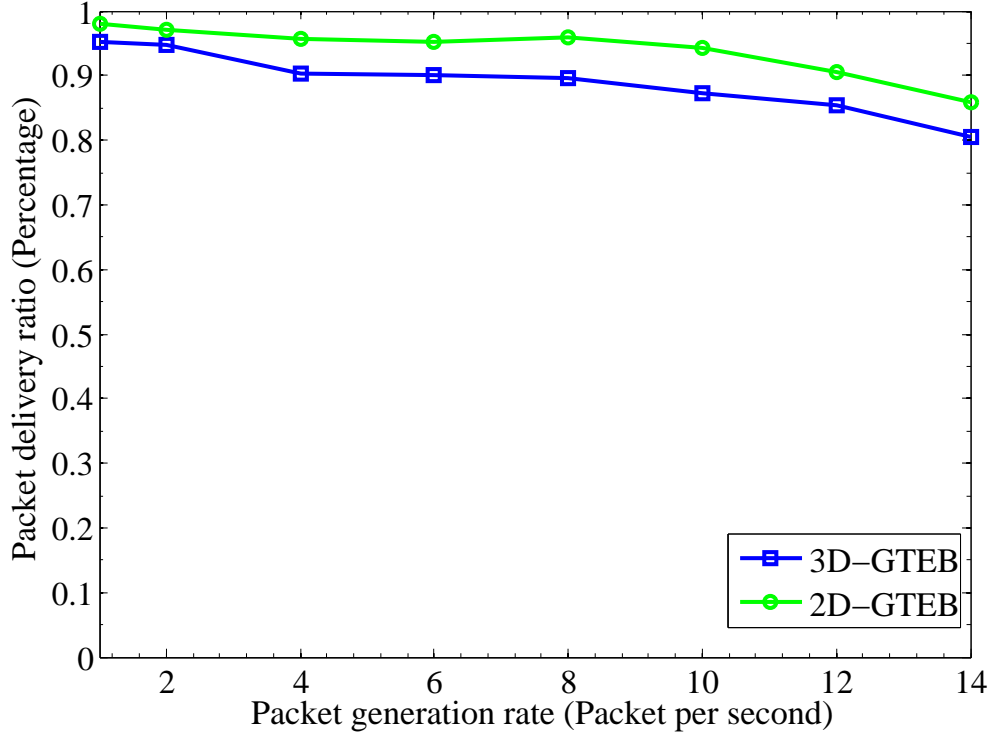


Figure 4.6. Packet delivery ratio versus different network densities.

if they are not located in the forwarding region because of nodes projection on a flat surface.

4.4 Summary

This chapter proposes a decentralized and scalable routing protocol, called three dimensional game theoretic energy balance (3D-GTEB). This protocol utilizes 3D information in geographical routing to enhance the routing decisions and to minimize the network overhead. Additionally, energy balance in the protocol was further improved by using two levels of game theoretic decision making. The first level is called wedge level energy balance, which employs evolutionary game theory to balance traffic load over a set of forwarding wedges. EGT shows effective improvement in network lifetime and energy consumption per packet. The second level is called

node level energy balance. This technique utilizes the advantage of classical game theory to capture the selfish behavior of nodes, where they tend not to participate in forwarding to preserve their energy, and to encourage them to participate in forwarding. The simulation results shows that 3D-GTEB provides significant improvement in network lifetime over similar 2D-GTEB. Moreover, considering third dimension in 3D-GTEB can further extend the network lifetime.

5.1 Introduction

The effectiveness of combined RLEB evolutionary game and NLEB N -player non-cooperative game in GTEB was tested against three random test protocols. These three random test protocols are labeled as: *Random-Random*, *Random-CGT*, and *EGT-Random*. In these labeling, the first label indicates the decision making mechanism of packet forwarding sub-region selection and traffic load assignment and the second label indicates the decision making mechanism of forwarding node selection in a sub-region.

Table 3.3 shows the simulation parameters that are used to configure WSNs. Random test protocols and GTEB protocol have been evaluated using OMNET++ 4.2.2 network simulator with MiXiM framework [81].

In this analysis study, the transmission range of a sender/relay node is divided into K packet forwarding sub-regions. Different network scenarios in term of the number of deployed sensors and traffic generation rates were considered. Every random test protocol was designed to evaluate the effectiveness of using one of the game theoretic decision making in one level on the network performance. Additionally, the influence of different sizes of packet forwarding regions on network lifetime was also evaluated.

