

A game theoretic approach to improve energy efficiency of wireless sensor nodes

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Declaration

I, Willem Christoffel Petzer, hereby declare that the dissertation entitled “**A game theoretic approach to improve energy efficiency of wireless sensor nodes**” is my own original work and has not already been submitted to any other university or institution for examination.



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Signed on the 1st day of May 2015 at Potchefstroom

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For all who have played a role, large or small

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Abstract

Wireless sensor networks (WSNs) are becoming increasingly pervasive in a number of applications. Due to the nature of WSNs, one of their biggest constraints is limited node energy. As WSNs grow in popularity, the prevalent issue remains to keep wireless sensor nodes alive for as long as possible, or risk disrupting the network. This dissertation develops a model based on the principles of game theory to improve the energy efficiency of wireless sensor nodes and increase the network lifetime by influencing the way routing takes place. The benefit of this model is a routing algorithm that is easily implementable and increases network lifetime by improving energy efficiency in the network.

Keywords: *Wireless Sensor Networks, game theory, energy efficiency*

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List of Abbreviations

<i>APS</i>	-	Application Support Sublayer
<i>ACK</i>	-	Acknowledgement
<i>CCA</i>	-	Clear Channel Assessment
<i>DVS</i>	-	Dynamic Voltage Scaling
<i>MAC</i>	-	Media Access Control
<i>NWK</i>	-	NWK Layer
<i>PHY</i>	-	Physical Layer
<i>PRI</i>	-	Preference Relationship Index
<i>Rx</i>	-	Receiver
<i>Tx</i>	-	Transmitter
<i>WANET</i>	-	Wireless Ad Hoc Network
<i>WSN</i>	-	Wireless Sensor Network

Chapter 1 – Introduction

1.1 Introduction

In this chapter we discuss the background that leads to our research question, and from this follows the motivation for and significance of our research. A concise description of the proposed research is then formulated, followed by our research objectives and the methodology to satisfy these objectives.

1.2 Background

Wireless sensor networks (WSNs) are essentially networks consisting of wireless sensor nodes (see Section 2.2). These sensor nodes are usually distributed spatially in an environment and are used to record information from their surroundings which can be processed, stored and interpreted [1]. WSNs can be used to detect pending failure in infrastructures, improve security and enable applications such as context-aware systems and

smart home technology [1]. Due to the wireless nature of sensor nodes and the rising popularity of these networks, one of their biggest constraints is limited node energy [2] [3]. In many cases, it becomes too expensive to replace a node or its battery once it dies, so the node needs to stay alive for as long as possible or run the risk of adversely impacting the network performance. Energy aware routing schemes do exist where packets are relayed to nodes with the highest energy levels available. This works well to decrease the load on nodes with low energy, but can lead to the high energy nodes being inundated with traffic, draining them much quicker than would originally be the case [4].

Game theory is a study based on the premise that all entities capable of making rational decisions are inherently selfish, and will exercise all of their decisions in such a manner that they themselves receive the best possible payoff available [5] [6]. Simply stated, game theory offers general mathematical techniques [5] which can be utilised to analyse a scenario wherein two or more rational entities make decisions that affect each other's wellbeing. It offers a set of tools which can effectively be used to predict the decisions of these rational entities and even coerce them into making certain decisions. Through a game theoretic approach, wireless sensor nodes can be described as selfish, rational entities. In most cases, they are completely autonomous [7] and independently make decisions out of self-interest with no regard for the other nodes in the network, even though nodes communicate with each other and depend upon each other to cooperatively propagate data through the network by sending packets from node to node towards a central processing station, called a base node [1]. Multi-hop transmission, where intermediate nodes forward packets from the source to the base node, is an integral part of large wireless sensor networks. Autonomous, selfish nodes may refuse to expend their own resources to propagate the packets of other nodes. This causes a situation where messages have to be retransmitted or rerouted along different paths towards their destination [7]. The nodes also have limited knowledge of the network operating state on which they have to base their decisions. These observations have presented the motivation below which has led to the formulation of our problem statement.

1.3 Motivation

WSNs are becoming increasingly popular [8] because of their usefulness in an array of applications such as military, security and smart-home technologies [9]. These sensor nodes are wireless and battery operated, so they have finite lifetimes which can adversely affect their networks. With this in mind, we formulate our problem statement.

1.4 Problem Statement

It is clear that one of the greatest challenges faced by WSNs is limited node energy [1] [2] [3], and the problem of prolonging the life of wireless sensor nodes is becoming a popular and relevant research topic [10]. The longer wireless sensor nodes stay alive, the more reliable the network in question will be, due to a higher throughput and lower costs [1]. Adding to the fact is the ever growing cultural awareness of our impact on the environment. As engineers, we hold an ethical and moral responsibility to ensure that our work has as little negative impact on the environment as possible [11].

1.5 Research Objectives

The proposed research endeavours to reach the following objectives:

- Gain an understanding of the WSN environment, especially with regards to the energy usage of wireless sensor nodes
- Develop an energy efficient routing framework based on the principles of basic game theory
- Implement this framework on a model of a WSN and obtain quantifiable results
 - Improve the energy efficiency of wireless sensor nodes
 - Increase overall network lifetime
 - Increase throughput
- Compare our results to a basic routing scheme to ascertain any improvement
- Verify our model by determining if it is mathematically accurate
- Validate our model with an existing model

1.6 Research Methodology

The most important step in the research process is to identify a problem and define a concise problem statement that needs to be addressed. The research problem arises through an initial literature study which is focussed on a broader field of interest. In-depth knowledge on the subjects at hand is not necessary at this stage.

When the research problem has been clearly defined, an in-depth literature study ensues, covering the operation of nodes in a WSN, especially with regards to their communication and energy usage, as well as a study of game theory and all other relevant fields.

Once a thorough literature study has been completed that includes all relevant research fields, the obtained knowledge is applied in a practical study by simulating WSNs to gain a better understanding of specific concepts from the literature study and the operation of WSNs.

With a better understanding of these concepts, a game theoretic routing scheme is developed and implemented on a simulated model of a WSN.

The developed routing scheme is tested rigorously by means of experimentation and simulation and its capabilities are determined and evaluated. Any oversights or errors are identified and appropriately fixed. The model is refined and improved upon until the results satisfy the problem statement.

The verification and validation phases occur simultaneously with the testing phase, also leading to improvement of the model where necessary. The verification is done by ensuring that the model is mathematically sound and is correctly built, and the validation is done by comparing the model and its results to those from an existing, published model.

Finally, the final results are analysed, and conclusions are drawn regarding the realisation of the research objectives, the inadequacies and strengths of the model and its real-world applicability.

See Figure 1 for a diagrammatical illustration of the research methodology.

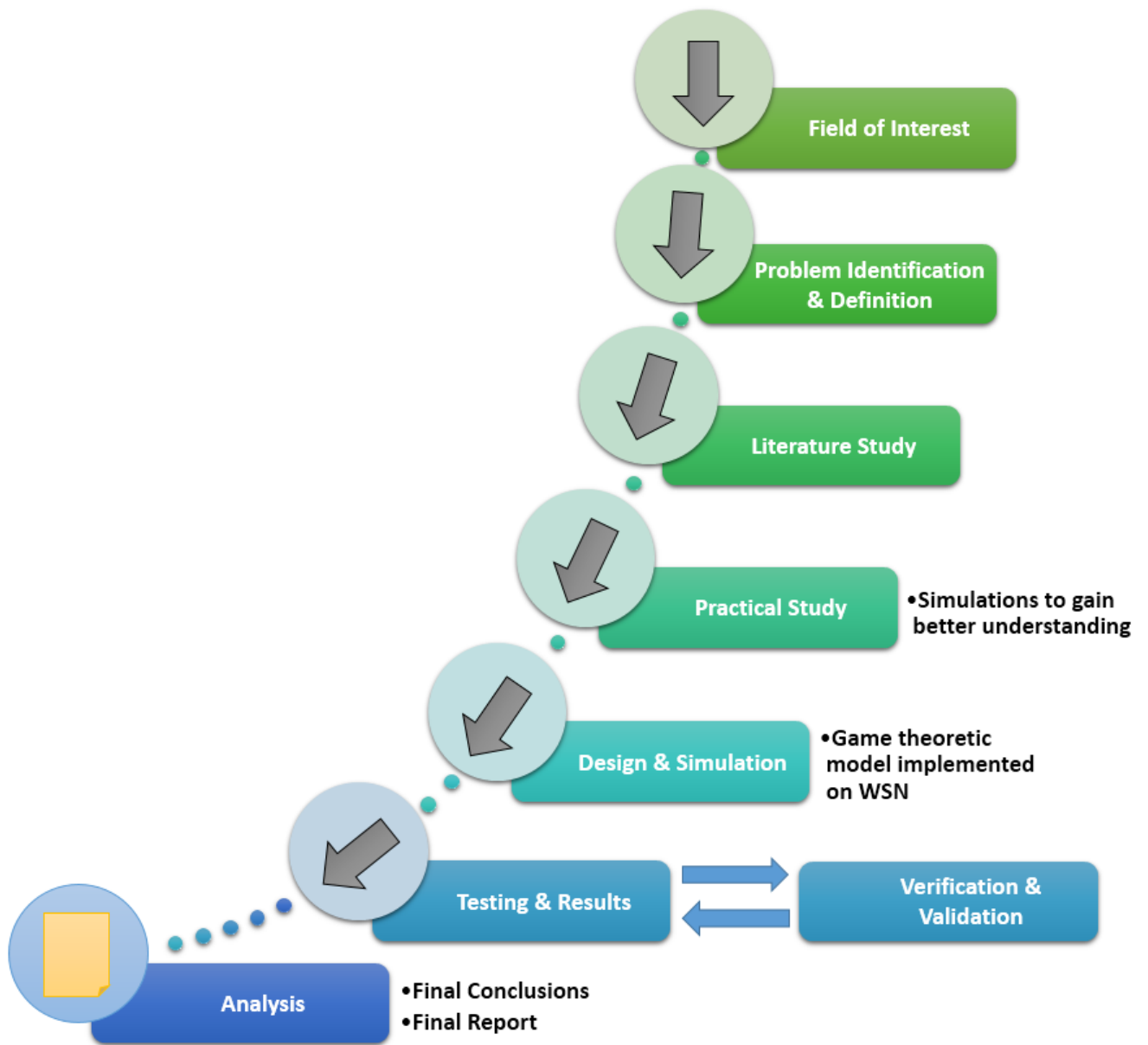


Figure 1: Research methodology

1.6.1 Verification and Validation

When our mathematical game theory model has been created and implemented on a WSN, we prove that the model is mathematically accurate and robust. We do this by constructing a small scenario with our model and obtaining results through simulation. We then recreate the same scenario on paper and do the same calculations by hand. The two sets of results are compared to prove that the model was built and implemented correctly, and makes mathematical sense.

To validate our model, we perform similar tests with our model to those done with a published model. Certain aspects of both models are mentioned and compared, as well as their results. This will prove that we built the correct model.

1.7 Dissertation Overview

We conclude this chapter with an overview of the rest of the dissertation. Chapter 2 contains a comprehensive literature study that provides the theoretical backbone of our research. Our mathematical game theory model is developed in Chapter 3, along with our simulation model of WSNs. The two concepts are also joined in this chapter and the game theoretic model is implemented in a WSN. This is followed by the verification of our model in Chapter 4. In Chapter 5, a series of simulations are run and the abilities of the model are illustrated and result sets are yielded. The model is then validated in Chapter 6, after which the dissertation is concluded in Chapter 7, where the realisation of our goals is discussed and recommendations and comments are made. A list of references can be found at the end, followed by Appendix A, which outlines our simulation setup, and Appendix B containing conference contributions from this research.

Chapter 2 – Literature Study

2.1 Introduction

In this chapter we provide the theoretical backbone upon which our research is based and from which the formulation of our problem statement originated. We discuss WSNs, the communication of wireless sensor nodes, the most prevalent protocols and standards as well as a thorough discussion on the science of game theory and the applicability of game theory on WSNs.

2.2 Wireless Sensor Networks

Wireless sensor networks (henceforth to be referred to as WSNs) are essentially networks that consist of wireless sensor nodes. These sensors are distributed spatially in a specific environment and record information from their surroundings which can be processed, stored and interpreted [1]. WSNs can be used to detect pending failure in infrastructures, improve security and enable applications like context-aware systems and smart home technology [1]. In WSNs, there is most often no form of central authority that controls the other entities in the network – for the most part, the nodes are completely autonomous [7]. This means that each node essentially operates independently and makes its own decisions. These nodes do

however, communicate with each other and work cooperatively to propagate data through the network, hopping packets from node to node towards a central processing station [1].

2.2.1 Network Performance

Below, three of the most important factors used to measure the performance of a WSN are discussed.

Survivability refers to the lifespan of wireless sensor nodes. These nodes have a limited amount of energy and when it is drained they cannot send or relay data, effectively rendering them useless [12] and impacting the network negatively. For this reason it is important that the nodes survive as long as possible.

Throughput refers to the number of packets that have successfully reached the base node in a certain amount of time [13]. The term 'maximum throughput' can essentially be interpreted in four different ways.

- Maximum theoretical throughput is the maximum amount of data that can be delivered under ideal circumstances [14].
- Maximum achievable throughput is the throughput that can be delivered when taking into account factors like host speed, network protocol and network path [15].
- Peak measured throughput is the actual throughput measured over a short period of time and is especially relevant for systems relying on burst data transmission [16].
- Maximum sustained throughput is the average of the throughput considered over a long time and is the most reliable indicator for high duty cycle networks.

Latency (Delay) is the time period that has passed from the moment the first bit of a message is transmitted from the source, until the moment the complete message has been delivered to its destination. According to [12], latency consists of propagation time (the time in which a bit is transmitted from source to destination), transmission time, queuing time and process delay. It is important for latency-sensitive applications such as VoIP to have a low latency or else the reliability of the service can be disrupted, whereas email is not affected as much by high latency as the immediate delivery of its data is not paramount.

2.2.2 Wireless Sensor Network Topologies

There are four basic types of WSN topologies:

2.2.2.1 *Peer-to-Peer*

In a peer-to-peer network, nodes can communicate directly with each other without the need of a centralised communications-hub. Each device has the capacity to function as a server or a client to the other nodes in the network [17].

2.2.2.2 *Star*

In a star network, nodes cannot necessarily communicate with each other directly, but need to use a centralized hub to relay messages across to each other. The nodes in the network act as clients and the hub as the server [17].

2.2.2.3 *Tree*

In a tree network, a *root node* serves as the primary communications router. This root node communicates with central hubs, and the hubs in turn form a star network with the other nodes in the network. Essentially, the tree network is a hybrid between the star and peer-to-peer topologies [17].

2.2.2.4 *Mesh*

In a mesh network, data is hopped from node to node until it reaches its destination or it is dropped. Mesh networks are self-healing, meaning that the death of one or more nodes does not necessarily render the network incapacitated. In especially large wireless sensor mesh networks, packets can be relayed along many different routes towards their destination, so if

one route becomes unavailable, there should be others available. Mesh networks can become quite complex [17] as the number of nodes increases. The mesh topology is of significance to our research.

2.2.3 Wireless Ad Hoc Networks

Wireless Ad Hoc Networks (WANETs) are essentially Wireless Sensor Networks, as they are formed by wireless sensor nodes but do not adhere to any infrastructure. The nodes autonomously set up a network, communicate in an ad hoc manner and have no need of a centralized authority or controlling unit. The nodes can also travel freely in space and such a network may consist of different kinds of nodes [18].

2.2.4 Sensing and Wireless Sensor Networks

Gathering information about a physical item or process and events that may occur is called sensing, and the device used to perform such sensing is called a sensor. In a technical sense, a sensor converts physical events into electrical energy that can be sent to a computing system to be analysed [1]. A wide range of sensors exist and include the following: temperature, pressure, electromagnetic, acoustic and optical [1].

Wireless sensors do not only have sensing components, but on-board processing, storage and communication capabilities as well. With these components, sensor nodes are responsible for more than just data collection. They must be able to perform in-network analysis, correlation and fusion of their own data and data from the other sensor nodes [1]. Simple nodes only collect information and communicate that information, but more powerful devices can perform more extensive processing and also form part of a communication backbone to help other resource-constrained devices reach the base station [1]. A wireless sensor network consists of many sensors that cooperatively monitor large environments.

2.2.5 Data Propagation

2.2.5.1 Single-hop

When wireless sensor nodes are close enough to the base station and their transmission range allows it, they can transmit their packets directly to the base station (see Figure 2). Each node can communicate directly with the base station using a single hop [1], so no other nodes need to expend their own energy to relay packets for these nodes. The downside to being one hop away from the base station, is that these nodes will have to relay packets towards the base node for other nodes who are more than one hop away from the base node (See Figure 3). This causes these nodes to become flooded with traffic, draining their energy faster.

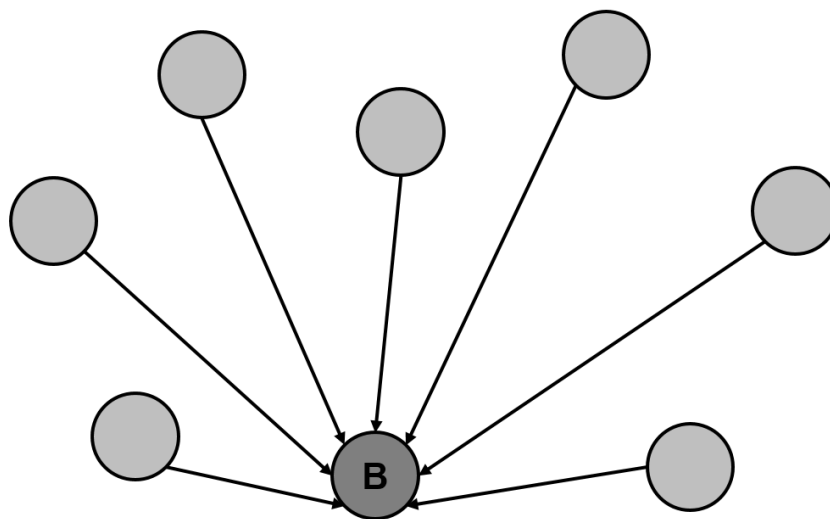


Figure 2: Single-hop communication in WSNs

2.2.5.2 Multi-hop

Sensor networks often cover large areas and radio transmission power must be kept as low as possible to conserve energy [1]. This is where multi-hop communication is employed using mesh topology. The sensor nodes now not only capture and distribute their own data, but also effectively operate as relays for the other sensor nodes in the network. The nodes then collaboratively propagate data to the base station [1]. A benefit that arises is that nodes that serve as relays for multiple routes have the opportunity to analyse the sensor data in the

network, eliminating redundant data or aggregating a set of data to be smaller than its original counterpart [1]. Plenty of research has been dedicated to this routing problem, i.e. finding multi-hop paths from sensors to the base station [1]. Routing can also be initiated at the source or at the destination [19].

Routing methods via multiple hops in WSNs are can be classified in a number of ways. Two of these are:

- Proactive routing - In this case the paths via which data is sent are set up in advance and are maintained in routing tables [19].
- Reactive routing - Routing tables and paths are created on the spot as needed [19].

Energy aware routing protocols have been developed to prolong the life of wireless sensor nodes (see Section 2.2.9).

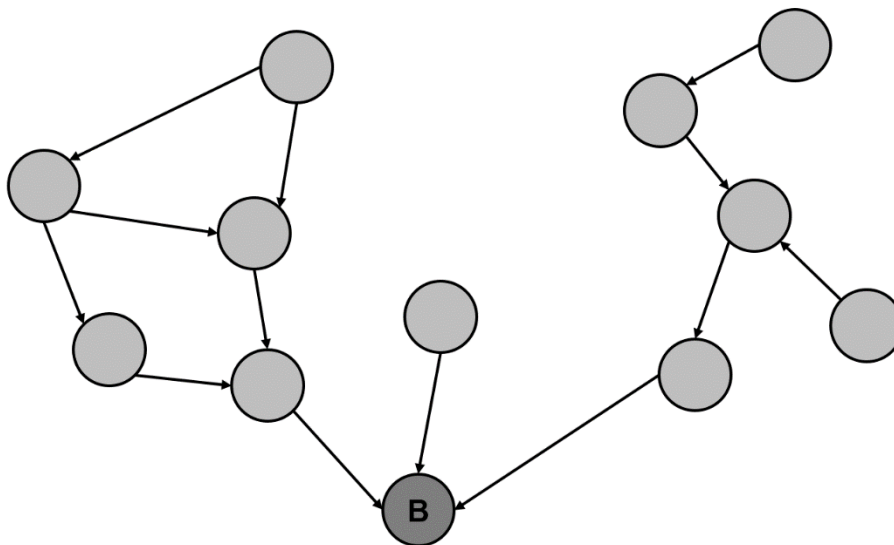


Figure 3: Multi-hop communication in WSNs

2.2.5.3 *Design Constraints on Routing*

When deciding on routing protocols to use in a network, it is important to take the algorithm paradigm into account as it will greatly influence the purpose of the protocol and its implementation. According to [20], three types of algorithm paradigms exist in WSNs:

Centralized Algorithms are implemented in nodes that possess knowledge of the entire network. Centralized algorithms are not very popular because of the high cost of transmitting data to inform the nodes of the status of the entire network [21].

Distributed Algorithms are used to when communication depends on nodes passing messages [21].

Local Based Algorithms are implemented when the nodes use limit data retrieved from a local area [21].

Routing protocols in wireless sensor nodes need to adhere to certain constraints in order for the nodes to operate effectively and for as long as possible [20] [22].

- The nodes need to operate autonomously, because WSNs more often than not do not have a centralized entity of authority that can make routing decisions.
- Routing protocols should endeavour to prolong network lifetime by take energy efficiency into account.
- Scalability of the routing protocols is important, as WSNs can consist of hundreds or thousands of nodes.
- Robustness of the network is important because nodes can stop operating at any moment due to environmental factors or the depletion of their batteries. Routing protocols should be able to handle situations where nodes may disappear from the network.
- Heterogeneity of devices needs to be taken into consideration by routing protocols. In some WSNs, the use of different devices as nodes are beneficial to the network, including increased scalability and improved bandwidth [20].