The performance of the proposed protocol, GTEB, was analyzed for the following three routing matrices: *network lifetime*, *average energy consumption per packet*, and *packet delivery ratio*. The three random test protocols will be discussed in Section 5.4, the evaluation and analysis study presented in Section 5.3. In Section 5.4, the influence of different sizes of packet forwarding regions is analyzed. Finally, the summary of the chapter is presented in Section 5.5.

5.2 Random Test Protocols

5.2.1 Random-Random protocol

The objective of this test protocol is to evaluate the influence of applying two levels of game theoretic decision making on the network performance. In this scenario, the forwarding region were choose randomly and the forwarding node in a forwarding region was also selected randomly. The amount of the proportions of the packets that assigned to the forwarding sub-regions and the nodes in the sub-region were randomly determined regardless the amount of residual energy in the nodes and regions. In this forwarding routing algorithm, the sender spreads it's traffic load randomly on it's neighborhood and a potential forwarding node generates a random number either 0 and 1 and if the this number is 1 the node forwards the packet otherwise drops it.

5.2.2 Random-CGT protocol

The objective of this random test protocol is to assess the performance of the network when the traffic load is randomly distributing over the set of packet forwarding sub-regions, while in the forwarding subregion one node is selected to perform the packet forwarding task based on the classical game theory. In the region level, the sender randomly distributes its traffic population over the forwarding sub-regions, while in the node level N -player non-cooperative game was used to distribute the traffic load

among the region nodes. Every node in forwarding subregion forward or drop the received packet on it's forwarding probability as given in (3.26) and Nash equilibrium in equation (3.24). The detail of N -player non-cooperative game is discussed in Section 3.2.5.

5.2.3 EGT-Random protocol

This protocol is used to evaluate influence of EGT utilization on the network lifetime and packet delivery ratio. In this test scenario, the sender spreads it's packet population over a set of packet forwarding sub-regions based on their residual energy using the concepts of replicator dynamics in EGT, while a forwarding node in the sub-region was chosen randomly. The detail of the RLEB evolutionary game is stated in Section 3.2.1. The findings of this experiment signifies the effectiveness of combining two different games in GTEB in comparison with one game in EGT-Random on the network performance. The results of these studies are presented and discussed in the next section.

5.3 Network Performance Analysis

5.3.1 The effect of network density on network lifetime

In this set of experiments, the packet generation rate was chosen to be two packets per second whereas the number of sensor nodes is varied from 120 to 520 nodes. Figure 5.1 presents the network lifetime versus the number of nodes in deployment space. The figure shows GTEB provided 9% to 38% longer network operation compared to other three random forwarding algorithms. This superior performance is because of balancing the energy consumption in nodes surrounding the senders/relays using evolutionary game and eliminating redundant transmissions in the forwarding sub-regions

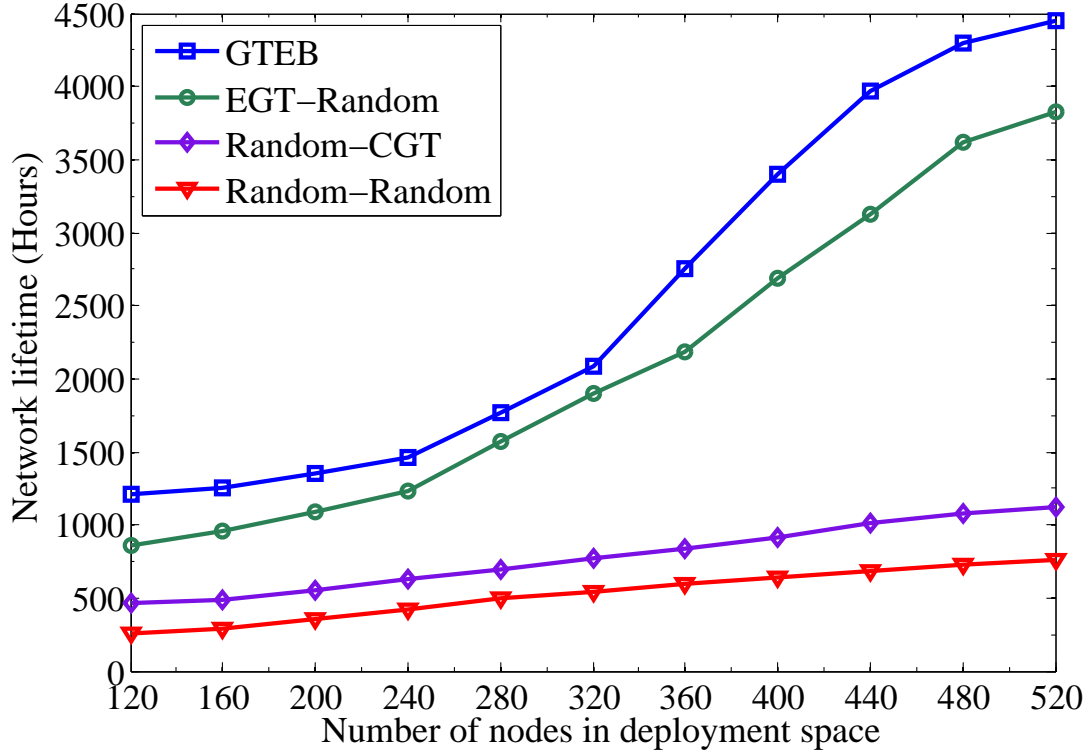


Figure 5.1. The effect of network density on lifetime in GTEB and the three protocols.

using N -player non-cooperative game. However, EGT-Random curve shows similar trend as GTEB but with relatively lower lifetime, since at node level, the random node selection algorithm does perform as good as game theoretic approach. On the other hand, for the two other approaches, namely Random-CGT and Random-Random, the packets are randomly distributed to the regions, and lifetime is significantly reduced as a result. That confirms unfair packet distribution over forwarding regions significantly shorten the lifetime. Although, the increased node density may cause more redundant transmissions, GTEB effectively managed forwarding decisions to distribute the packets among the nodes and achieved the best result.

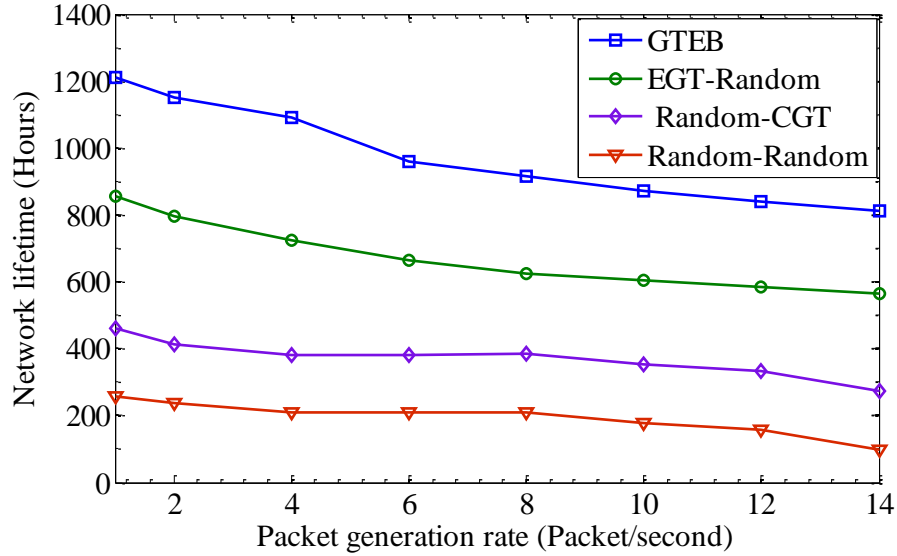


Figure 5.2. The effect of traffic load on the network lifetime in GTEB and the three protocols.

5.3.2 The effect of traffic load on network lifetime

This set of experiments was conducted to check GTEB’s ability to deal with various traffic load amounts when the network size is fixed. Figure 5.2 illustrates the performance of GTEB with increasing the packet generation rate in a fixed network size of 120 nodes. This figure shows that the GTEB protocol performance is better than the other three random protocols even with increased traffic load by 30% to 78%, due to intelligent forwarding decision making.

This figure proves that using forwarding probability provided by Nash equilibrium condition and fitness function in game theoretic approaches will allows better utilization of energy in each sensor network compared with other random protocols. GTEB integrates the accumulated energy in various sub-regions and the remaining energy in every individual node in sub-region in forwarding decision, while for other random protocols at least one level does not consider the energy factor in their forwarding decision and forwards the packet randomly.