2.2.6 Node Communication

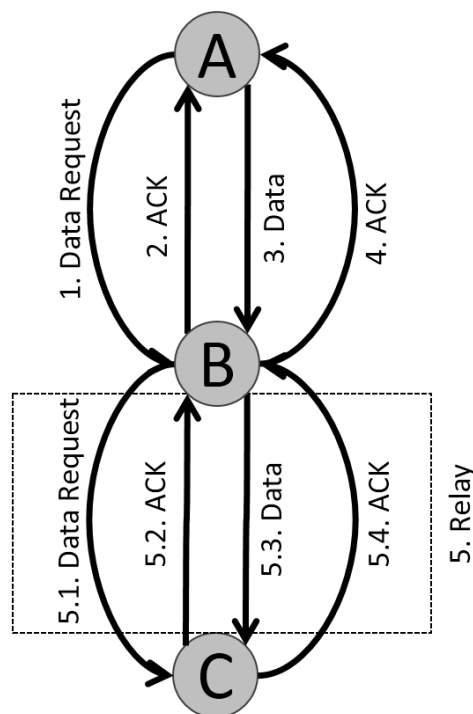


Figure 4: Handshaking process during node communication

Consider Figure 4, where *node A* attempts to communicate with *node C* but because it is too far to communicate directly, it needs *node B* to relay the message for it. Communication between the nodes occurs as follows:

1. Node A sends a *data request* to node B.
2. Node B decides if it will relay the message for node A. If node B concedes, it sends an acknowledge (ACK) message back to node A, signalling that the data can be sent.
3. Node A transmits the data.
4. Once node B receives the data, it sends another acknowledge message to node A that it has successfully received all data
5. The entire handshaking process described in steps 1 to 4 is then repeated between node B and node C. If node C returns a positive acknowledgement, node B can relay the message to its final intended destination, node C.

The example above illustrates the case where the source node (A) is two hops away from the destination node (C). In actual WSNs, source nodes can be multiple hops away from their destination nodes, so for the entire journey of a message from source to destination, the abovementioned handshaking process occurs between every pair of nodes where the message is exchanged.

2.2.7 Protocols & Standards

In wireless sensor networks, the two most prevalent communication standards are IEEE 802.11 and IEEE 802.15.4 [23]. IEEE 802.11 was designed for Wireless Local Area Networks, but due to the high-energy overheads associated with IEEE 802.11 networks, it is not as suitable for low power sensor networks [1]. IEEE 802.15.4 was designed to better focus on short range wireless communications, specifically supporting wireless sensors with low cost, low complexity and low power consumption [24], making IEEE 802.15.4 the most widely accepted standard for low-cost wireless communication. The IEEE 802.15.4 standard focuses on lower energy consumption, but lacks when it comes to throughput and delay [25]. It serves as the basic framework for the ZigBee, MiWi and WirelessHART specifications, supports a raw data rate of 250 kb/s [26] and a communication range of 10 m or more, depending on the conditions [27].

2.2.8 Energy Usage in Wireless Sensor Nodes

According to [1], a limited energy budget is the biggest constraint associated with the design of wireless sensor networks, so energy conservation is extremely important in these networks [2] [3]. These sensors nodes are usually battery-powered, meaning that their batteries must be replaced or recharged once they have been depleted [1]. This is not possible for all nodes, and some are simply discarded when their energy sources have been depleted. If a sensor uses non-rechargeable batteries, it must be able to operate until its *mission time* has elapsed or the batteries can be replaced. The mission time is dependent on the application for which the sensors are used and can cover anything from a few hours (in the case of a battlefield scenario) to years (such as scientists monitoring glacial movements) [1].

It becomes evident that the first and foremost design challenge that has to be taken into account when designing WSNs is energy efficiency. This requirement is present in every aspect of designing sensor nodes and networks [1]. For example, the design decisions made at a sensor node's physical layer will affect the entire device's energy consumption and the design of higher-level protocols [28].

The routing protocols in WSNs need to take energy usage of the nodes into account, otherwise problems such as node isolation can occur.

In CMOS-based processors, the total energy consumption is greatly attributed to leakage energy and switching energy [1]. Consider Equation 1:

$$E_{CPU} = E_{switch} + E_{leakage} = C_{total}V_{dd}^2 + V_{dd}I_{leak}\Delta t \quad (1)$$

C_{total} is the total capacitance switched by the computation

V_{dd} expresses the supply voltage

I_{leak} gives the leakage current and

Δt denotes the duration of the computation.

Switching energy still constitutes the largest part of the energy consumed by processors, but according to [29], leakage energy will constitute over half of the energy consumption in future processor designs. Techniques have been developed to control leakage energy, such as progressively shutting down idle components and a software-based technique called Dynamic Voltage Scaling (DVS) [1].

Except for having an effect on network protocols, energy efficiency has an impact on how operating systems are designed (efficient task-switching, small memory footprint etc.) and it also influences middleware, security mechanisms and even the applications.

An example of this is when *in-network processing* is employed to remove redundant sensor data or to aggregate the readings of multiple sensors. This results in a trade-off between processing (sensor data) and communication (transmitting the original data vs. processed data), which can be utilized to achieve energy savings [30].

Further, the communication subsystem of a node consumes much more energy than the computation subsystem. According to [30] the energy dissipated to transmit one bit of data can be equivalent to a few thousand instructions being executed. The sensing subsystem can also be responsible for consuming plenty of energy [10].

2.2.8.1 *OSI Layers and Energy*

2.2.8.1.1 MAC-Layer

The MAC-layer (Medium Access Control) provides the sensor nodes with access to the wireless channel. Many MAC strategies are contention-based, meaning that the nodes can essentially try to access the medium at any time, which could possibly lead to collisions between multiple nodes [1]. This issue must be addressed by the MAC-layer so that the transmissions do eventually succeed. There are several negative aspects involved with this approach, including the energy overheads and delays caused by the collisions and the recovery mechanisms, and the fact that the sensor nodes have to continuously listen to the medium to make sure that no transmissions can be missed. For this reason, MAC protocols have been developed that are contention-free, meaning that access to the medium is regulated strictly, so collisions can be eliminated and sensor nodes can turn off their radios when they do not expect communication.

2.2.8.1.2 Network Layer

The responsibility of the network layer is packet forwarding and routing. It determines suitable routes from a sensor node to the base station, and determines certain route characteristics like the number of hops, the required transmission power and the energy the relay nodes have available so that the energy overheads of multi-hop communication can be established [1].

2.2.9 *Current Energy-Efficient Techniques*

Various techniques have been developed to assist in conserving energy in wireless sensor nodes, including designing hardware to consume less power and software to manage power usage more effectively [31].

- A reduction in the power consumption of the transistor has led to great improvements in the amount of energy consumed by electronic circuits [31].
- According to [31], nodes can harvest energy from the environment through use of solar cells in addition to a battery.

-
- Transducers have been developed which can convert vibration energy collected from places such as stairs and floors into electrical energy [31].
 - There are also transducers for converting pressure or temperature changes into electrical energy [31].
 - Software may power down electronic components when they are not being used [31].

2.2.9.1 Energy-Efficient Routing Protocols

Although the techniques and technology for energy efficiency are legion, the main focus of our research is on energy efficient protocols and algorithms.

Energy Aware Routing (EAR) is a protocol that endeavours to increase network lifetime by preserving a set of paths rather than one optimal path to relay data across. According to [32], employing the lowest energy path doesn't necessarily optimise the network lifetime, but occasionally employing sub-optimal paths can lead to a considerable increase in network lifetime. A probability factor is used to select and maintain these routes and is determined by the lowest amount of energy used in each path [33].

Low-Energy Adaptive Clustering Hierarchy (LEACH) is a cluster-based protocol which aims to uniformly distribute the energy load between wireless sensors by randomly rotating cluster base stations. It was developed because according to [34], conventional protocols such as direct transmission, multi-hop routing, minimum transmission energy and static clustering are not always ideal for sensor networks. LEACH enables scalability and robustness in dynamic networks by using localised coordination and also reduces the data to be transmitted to the base station by employing data fusion [34].

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) does not create clusters, but rather creates a chain of nodes wherein each node can transmit packets and relay packets for a neighbour. Only one node can send data towards the base node at a time [35]. Data are aggregated as they move from node to node and PEGASIS has proven to be 100-300% more effective than LEACH for networks of different sizes and topologies [36].

Hierarchical Power-Aware Routing (HPAR) aims to optimize network lifetime by grouping sensors which are geographically close to one another in a zone and dividing the network into different zones [37]. Each zone operates as an individual entity and messages are routed by implementing the $max - min zP_{min}$ algorithm. This algorithm combines the advantages of

choosing the path with the minimum power consumption and that of the path that maximises the minimum residual energy in the nodes [37].

Priority-Energy Based Data Forwarding (PEDF) is an algorithm which allows each node to select the best path to forward a packet along by taking the priority of the packet and energy levels of the available forwarding nodes into consideration. The benefit of this algorithm is that it dynamically adapts to the energy status of the network and it minimizes delay and energy usage and increases throughput and network lifetime [38].

2.3 Game Theory

Game theory is a study of the mathematical models derived from the conflict and cooperation that arise between entities capable of making rational, intelligent decisions [5] [6]. In layman's terms, game theory entails mathematically predicting the choices that individuals will make when given certain decisions by assuming that their motives are always selfish. The decision makers are modelled as *players*, and the complex decisions facing them are modelled as *moves*, as if the entire scenario were a game. The fascinating part of game theory is that all the *players* in a game directly influence the success of the *moves* of the other *players*. There are various types of games, depending on the nature of the scenario in question. A few will be discussed in the following section.

The discipline is alternatively also named *interactive decision theory* [39] and is used to analyse social sciences in a wide range of applications that include psychology, economics, biology and political science [5]. Even though they are numerous, game theory is not limited to the aforementioned applications, and has been applied to computer science and engineering from the early 1990s [40].

2.3.1 Types of Games

In game theory, a *game* refers to a social scenario wherein two or more individuals take part [5]. There are essentially two branches of game theory, i.e. cooperative and non-cooperative.

Non-cooperative Game Theory: In this case, the game model consists of all the moves that the players have available [41].

Cooperative Game Theory: In this case, only the outcomes are described that may arise when the players work together in different combinations or coalitions [41].

2.3.2 Nash Equilibrium

When a situation arises where none of the players can improve their payoff, the game has converged to the *Nash equilibrium* (or alternatively, *non-cooperative equilibrium*) [42]. This means that none of the players have anything to gain by making any changes to their game, as long as the other players in the game also do not make any further changes.

2.3.3 Pareto Optimality

When a player's game can be improved without having a negative effect on the games of the other players, then such an improvement is called a Pareto improvement [43]. When there is no possibility left for any Pareto improvements, then the game has reached the point of Pareto optimality.

2.3.4 Critical Components of a Game

Although more elaborate games do exist that require additional components, the following three are always necessary and form the basis of a game [44]:

- A set of two or more players: $N = \{1, 2, \dots, i, j, \dots, n\}$
- A set of possible actions available for every player: $A = A_1 \times A_2 \times \dots \times A_n$, where A_i is the set of possible actions for player i (and $1 \leq i \leq n$)
- A set of preference relationships [5] [44] for each player for every possible action available: $\{u_i\} = \{u_1, \dots, u_n\}$

2.3.5 Example of a Game

2.3.5.1 Standard Prisoner's Dilemma

The most well-known, yet simple game theory example is the *prisoner's dilemma*. It illustrates why, even though it may be in the best interest of both players, they may choose not to cooperate [45].

Scenario: Two criminals have been caught and the police are interrogating them in separate rooms. They are both given the following choices:

- If both confess to their crime, both will be sentenced to jail for 5 years.
- If only one confesses, he will not be sentenced and the one who doesn't confess gets 10 years.
- If neither one confesses, both will be sentenced for 1 year.

Consider the game table or payoff matrix below:

Table 1: Payoff matrix for Prisoner's Dilemma

		Prisoner B's Decision	
		Confess	Hold Out
Prisoner A's Decision	Confess	5 years, 5 years	0 years, 10 years
	Hold Out	10 years, 0 years	1 year, 1 year

By considering Table 1, it becomes evident that both players in the game (the prisoners), have a choice to make by taking their own personal well-being into account, as well as all possible choices that the other player might make and the outcome of the combination of both sets of choices [45].

If prisoner A confesses, it would be in the best interest of prisoner B to confess as well. If prisoner A doesn't confess, then it would most benefit prisoner B to confess and least benefit prisoner A. However, if neither A nor B confesses, then both would benefit, as their sentences would be 1 year each.

The game has been cleverly designed to get both prisoners to confess to their crime, as confessing would be the most beneficial to both, if all possible outcomes are taken into account.

In this scenario, both players have *dominant* strategies [5]. For example, for player A this means that, regardless of player B's decision, confessing remains the highest payoff possible for player A. The rule in game theory is that, if you do have a dominant strategy, it should be used because there is no possible way to do better. Both players also have *dominated* strategies [5], meaning that there are available choices with payoffs worse than those of other possible choices. The rule is also that dominated strategies should never be chosen, because at the least, there is one other strategy with a higher payoff. *Optimal strategies* [5] [6] also exist, which relates to the highest possible outcome for a player – this would be if one player confesses and another does not. However, if both use their optimal strategies, then neither reaches their optimal outcome.

It would seem likely that the obvious choice for both prisoners would be to hold out and not confess, as this is the most beneficial option, but if the prisoners cannot communicate with each other, each is left to guess what the other might decide. This is where the selfish natures of the players arise. Assuming that both players are rational and intelligent [5] [44] in accordance with the criteria for a player, each will aim to achieve an outcome that is most beneficial for himself. Both will realise that the other player might make a selfish decision and the game will converge towards the Nash equilibrium (the case where both confess). This ultimately leads to both confessing to the crime.

It is interesting to note that, if a player makes an error and accidentally makes an incorrect decision that deviates from their planned strategy, it will almost always have a worse outcome rather than a better outcome for that player. In game theory, it is also assumed that such a decision is most definitely a mistake, because no rational being would deliberately make a decision to harm himself.

2.3.5.2 *Iterated Prisoner's Dilemma*

If the rules of the game are changed, it can become rather complicated. The game can be iterated a finite or infinite number of times (or stages) [5] [6], and with each iteration the sentence time for the players are added to their total. In this case, the players suddenly have to take into account the effect of the previous stages as well as the future stages. The player's

strategies will change. The need for cooperation becomes much greater because the result of not cooperating becomes much worse. It is also true that, if player A defects, then player B might realise it in the next round and punish the first player by also defecting, leaving player A in a worse position than before. Again, this doesn't mean that both will cooperate, as rational players are selfish players.

If the last stage is being played (finite game) and the players know it, the best move for a player is to defect (hold out and not confess) with the hope that the second player confesses. However, both players will realise this and then both will defect. This affects their entire game plan, as both players will realise this and both will defect in the penultimate stage too, as well as in the one before that, all the way backwards to the first stage. This results in both players defecting for every single stage of the game [5] [6].

If the game is infinite and the players know it, it would be wise for both to cooperate in every stage, resulting in all the stages of the game having a dual cooperation result. This is the point at which the game has converged to the Pareto optimal. Thus, the rules can be changed by setting the length of the game to an unknown number of iterations *or* an infinite number, each yielding a completely different set of results [5] [6].

2.4 Game Theory and Wireless Sensor Networks

In accordance with the requirements for a player [5] [6], wireless sensor nodes are entities capable of rational, selfish decisions [7], and the wireless sensor network environment is a competitive playing field for these nodes, with rules that need to be enforced.

2.4.1 Critical Components of a Wireless Sensor Game

Consider the following mathematical expressions:

- A set of two or more *nodes* as the *players*: $N = \{1, 2, \dots, i, j, \dots, n\}$
- A set of possible actions available for each *node*: $A = A_1 \times A_2 \times \dots \times A_n$, where A_i is the set of possible actions for *node* i (and $1 \leq i \leq n$)

-
- A set of preference relationships for each *node* for every possible action: $\{u_i\} = \{u_1, \dots, u_n\}$ These performance metrics include: available energy, throughput and node *PR*I (see Section 3.2.1).

If a game can be created with the nodes as the *players*, and the possible choices the nodes have available as *actions*, then a mathematical model can be derived on which the nodes can base their routing decisions.

2.4.2 Previous Applications of Game Theory in Wireless Networks

According to *Game Theory for Wireless Engineers*, a textbook dedicated to discussing the uses of game theory on wireless networks [46], there has been an increased interest in the application of game theoretic methods to solve an array of issues in the field of wireless networking and communications. This is further shown by the number of research outputs on the topic in recent years. Below a few applications of game theory on wireless networks are discussed.

2.4.2.1 Game Theoretic Energy-aware Clustering Algorithm

In order to mitigate the effects of hot-spots (clusters of nodes in a WSN which are prone to a high relay-load, and thus more inclined to die faster than their peers), [47] has proposed an energy-aware clustering algorithm which employs game theory to balance the energy consumption in the network. This *Game Theoretic Clustering* (GTC) algorithm determines the cluster sizes and corroborates cooperation between the cluster heads. By applying their GTC algorithm through simulation, they have shown that the energy consumption can be sufficiently balanced to achieve an increase in the network lifetime.

2.4.2.2 Improved Cooperation in Wireless Multihop Networks

Due to the problem of selfish node behaviour, [48] has developed an algorithm which employs game theory to achieve cooperation between nodes by introducing incentives and punishments to coerce nodes into cooperation. The payoff mechanisms associated with game

theory is exploited to achieve a mutual agreement between nodes regarding the collusive packet loss probability [48]. The authors have put forth a model that derives the conditions for forwarding collusive (secret) packets, truthfully routing broadcasts and correctly implementing packet acknowledgement that occurs in a lossy, multi-hop environment by applying the principles of game theory.

2.4.2.3 Cross-layer Design in Cognitive Wireless Networks

In [49], with the aim of improving energy efficiency at the MAC-layer, the application of game theory to achieve optimal power transmission and analyse conflicting nodes is examined. They developed a game theoretic price optimization power saving model which showed that, while taking data rate, interference and noise variation into account, game theory is effective when used for optimum energy allocation at the MAC-layer when transferring data.

2.4.2.4 Cluster-based Control Algorithm in Wireless Ad-Hoc Networks

With the focus on connectivity and energy efficiency, [50] has proposed an algorithm which aims to find a network topology within a reasonable convergence time, with close to optimum energy consumption. Game theory is used to prove the convergence properties of the proposed algorithm and clustering is used to reduce the convergence time.

2.4.2.5 Cooperative Game Theory for Energy Efficient Policies in WSN

By employing cooperative game theory, [51] proposes a framework to be used as a theoretical backbone for energy aware agreements of cooperation between cellular network providers. Their approach focusses on an energy-aware cooperative management scheme between different cellular access networks which provide their services over the same areas.

2.4.2.6 Energy-Efficient MAC Protocol for WSNs

By viewing energy conservation (over parameters like delay and throughput) as the primary goal, [52] aimed to develop an incompletely cooperative game-theoretic MAC protocol which is energy-efficient and improves system performance.

Table 2: Comparison of research on game theory and wireless networks

Algorithm:	Network Type:	Node Deployment:	Simulation Parameters:	Performance:	Comments:
GTC (Game Theoretic Clustering) [47]	Wireless Sensor Network	Nodes uniformly deployed	Nodes: 1000 Area: 100mx400m Node Energy: between 2J and 4J	Increase in network lifetime: between 2.61% and 8.14%	The method showed an improved network lifetime, however, it was only applied to simulated networks with uniformly deployed nodes and the assumption of one cluster-head per region.
SR ³ (Selfishness Resilient Resource Reservation) [48]	Wireless Sensor Network	Unknown	Unknown	Improved node cooperation, even in networks with various packet loss rates and variable bandwidth rates.	This research showed that cooperation between selfish nodes is possible with game theory. They assumed certain parameters (such as their collaborative packet relay probability), but will address this issue in future research.

Game Model [49]	Cognitive Wireless Network	N.A.	Channels: 30 Channel Rate: 256kbps, 400kbps & 512kbps Package Size: 4B BER: 0.001	Their results showed that game theory had a positive effect in optimum power allocation at the MAC-layer for transferring data.	This research focussed specifically on the MAC-layer, as well as the optimal utilization of transmission power per node.
QDTC (Quasi Distributed Topology Control) [50]	Wireless Ad-hoc Network	Randomly deployed	Nodes: 60 to 200	Their game theoretic QDTC algorithm converged ten times faster than the original DTC (Distributed Topology Control) algorithm, and increases power efficiency in nodes	This research aimed to establish an energy efficient topology control algorithm by using game theory. They admit they needed to focus on throughput and optimal transmission time as well, and would do so in future research.
G-ConOpt (Game-Theoretic Constraint Optimization) [52]	Wireless Sensor Network	Star Topology	Nodes: 50 Channel Rate: 1Mbps	An improvement in energy efficiency from 7kb/s/mJ to 13.5kb/s/mJ over the same simulation time	Their results showed an improvement in energy efficiency, though their simulation was only done over an ideal channel, which should be addressed in future.

2.5 Motivation

The energy usage and network lifetime problems inherent to wireless sensor networks have been discussed in this chapter. Except for physical improvements to the hardware and technology of wireless sensor nodes, it is evident that the software and protocols that regulate the communication between the nodes can have a significant influence on the longevity of the network lifetime and the overall throughput (see Section 2.2.9). According to [46], the application of game theory in wireless sensor networks, especially with a focus on energy efficiency, has been receiving an increasing amount of attention in recent years. Various game theoretic models that focus on very specific problems have been put forth (see Section 2.4.2), but according to [46], the surface has barely been scratched on what can be done with game theory in the wireless network environment. This in itself warrants further research, but given the fact that game theory is such a versatile tool, and the fact that energy efficiency is a pervasive problem, this warrants applying the principles of game theory on wireless sensor networks with the aim of achieving an improvement in network energy efficiency.

2.6 Summary

In this chapter we gave the core background upon which our research is based. This includes the discussion of WSNs and their applications, the most prevalent protocols and standards for WSNs, the process of multi-hopping, node communication and energy efficiency in WSNs. A detailed discussion of game theory was provided and finally the chapter was concluded with a focus on the applicability of game theory on WSNs and previous research done on this topic.

Chapter 3 – Mathematical Model

3.1 Introduction

In this chapter we discuss the novel application of a game theoretic model as applied to wireless sensor networks. We introduce new concepts we developed such as the *preference relationship index* and a new node rating scheme, in an attempt to utilize game theory effectively in order to improve the energy efficiency of nodes in a wireless sensor network.

3.2 Game Theoretic Model

The aim of the model is to illustrate the effects of a game theoretic approach to routing in wireless sensor networks.

In accordance with the requirements for a player [5] [6], wireless sensor nodes are entities capable of rational, selfish decisions [7], and the wireless sensor network environment is a competitive playing field for these nodes where each decision made by a node can affect the wellbeing of the other nodes in the network.

The following three components are always necessary and form the basis of a game [44]:

- A set of two or more nodes as players: $N = \{1, 2, \dots, i, j, \dots, n\}$
- An action set of possible actions available for every node: where A_i is the set of possible actions for node i (where $1 \leq i \leq n$) and A is the action space formed from $A = A_1 \times A_2 \times \dots \times A_n$. Furthermore, a_i denotes a particular action chosen by node i , where $a_i \in A_i$
- A set of preference relationships for each node which expresses a node's preference of one outcome over another for every possible action $\{u_i\} = \{u_1, \dots, u_n\}$. The performance metrics taken into account here include node energy and *PRI* (see Section 3.2.1). A utility function is created and assigns a number for every possible outcome available, and a higher number implies the outcome is preferred more. See Figure 6 for an illustration of the available choices and their outcomes.