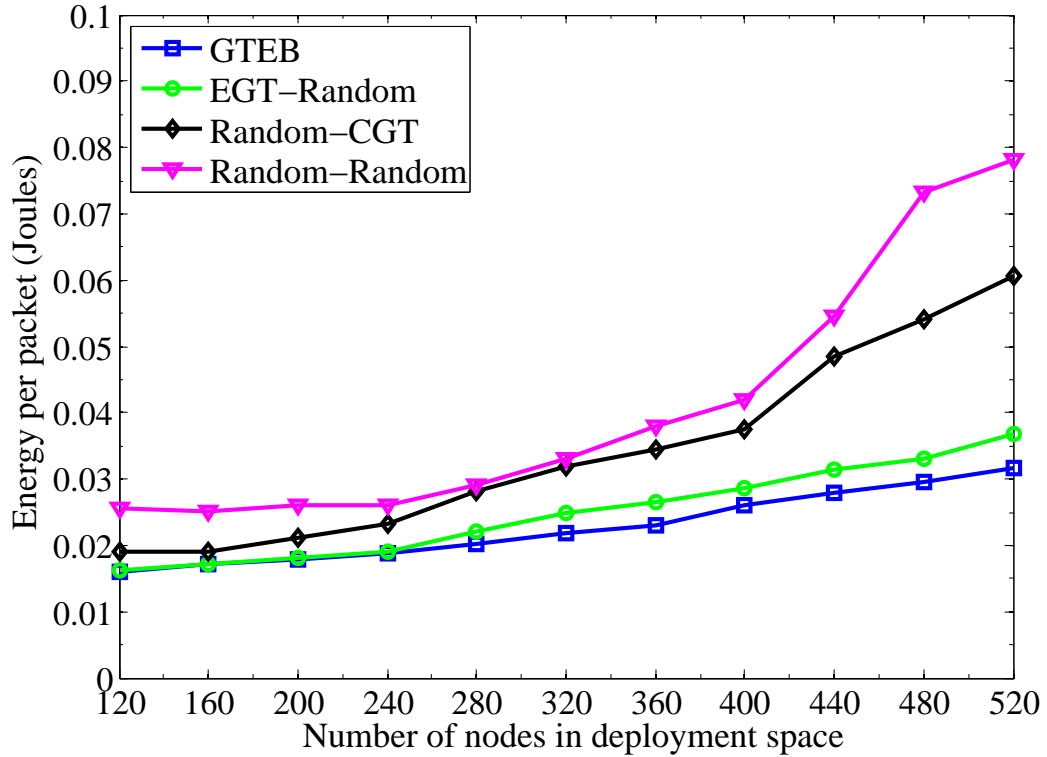


Figure 5.3. The effect of network density on energy per packet in GTEB and three random protocols.

5.3.3 The effect of network density on average energy consumption per packet

The energy that is required for successfully delivering a packet to the destination is evaluated in this section. In this scenario, GTEB is evaluated with three random protocols. Figure 5.3 shows that the average consumed energy per packet in GTEB, is better than other random algorithms by 1.12% to 60%. In this figure, the results are obtained based on different network densities with packet generation rate of two packets per second. The figure shows that the increase in the number of sensor nodes increases the energy consumed per packet, because random protocols do not consider the residual energy or do not considered ideal number of packets to be forwarded by each node and forwarding region.