With the abovementioned mathematical model, a game can be created with the nodes as the *players*, and the possible choices the nodes have available as *actions*. From this a framework can be derived on which the nodes can base their decisions [44] when taking their one-hop neighbours into account, in order to make the most energy efficient decisions for the benefit of the entire network.

3.2.1 Applied to Wireless Sensor Network

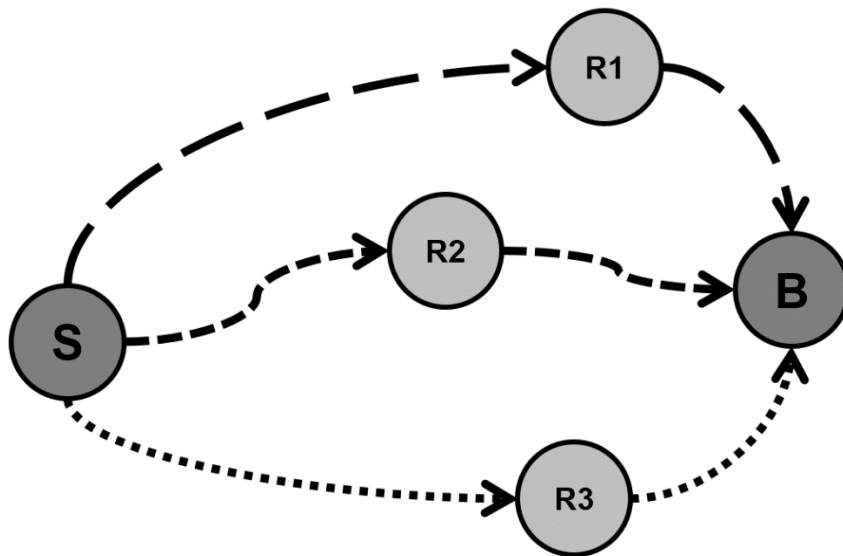


Figure 5: Relaying scenario in a WSN

Consider Figure 5. A source node, *node S*, is trying to relay a packet to the base node, *node B*. It is evident that node S is at best two hops away from node B, with nodes *R1*, *R2* and *R3* all possible relay nodes for node S's packet, as they are all only one hop away from the destination node. The stage is now set where all of the nodes are to be players in a round of basic game theory.

Nodes can choose to either relay messages for each other, or refuse to, depending on the possible payoffs available for the nodes in question. The catch is, each decision has a consequence, and each node will exercise its decision in such a manner to ensure that it gets the best possible payoff available.

We will now introduce our rating scheme: all of the nodes initially receive an identical rating of 0. This rating tells other nodes how reliable the node is with regards to relaying data, basically serving as a measure of the trustworthiness of a node. The more a node relays data for other nodes, the higher its rating will be, even though it will expend more energy to relay. The less often a node chooses to relay for other nodes, the lower its rating will be. If a node already has a low rating, other nodes may choose to refuse relaying for that node at less of a penalty to themselves, because the credibility of the node in question is so low (see Table 4). Conversely, the higher the node rating is, the higher the penalty if refusing to help that node. A node also loses less rating points if its own energy is already low and it refuses to relay for others in order to conserve its own energy. It is important that a node finds the right balance in the trade-off between maintaining a good rating and preserving energy.

Tiers: In our simulation, every single node is divided into a *tier*, based on its hop-distance from the base node. If a node is one hop away from the base node, it falls into tier 1, and if it is two hops away, it falls into tier 2, and so forth. As some nodes die, the tiers of the remaining nodes are updated. Node S looks at all of its one hop neighbours' tiers and then selects all the neighbour nodes that fall in the lowest available tier as possible relay nodes.

Node S has a decision to make regarding which of these selected one-hop neighbour nodes would be the best option to relay its message to the base node. For the sake of the simulation, it is assumed that each node knows the energy levels, ratings, and tiers of all its one-hop neighbours, but in practice this can be implemented as an external protocol [53].

Table 3: Node status table

Node	Energy	Tier	Rating
S	E_S	-	R_S
R1	E_{R1}	T_{R1}	R_{R1}
R2	E_{R2}	T_{R2}	R_{R2}
R3	E_{R3}	T_{R3}	R_{R3}

By considering these factors through a game theoretic viewpoint, node S makes a decision regarding which node to approach for relaying its data to the base node.

By considering the set of nodes in the game, $N = \{S, R1, R2, R3\}$ and the action set available for node S, $A_s = \{RR, DNRR\}$ where *RR* denotes the *Request Relay* and *DNRR* denotes the *Do Not Request Relay* actions available for node S [7]. *DNRR* will occur if the source node is one hop from the base node and can deliver its own messages directly.

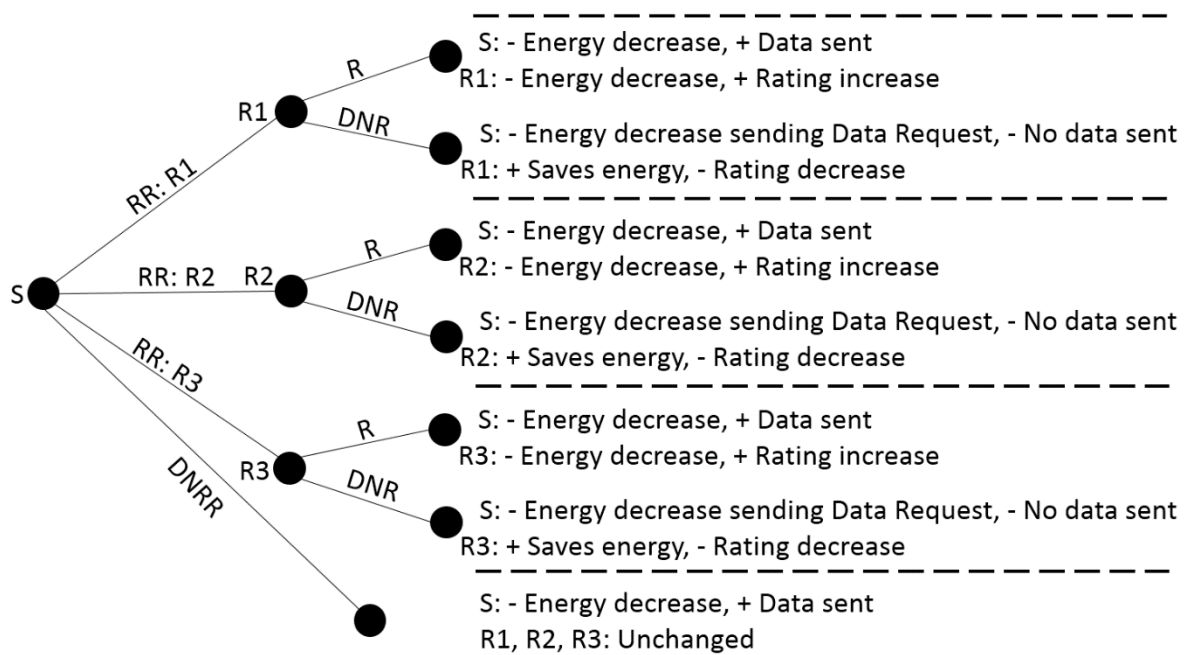


Figure 6: Actions and effects for game between source node and relay nodes

Node S now takes into account the energy levels of nodes R1, R2 and R3, as well as their ratings and tiers. The tier levels sift the available relay options by offering all of the least-hop routes. For the sake of illustration, nodes R1, R2 and R3 are all tier 1 nodes. The node energy level is the most important factor and bears the most weight in node S's decision, and the node rating the second most weight. We now introduce our novel concept, the *Preference Relationship Index* (PRI), which is an aggregate consisting of 80% energy and 20% rating (see Equation 2) of the node in question. This ratio of energy to rating is not set in stone and can be tweaked for individual networks to determine which ratio yields the best results per specific instance. For the purpose of simulation, we have decided through trial and error on the given ratio. Node S creates a set of PRIs for all possible relay nodes.

$$\left(\frac{E_{node}}{E_{max}}\right) (80) + \left(\frac{Rating_{node}}{Rating_{max}}\right) (20) = 40\% \quad (2)$$

A node with 50% of its energy left (where 1J is the maximum) and a rating of 0 (where 0 is neutral, -100 is the minimum and 100 is the maximum) will have an aggregate of 40%.

Node S selects the node with the highest PRI aggregate as the first node to request relaying from. For argument's sake, assume that node S has chosen node R3 as the most viable relay node and sends a *data request* to node R3. Node R3 then creates its own game by taking its own energy into account, as well as the energy and rating of node S and decides whether to relay or not. Table 4 below shows the penalty a node receives if it refuses to relay for another node with a rating between certain boundary values, as well as the reward it will receive if it does choose to relay. If the relay node's energy is below 25%, it can refuse relaying at a fixed penalty of -1, regardless of the rating of the sender node. For an energy level above 25%, the *Rating Table* (Table 4) is used. In Table 4, a rating scale ranging from the minimum -100, to the maximum 100 is shown, with the appropriate penalties. Each node starts at neutral at the beginning of its life, which is zero, and then either increases or decreases its rating according to its actions, and may reach its minimum or maximum value. The two extreme constraint values are set to serve as boundaries to prevent any node rating from running away in either direction, forcing each node to be in a constant state of caring for its rating and effectively take part in the game.

Table 4: Rating penalties vs. rewards

Sender Node Rating	Node Penalty for not Relaying	Node Reward for Relaying
$-100 \leq R \leq -50$	-1	3
$-50 < R < 50$	-2	2
$50 \leq R \leq 100$	-3	1

Consider the set of nodes in the game case of node R3, $N = \{S, R3\}$ and the action set available for node R3 $A_{R3} = \{R, DNR\}$ where *R* denotes the *Relay* and *DNR* denotes the *Do Not Relay* [7] actions available. A utility function of the preference relationships is then created for node R3 [44] :

$$u_{R3} = \begin{cases} a_{R3} = R \rightarrow \text{Expend } X \text{ Energy, Rating Increase } Y \\ a_{R3} = DNR \rightarrow \text{Save } X \text{ Energy, Rating Decrease } Y \end{cases}$$

If node R3 has an energy level above 25%, it will want to relay for node S, as it still has a relatively healthy energy level and does not want to be penalized by not relaying. However, if its rating has dropped below -50, and node S has a rating above -50, node R3 will relay for node S to increase its rating, despite its own low energy.

If node R3 relays, it sends an *ACK* message to node S and the handshaking process in Figure 4 takes place (refer to Section 2.2.6). Alternatively, if node R3 refuses to relay, node S then approaches the second best node in its PRI for data relaying.

Node R3 will then ultimately relay the packet to node B, where the handshaking process described in Section 2.2.6 takes place, but since node B is the base node to which all data is forwarded, it automatically accepts the packet without the need of creating a game.

It would do well to remember that aim of the game, so to speak, is to improve the energy efficiency in the network, but without hindering throughput. For this reason, choosing the most energy efficient route is of paramount importance, but the priority of nodes is still to deliver packages effectively. This is why a node which is the sole available relay node, or the sender node's last resort, will always relay.

In conclusion, our model endeavours to improve energy efficiency in WSNs by prolonging node lifetime through effective routing choices. Improved node life will delay node isolation, leaving more viable routes, leading to a higher throughput per unit of energy expended.

3.2.2 Energy Model

The nodes and their operation and communication protocols are modelled as Zigbee devices [54]. All relevant constants, values and equations are obtained from valid ZigBee and IEEE 802.15.4 specifications.

3.2.2.1 Packet Size

In order to determine the energy expended by a node, the size of the packets it transmits is needed. According to the IEEE 802.15.4 [55] standard and the protocol for Zigbee devices, the size of a packet can be calculated with Equation 3:

$$Data = Payload + Overhead \quad (3)$$

$$Data = Payload + (APS + NWK + MAC + PHY)$$

The *payload* is the size of the actual message and *overhead* consists of the headers of the APS, NWK, MAC and PHY layers, where their sizes are defined by the IEEE 805.15.4 and Zigbee protocols [56]. Thus, if the payload is 3 bytes:

$$Data = 3 + (8 + 8 + 9 + 2)$$

$$Data = 30 \text{ bytes}$$

3.2.2.2 Energy Calculation

According to [54], a node wishing to send a message will turn on its radio to active mode and wait a random amount of time before performing a CCA. If CCA shows that the channel is busy, a node will back off for a random amount of time before trying again. This back off period is a multiple of the unit back-off period, which is equal to the MAC constant, *UnitBackoffPeriod* symbols [54].

This random amount of time is an integer between 0 and $2^{BE} - 1$, with BE incremented by 1 after every unsuccessful attempt [54].

$$Backoff = (A \text{ random integer between } 0 \text{ and } 2^{BE} - 1) \times aUnitBackoffPeriod \quad (4)$$

In [55], the CCA detection time is defined as 8 symbol periods and *aUnitBackoffPeriod* as 20 symbol periods. One symbol period is 16 μ s.

With this in mind, the CCA time can be calculated with Equation 5 [56]:

$$CCA_{total} = Backoff + CCADetectiontime \quad (5)$$

$$CCA_{total} = (2^{BE} - 1) \times UanitBackoffPeriod + CCADetectiontime$$

$$CCA_{total} = (2^3 - 1) \times (20 \times 16\mu s) + (8 \times 16\mu s)$$

$$CCA_{total} = (2^3 - 1) \times (320\mu s) + (128\mu s)$$

$$CCA_{total} = 2.368ms$$

The time it takes for a message to be processed is the time the device spends in R_xT_x mode and is calculated with Equation 6 [56]:

$$R_xT_x = \frac{(k)}{(b)} \quad (6)$$

where k is the size of the message in bits (hence the multiplication by 8) and b is the bitrate of the radio chip in bps, which is 250kbps [56]. According to [56] the size of a *data request* message is 12 bytes. By substituting in Equation 6:

$$T_xdatarequest = \frac{(12)(8)}{(250 \times 10^3)} = 384\mu s$$

The size of an ACK message is 5 bytes:

$$ACK = \frac{(5)(8)}{(250 \times 10^3)} = 160\mu s$$

Equation 6 is also used to calculate the time it takes to transmit or receive a message of 30 bytes.

$$T_xdata = \frac{(30)(8)}{(250 \times 10^3)} = 960\mu s$$

The time a device takes to make the transition between sending and receiving is given as [56]:

$$R_x T_x \text{receiver} = R_x T_x \text{sender} = 192\mu\text{s}$$

The energy consumption model for the simulation is based on the IEEE 802.15.4 [55] standard. The energy expended by a node is calculated by determining the time it spends in active mode. The total time can then be calculated with Equation 7:

$$t_{total} = (CCA_{total}) + (T_x \text{datarequest}) + (R_x T_x \text{receiver}) + (R_x \text{ACK}) + (R_x T_x \text{sender}) + (T_x \text{data}) + (R_x T_x \text{receiver}) + (R_x \text{ACK}) \quad (7)$$

Table 5: Variables and their descriptions for Equation 4

Variable	Description	Value
CCA_{total}	The total CCA detection time until the channel is clear	2.368ms
$T_x \text{datarequest}$	The time it takes to send a data request	384μs
$R_x T_x \text{receiver}$	The time the receiving device takes to transition between R_x and T_x mode	192μs
$R_x \text{ACK}$	The time it takes to transmit the acknowledge message	160μs
$R_x T_x \text{sender}$	The time the transmitting device takes to transition between R_x and T_x mode	192μs
$T_x \text{data}$	The time it takes to transmit a message	960μs

By substituting the values from Table 5 in Equation 7, the total time the node spends in active mode (hence the total time a node spends expending extra energy), is calculated.

$$t_{total} = (2.368ms) + (384\mu\text{s}) + (192\mu\text{s}) + (160\mu\text{s}) + (192\mu\text{s}) + (960\mu\text{s}) + (192\mu\text{s}) + (160\mu\text{s})$$

$$t_{total} = 4.608ms$$

The energy dissipated by the sender node can then be calculated with Equation 8 [56]:

$$E_{sender} = (V)(I)(t_{total}) \quad (8)$$

$$E_{sender} = (2.4V)(17mA)(4.608ms) = 188\mu J$$

3.2.3 Wireless Sensor Network Model

The parameters used for the wireless sensor network simulation is briefly described below.

For the simulations, the optimal radio range according to [56] is calculated with Equation 9 for each network:

$$R = \phi \sqrt{\frac{\log N}{N}} \quad (9)$$

The symbol ϕ represents the diameter of a 2D plane and N the number of nodes in the network. If a network with 100 nodes is deployed in a 100x100m area (with 141.42m diameter), then the optimal radio range for the network is calculated as:

$$R = (141.42) \sqrt{\frac{\log 100}{100}} = 20m$$

giving an optimal radio range of $R = 20$ m.

3.3 Conclusion

In this chapter we developed a game theory-based algorithm for nodes to use when sending and relaying messages through a network. We also introduced the novel concepts of node ratings and the PRI, which are used as an incentive to ensure that the nodes in the game will make their decisions in a manner conducive to the energy efficiency of the network, or risk being penalized. The energy model of ZigBee devices, upon which the nodes in our simulations are modelled, was calculated and the optimal radio range was discussed.

Chapter 4 – Verification

4.1 Introduction

In this chapter our mathematical model and results will be verified. During the verification stage, we confirm that the model is mathematically sound and performs correctly. We do this by creating a small simulation scenario and obtaining two sets of results – the first set of results are those yielded by the simulation itself, and the second set is calculated by hand. The two result sets are then compared to prove that the simulation results are possible and correctly obtained.

4.2 Verification

For the verification phase, a network similar to the one in Figure 7 will be simulated, and the results yielded will be compared to a set of results obtained though calculation by hand. The scope of the simulation is small, containing only five nodes, but serves to illustrate the mathematical accuracy of the model. Instead of verifying every aspect of a complete

simulation, which would become too arduous and time consuming to justify the exercise, we aim to verify the operation of submodules of the simulation on a smaller scale in order to prove the accuracy of the model.

4.2.1 Simulation 1: Two-hop Communication

5 nodes are positioned as seen in Figure 7. For the purpose of simulation, the node energy has been decreased dramatically, allowing each node to relay about three packets before dying.

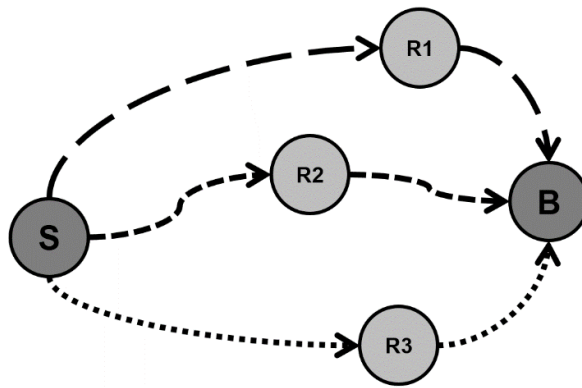


Figure 7: Relaying scenario in a WSN

4.2.2 Simulation Results

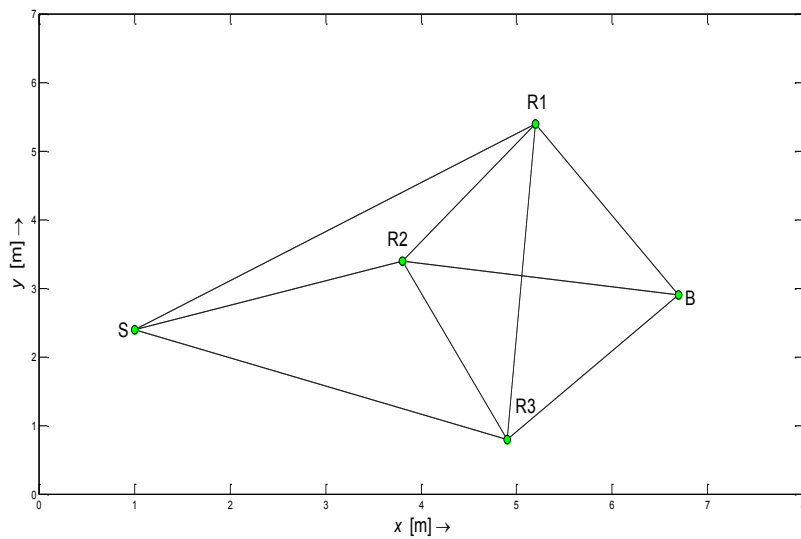


Figure 8: Simulation for verification phase

Table 6: Verification - Simulated results

Node	Action	Simulated Results
S	Messages Sent	5
R1	Messages Relayed	1
	Energy Expended	40%
	Change in Rating	-50 to -48
	Change in PRI	61 to 34
R2	Messages Relayed	2
	Energy Expended	80%
	Change in Rating	0 to 4
	Change in PRI	74 to 10
R3	Messages Relayed	2
	Energy Expended	80%
	Change in Rating	50 to 54
	Change in PRI	87 to 18
B	Messages Received	5

4.2.3 Calculated Results

We will break up the communication process step for step, following the node parameters as we go along. For the purpose of clarification, a simplified model is used and the nodes have little energy available, allowing the relay nodes enough energy to relay about two or three messages before dying. This causes the results to be more readily available without the need of calculating hundreds of transmission rounds by hand. Instead, five rounds will suffice before

all the relay nodes are drained. Furthermore, there is assumed that only node S sends packets to node B.

The initial node parameters are given in Table 7 below.

Table 7: Verification - Node parameters

Node	Rating	Energy	Preference Relationship Index	Packets Processed
S	80	N.A.	N.A.	0
R1	-50	68%	60	0
R2	0	75%	70	0
R3	50	81%	80	0

Transmission Round 0:

1. Node S considers which node would be the best relay node for the message it wishes to send to node B. According to the game theory rules, it chooses the node with the highest PRI value, which is node R3.
2. It contacts R3 through the handshaking process described in Section 2.2.6.

Transmission Round 1:

3. By applying game theory, R3 takes its own energy and rating into account as well as the rating of node S. Node 3 has to decide between the trade-off of maintaining a good rating, and preserving its own energy. In this case, R3 has enough energy to relay for S and does so.
 - a. R3: +2 rating increase
 - b. R3: 40% Energy decrease

Transmission Round 2:

4. R2 now has highest PRI. S approaches R2 to relay message. R2 concedes.
 - a. R2: +2 rating increase.
 - b. R2: 40% Energy decrease.

Transmission Round 3:

5. R1 now has highest PRI. S approaches R1 to relay message. R1 concedes.
 - a. R1: +2 rating increase.
 - b. R1: 40% Energy decrease

Transmission Round 4:

6. R3 now has highest PRI again. S approaches R3 to relay message. R3 concedes.
 - a. R3: +2 rating increase
 - b. R3: 40% Energy decrease

Transmission Round 5:

7. R2 now has highest PRI. S approaches R2 to relay message. R2 concedes.
 - c. R2: +2 rating increase.
 - d. R2: 40% Energy decrease, R2 dies.