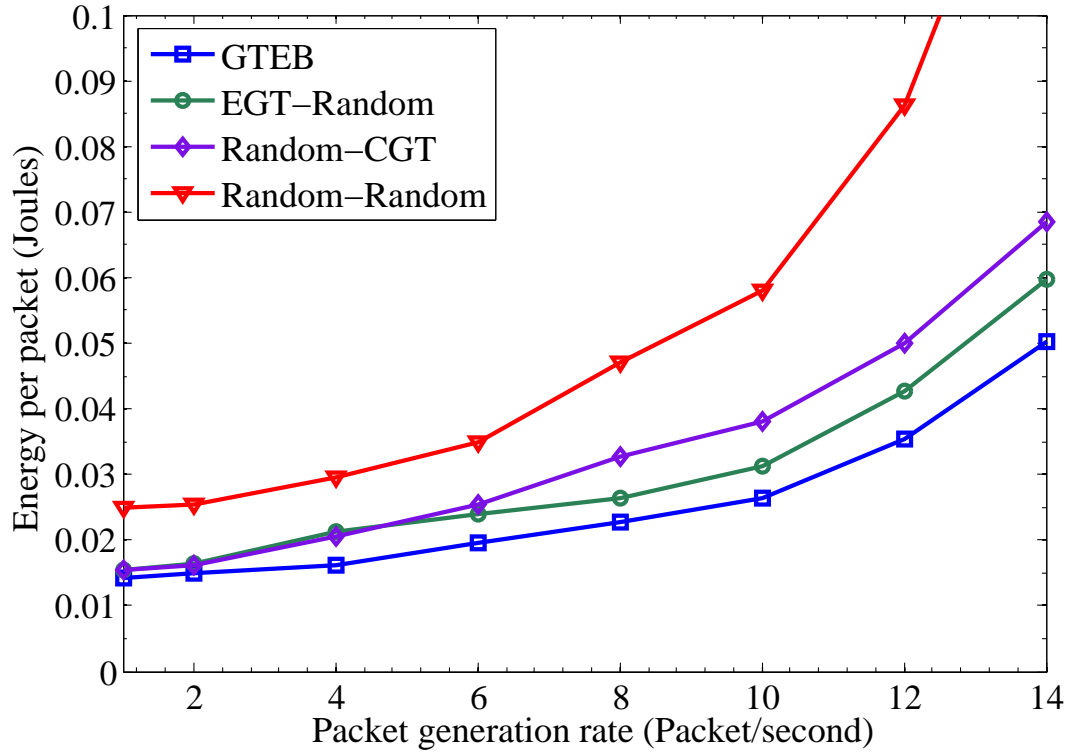


Figure 5.4. The effect of traffic load on energy per packet in GTEB and three random protocols.

5.3.4 The effect of the traffic load on average energy consumption per packet

This set of experiments measures the effect of varied traffic load on the energy consumed per packet. Figure 5.4 illustrates the energy consumption per packet in GTEB and other three random protocols with different packet generation rates. The figure shows that increased traffic in the network impacts on the average energy consumed per packet. However, despite of this traffic increase GTEB still has better performance because of every node makes ideal forwarding decision based on combination of Nash equilibrium and its forwarding probability which considered node's residual

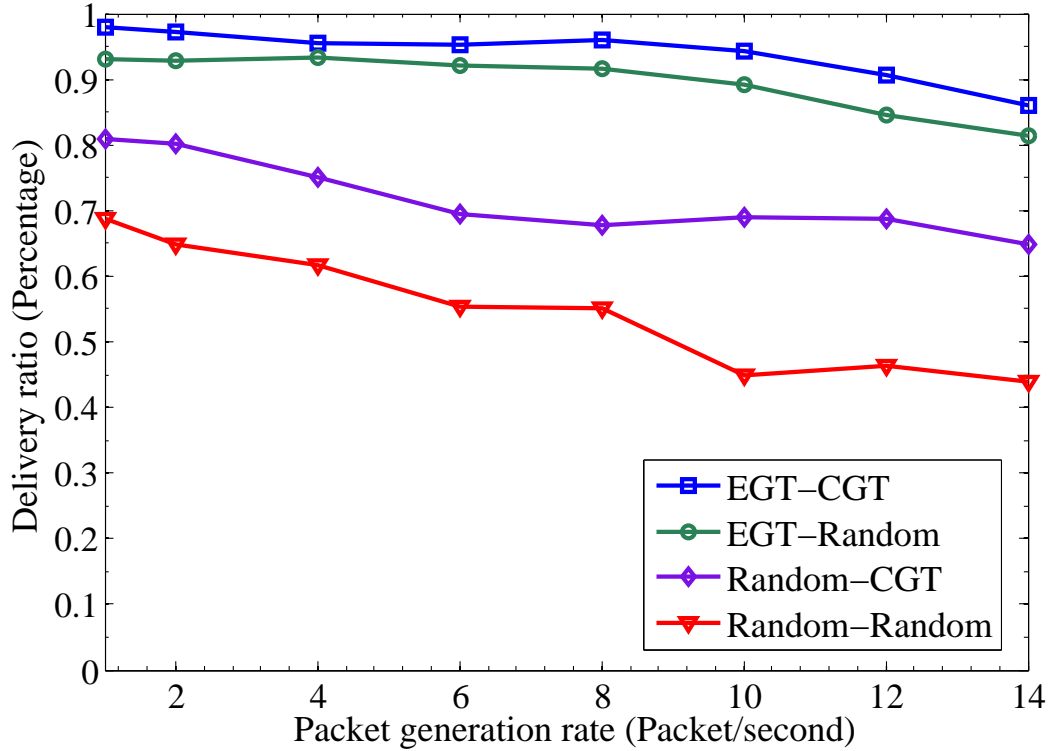


Figure 5.5. Packet delivery ratio in GTEB and three test cases.