It should be noted that in the case were all the nodes have quite low PRI values, the one with the highest value will still always be the first choice for the source node. The PRI decreases, as the energy of each node decreases, even though the rating may increase. This is expected, as the largest part of the PRI consists of the node energy.

Table 8: Verification - Hand calculated results

After Transmission Round	Node	Rating	Energy (%)	PRI	Messages Sent/Relayed per Round	Total Messages Sent
0	S	45	-	54.5	0	0
	R 1	-50	70	61	0	0
	R 2	0	80	74	0	0
	R 3	50	90	87	0	0
1	S	45	50	54.5	1	1
	R 1	-50	70	61	0	0
	R 2	0	80	74	0	0
	R 3	52	50	55.2	1	1
2	S	45	-	14.5	1	2
	R 1	-50	70	61	0	0
	R 2	2	40	42.2	1	1
	R 3	52	50	55.2	0	1
3	S	45	-	14.5	1	3
	R 1	-48	30	29.2	1	1
	R 2	2	40	42.2	0	1
	R 3	52	50	55.2	0	1
4	S	45	-	14.5	1	4
	R 1	-48	30	29.2	0	1
	R 2	2	40	42.2	0	1
	R 3	54	10	23.4	1	2
5	S	45	-	14.5	1	5
	R 1	-48	30	34	0	1
	R 2	4	0	10	1	2
	R 3	54	10	18	0	2

4.2.4 Conclusion

Table 9: Verification – Simulated results vs. calculated results

Node	Action	Simulated Results	Calculated Results
S	Messages Sent	5	5
R1	Messages Relayed	1	1
	Energy Expended	40%	40%
	Change in Rating	-50 to -48	-50 to -48
	Change in PRI	61 to 34	61 to 34
R2	Messages Relayed	2	2
	Energy Expended	80%	80%
	Change in Rating	0 to 4	0 to 4
	Change in PRI	74 to 10	74 to 10
R3	Messages Relayed	2	2
	Energy Expended	80%	80%
	Change in Rating	50 to 54	50 to 54
	Change in PRI	87 to 18	87 to 18
B	Messages Received	5	5

By considering the comparison between the two result sets obtained through simulation and calculation, it is evident that our model is mathematically accurate, yields realistic results and operates as expected.

Chapter 5 – Results

5.1 Introduction

In this chapter, we implement our game theoretic model on a set of WSN simulations and present the results of five tests, each designed to demonstrate a different aspect of our model. In these simulations, the key performance indicators throughout are energy usage, throughput, and network lifetime. For information on our simulation setup and the software used, please refer to Appendix A.

5.2 Simulation 1: Network with Randomly Placed Nodes

In this section we implement the model described in Chapter 3 in a simulated WSN environment. A set of Monte Carlo simulations are done on the game theoretic routing algorithm and another on the shortest path routing algorithm, and the result sets are compared. Monte Carlo simulations make use of repeated random sampling by running a simulation repeatedly and generating random inputs over a specified distributed set of data in order to provide accurate numerical results [57].

5.2.1 Scope and Purpose

The purpose of this test is to implement our game theoretic model in a simulated environment and see how it compares to the shortest path routing scheme in terms of network lifetime, throughput and energy usage.

5.2.2 Simulation Setup

In the simulation the nodes are homogeneous and each is equipped with a 1J battery. Communication occurs through rounds of data transmission. In each round every node in the network unicasts a packet towards the base node. Packets are multi-hopped through the network towards the base station (node 1 – see Figure 9), which is powered independently and has an unlimited energy reserve.

100 nodes are randomly deployed in a 100x100m area (see Figure 9), and each node has an optimal radio range of 20m, as calculated with Equation 9 in Chapter 3. For more comprehensive information on the simulation setup, refer to Chapter 3.

The transmission rounds are repeated until all the nodes one hop from the base station are dead, causing the base station to no longer be reachable and effectively end the network life.

At the end of simulation, a node will either be green, having 75% or more of its original energy left, yellow with between 25% and 75%, red with energy below 25%, or black meaning the node is dead with 0% energy left.

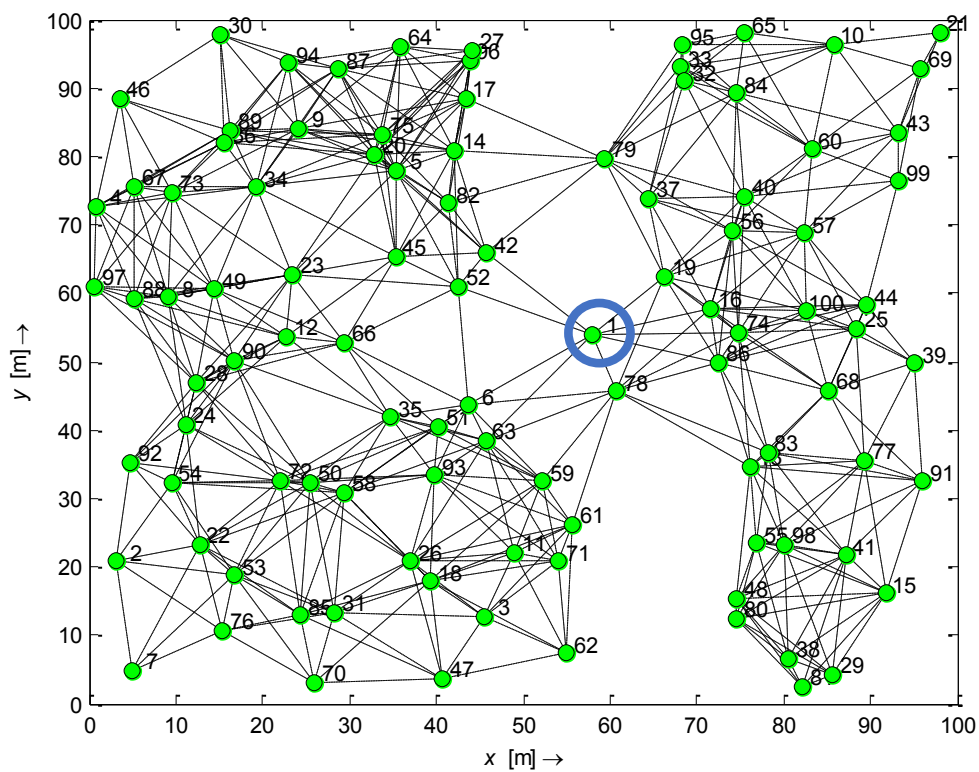


Figure 9: One instance of the WSN with randomly deployed nodes

5.2.3 Results for One Instance

To adequately explore the results, we will first discuss the results obtained from one simulation instance. This will be followed by the complete Monte Carlo simulation results.

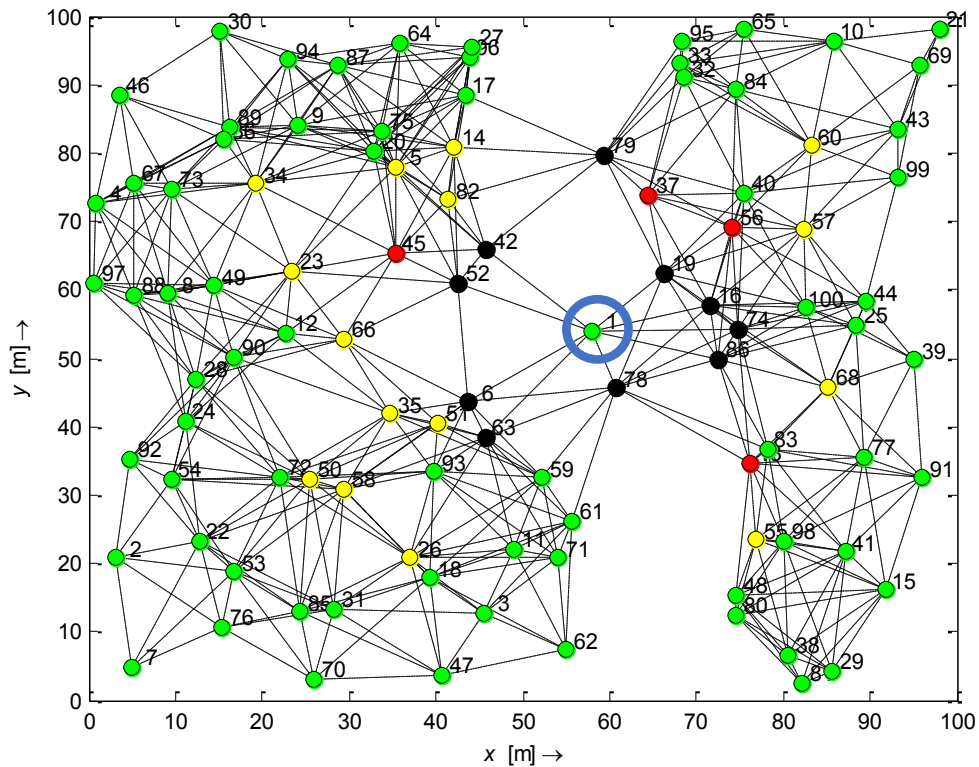


Figure 10: Shortest path – WSN after 470 transmission rounds

For the sake of illustration, one instance of a WSN is shown in Figure 10, where the shortest path method was used to relay packets. The network lifetime reached 470 rounds before the base node could no longer be reached by any nodes. The green nodes have 75% or more of their energy left, the yellow nodes between 25% and 75%, the red nodes below 25% and the black nodes are dead with 0% energy left.

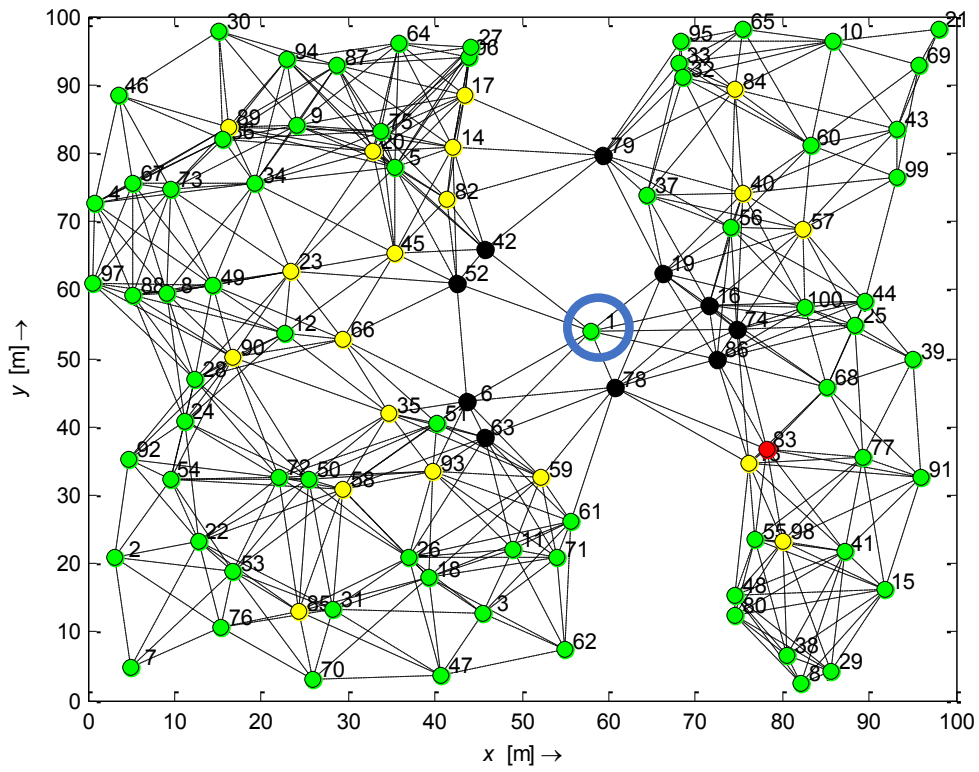


Figure 11: Game theory – WSN after 503 transmission rounds

In Figure 11, for the same WSN instance but with our game theory method, the network lifetime reached 503 rounds before the base node could no longer be reached by any nodes.