energy, its share of the packet forwarding and the share of packets that is assigned to it's own forwarding sub-region. Besides that, GTEB traffic distribution mechanism prevents the traffic load from condense in some parts of the network. GTEB performance is better than other random algorithms in average 1.12% to 87.13%. On the contrary, the randomness of forwarding tasks and unfair traffic distribution, in other protocols, causes this difference in energy depletion between them and GTEB protocol.

5.3.5 The effect of the traffic load on packet delivery ratio

In this set of experiments the packet delivery ratio of GTEB is evaluated with other random three random protocols with different packet generation rates varied from

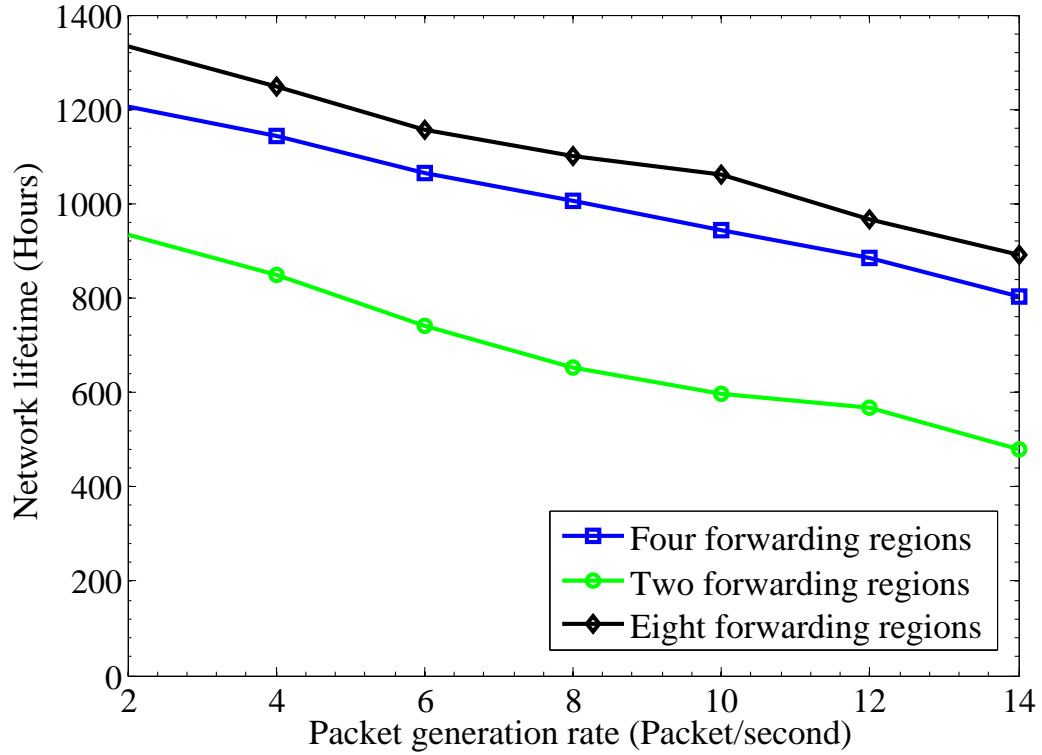


Figure 5.6. GTEB lifetime evaluation using two, four and eight packet forwarding regions.

1 to 14 packets per second. In Figure 5.5, the packet delivery ratio, in GTEB, is compared to three random test protocols. In this figure, GTEB shows better packet delivery rate by 2% to 52% in comparison with other random test protocols despite of increasing traffic load in the network. This promising results are obtained due to avoiding the congested areas in the network and region with low node density.

5.4 The effect of Packet Forwarding Region's Size on Network Lifetime

The objective of this experiments is to evaluate the effect of the size of forwarding sub-regions on the lifetime of the network. In these set of experiments, the network

lifetime is evaluated with different number and sizes of packet forwarding regions around sender/relay nodes. Figure 5.6 illustrates GTEB lifetime evaluation with two, four and eight forwarding regions. The figure shows that with the increase in the number of forwarding regions the network lifetime is significantly increased. This improvement is correlated with the size of forwarding regions, because with small size of regions there will be smaller number of nodes, which can participate in forwarding task, consequently more nodes preserve their energy. While with large regions, more nodes spent their energy for receiving and manipulating the packets. The figure shows that the average lifetime extension is from 8% to 44% in case of eight forwarding sub-regions.

5.5 Summary

In this analysis study, it is observed that employing two levels of game theoretic decision making is more effective than employing only one level to improve the network's performance. The simulation results showed that GTEB provided significant improvement in term of extending network lifetime and packet delivery ratio over a number of random test protocols (when only one level of game theoretic decision is used). Moreover, dividing the transmission range of a sender/relay node into smaller forwarding regions prolonged the network operation even further. The results also confirmed that GTEB is adaptive to different network factors including: network density variation, traffic load variation and asymmetric energy use.

6.1 Contributions

This dissertation has presented two adaptive, scalable, and energy balance routing protocols that utilize the location information of sensor nodes to provide wide energy balance in order to extend the network lifetime. In this dissertation two game theoretic: energy balanced routing geographical protocols for WSNs deployed in 2D space and 3D space were presented. In both protocols, the effectiveness of proposed methods was demonstrated through a set of numerical simulations. The results provided confirm that these protocols can be successfully implemented in many WSN application scenarios, to balance energy consumption and to extend WSN lifetime.

Both proposed protocols were designed based on the concept of an even distribution of the traffic load over a large section of the sensor network. The first protocol GTEB routing protocol for WSNs is designed to be implemented in 2D WSNs, while the second protocol, three dimensional 3D-GTEB is designed to work with a network that deployed in 3D space.

In GTEB and 3D-GTEB, the problem of energy balance is divided into two sub-problems, which are RLEB and NLEB. In RLEB, an evolutionary game was utilized to provide energy balance on a set of forwarding sub-regions around every sensor node

between source and destinations. The results provided in this dissertation shows that, the using of EGT was useful to balance the energy on a set of packet forwarding sub-regions because of its ability to capture the dynamic changes in the energy in those regions. In NLEB, N -player non-cooperative game was used to balance energy consumption in nodes that are located in the sub-regions. The evaluation experiments proved that N -player non-cooperative game will provide a good balance hence, the network lifetime was extended. A simulation study was conducted to compare GTEB proposed algorithm with RTLD [29], RPAR [35] and probabilistic forwarding protocols in term of network lifetime, energy consumption per packet and packet delivery ratio. The proposed protocol made the network function is longer than the function of other competing GRPs with better packet delivery ratio.

3D-GTEB was designed to benefit from the advantages of considering the third coordinate of the nodes' locations to provide an accurate routing calculation and lowering the network overhead. This protocol was named 3D-GTEB and designed to work with WSNs deployed in 3D terrain when the third coordinate can not be discarded. The simulation results showed that by considering the third coordinate in the routing algorithm will provide a better packet delivery ratio and the network operation will last longer than the GTEB, which was designed to work with WSNs deployed in 2D space.

The effectiveness of implementing evolutionary game theory and classical game theory on the network performance was evaluated based on various scenarios. GTEB was compared to three random test protocols: Random-Random, Random-CGT and EGT-Random. These random test protocols were employed by considering only one level game theoretic decision making either in region level or node level. The results confirm that GTEB will prolonged the network lifetime more than in other three protocols, less energy consumed per packet, and the ratio of delivered packets was higher than in comparison to other three random protocols.

6.2 Future Research Directions

In this dissertation, it assumed that the WSN is static and sensor node mobility is not inspected. Thus, it would be interesting to consider the network mobility to the improved version of both protocols GTEB and 3D-GTEB. However, it is expected that, with some minor modifications, the protocols would improve the performance of the 2D-WSNs and 3D-WSNs dynamic. Finally, the findings of this dissertation were conducted on the basis of numerical analysis using simulation tests. It would be interesting to implement the proposed GTEB and 3D-GTEB protocols in real sensors and evaluate the performance (network lifetime, average energy consumption per packet and packet delivery ratio) of the protocols in real life applications.

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A.1 Stability Analysis of RLEB Evolutionary Game Over K Regions

To provide stability analysis of RLEB evolutionary game over a set of K packet forwarding sub-regions, the set of differential equations of replicator dynamics is given by,

$$\dot{X} = P(X)X - X, \quad (\text{A.1})$$

which must have ESSs that satisfy the conditions in (2.6a) and (2.6b). In (A.1), $X = \{X_1, \dots, X_K\}$ packet proportion distribution over K sub-regions and $P(X)$ represents the transition probability matrix for a packet to move from one sub-region to any other sub-regions. The transition probability matrix is given by:

$$P(X) = \begin{pmatrix} 1 & \beta X_1(F_1(X) - F_2(X)) & \beta X_1(F_1(X) - F_3(X)) & \cdots & \beta X_1(F_1(X) - F_k(X)) \\ 0 & 1 - \beta X_1(F_1(X) - F_2(X)) & \beta X_2(F_2(X) - F_3(X)) & \cdots & \beta X_2(F_2(X) - F_k(X)) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 - \beta X_2(F_2(X) - F_k(X)) \end{pmatrix}$$

Hence, in order to find the equilibrium vector X^* , the set of equations in (A.1) must be equated to zero and solved where the following two conditions are satisfied,

$$X_k \geq 0 \quad \text{and}, \quad (\text{A.2})$$

$$\sum_{k=1}^K X_k = 1. \quad (\text{A.3})$$

Since the replicator dynamics in (A.1) depend on $P(X)$, which is a continuous function over the closed interval $[0, 1]$. Then the function $f(X)$ which is defined on the space of all X by $f(X) = P(X)X$ is also continuous on the same interval. Consequently, as proven by Brouwer fixed point theorem [87], there will be at least one fixed point for $f(X)$. This fixed point represents the equilibrium state of (A.1) and denoted by X^* . Since $P(X)$ has positive entries then the vector $X^* = P(X^*)X^*$ is positive.

In order to proof that X^* is ESSs, the system of equation (A.1) is linearized around X^* and Eigenvalues in Jacboain Matrix of (A.1) must have negative real parts. The linearization of (A.1) around X^* is given by,

$$\dot{X} = (X^*P(X^*) - X^*) + \sum_{j=1}^K (J_{k,j}(X^*)(X_j - X_j^*)) \quad (\text{A.4})$$

(A.4) can be simplified as,

$$\dot{X}_k = \sum_{j=1}^K (J_{k,j}(X^*)(X_j - X_j^*)), \quad (\text{A.5})$$

where $J(X) = [J_{k,j}(X^*)]$ is Jacobian Matrix and can be defined as below equation,

$$J(X) = \begin{pmatrix} X_1\beta \sum_{j=2}^K X_1 \frac{\partial F_1(X)}{\partial X_1} & -X_1 X_2\beta \frac{\partial F_2(X)}{\partial X_2} & -X_1 X_3\beta \frac{\partial F_3(X)}{\partial X_3} & \dots & -X_1 X_k\beta \frac{\partial F_k(X)}{\partial X_k} \\ -X_2 X_1\beta \frac{\partial F_1(X)}{\partial X_1} & X_2 X_1\beta \frac{\partial F_2(X)}{\partial X_2} + X_2\beta \sum_{j=3}^k X_j \frac{\partial F_2(X)}{\partial X_2} & -X_2 X_3\beta \frac{\partial F_3(X)}{\partial X_3} & \dots & -X_2 X_k\beta \frac{\partial F_k(X)}{\partial X_k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -X_k X_1\beta \frac{\partial F_1(X)}{\partial X_1} & -X_k X_2\beta \frac{\partial F_2(X)}{\partial X_2} & -X_k X_3\beta \frac{\partial F_3(X)}{\partial X_3} & \dots & X_k\beta \sum_{i=1}^{k-1} X_j \frac{\partial X_k(X)}{\partial X_k} \end{pmatrix}$$

Since the summation of the columns' elements in $J(X)$ are zeroes then Jacobian matrix has Eigenvalues of zeroes. Furthermore, the diagonal elements $J_{i,i}(X)$ are negative because $\frac{\partial F_i(X)}{\partial X_i} < 0$ and $J(X)$ is diagonally dominant in a way such that $J_{i,i}(X) + \sum_{j \neq i} |J_{j,i}(X)| = 0 \quad \forall i$. Greshgorin circle theorem [88] implies that all other Eigenvalues in $J(X)$ have negative real parts and this proves that X^* is ESSs [78].

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