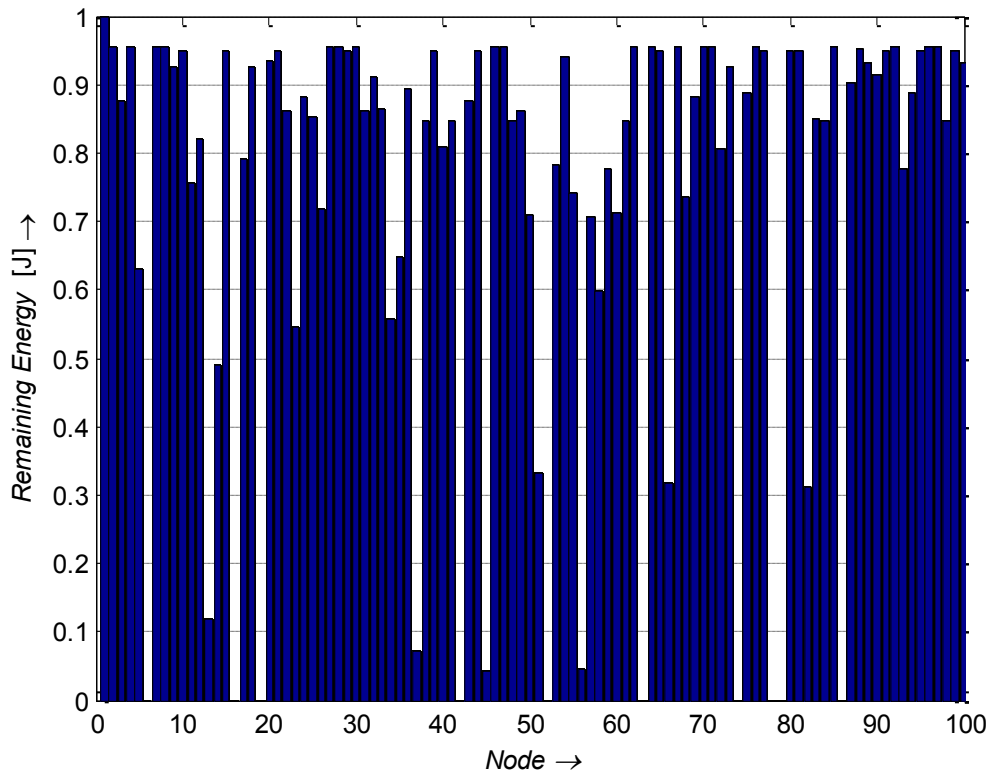


Figure 12: Shortest path – Remaining energy per node after 470 transmission rounds

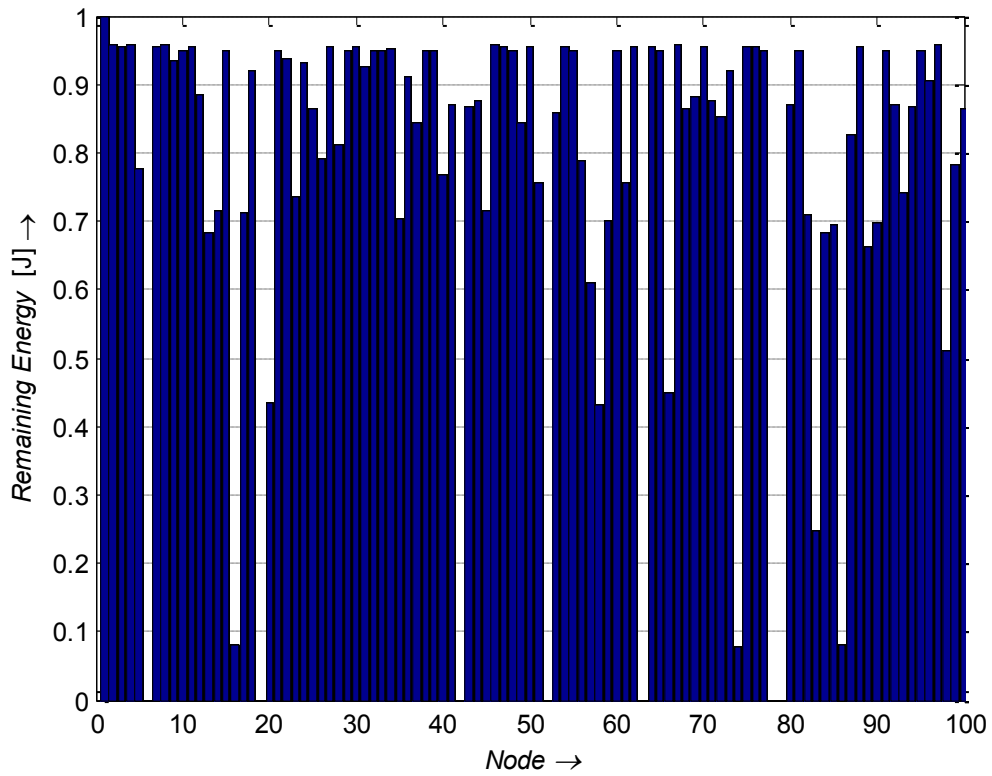


Figure 13: Game theory – Remaining energy per node after 470 transmission rounds

The shortest path simulation lasted 470 rounds, and the game theory simulation lasted 503. For a fair comparison of energy left, we compare the two simulations after the same number of transmission rounds. Figures 12 and 13 show the amount of energy each node has left after 470 transmission rounds. When all the blue bars are summed in each graph, the following is found:

- The total node energy left in the shortest path network after 470 transmission rounds is **73.393J**
- The total node energy left in the game theory network after 470 transmission rounds is **76.620J**

Table 10: Simulation 1 – Node lifetime

Shortest Path		Game Theory	
Total Dead Nodes	Transmission Rounds	Total Dead Nodes	Transmission Rounds
1	247	1	288
3	277	2	289
4	297	3	346
5	310	4	348
6	359	5	383
7	387	6	394
8	424	7	403
9	444	8	502
10	470	10	503

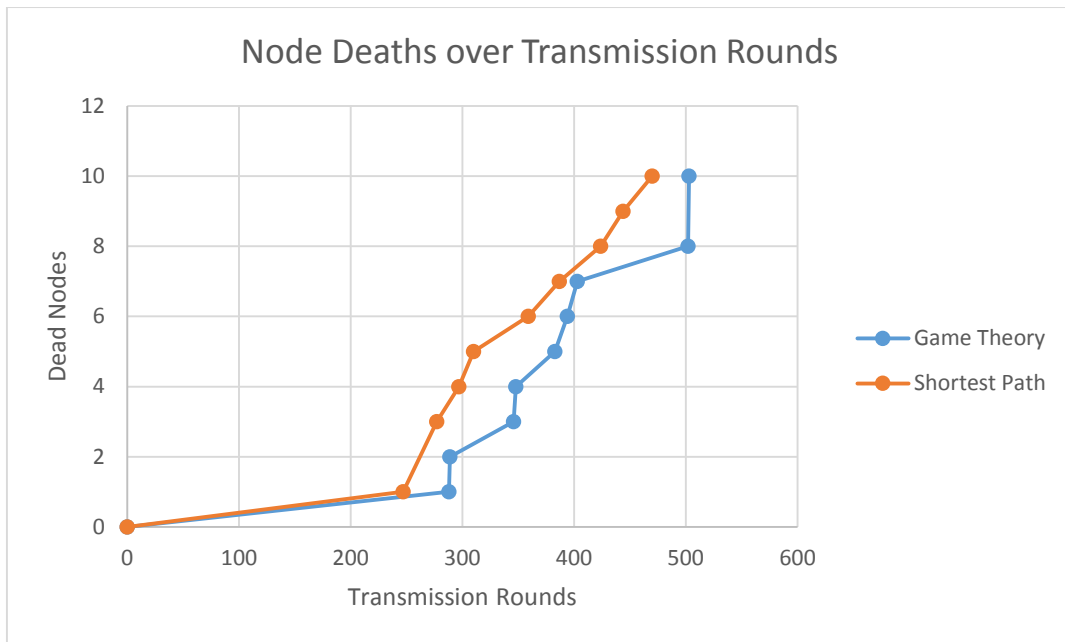


Figure 14: Simulation 1 - Node deaths over transmission rounds

Figure 14 shows that the nodes in the shortest path simulation died earlier than the nodes in the game theory simulation.

Table 11: Summary of Simulation 1 results

	Network Lifetime (Transmission Rounds)	Throughput (Packets)	Sum of Node Energy in Network (J)
Shortest Path	470	42746	73.393
Game Theory	503	42950	76.0172

5.2.4 Results for Monte Carlo Simulation

A set of Monte Carlo simulations were done in order to verify that the results yielded are consistent. The results obtained after the Monte Carlo simulations are given in Table 12 below:

Table 12: Monte Carlo results - Simulation 1

	Network Lifetime (Transmission Rounds)	Throughput (Packets)	Sum of Node Energy in Network (J)
Shortest Path	651	76680	57.272
Game Theory	744	79894	60.662

5.2.5 Discussion

Table 13: Simulation 1 – Model improvement

Increase in Network Lifetime	Increase in Throughput	Increase in Total Network Energy
14.29%	4.19%	5.92%

Even though each randomly generated WSN looks different, the Monte Carlo simulations yielded a consistent set of results showing that for this simulation, our model does produce an improvement in the network lifetime and throughput and a decrease in energy usage over the shortest path method.

5.3 Simulation 2 – Small Network with Randomly Deployed Nodes

In this section, we aim to investigate the effect of our model on small networks. This is achieved by Monte Carlo simulations which generate random WSNs wherein the nodes transmit messages until the base node becomes isolated.

5.3.1 Scope & Purpose

The purpose of this simulation is to determine if the game theoretic routing scheme is effective when applied to small WSNs. We simulate a small network with 16 randomly deployed nodes.

5.3.2 Simulation Setup

16 nodes are randomly deployed in a 20x20m area, with an optimal radio range of 7.76m as calculated with Equation 9 in Chapter 3. Each node is initially equipped with 1J of energy. A set of Monte Carlo simulations are run until the network lifetime is over.

5.3.3 Results for Monte Carlo Simulation

A set of Monte Carlo simulations were done in order to verify that the results yielded are consistent. The results obtained are given in Table 14 below:

Table 14: Monte Carlo results - Simulation 2

	Network Lifetime (Transmission Rounds)	Throughput (Packets)	Sum of Node Energy in Network (J)
Shortest Path	615	12556	10.92
Game Theory	832	13711	11.77

5.3.4 Discussion

Table 15: Simulation 2 – Model improvement

Increase in Network Lifetime	Increase in Throughput	Increase in Sum of Network Energy
35.28%	9.20%	7.78%

The results indicate that our method is effective in the case of small networks (see Table 15). The network lifetime, throughput and total network energy has shown improvement over the shortest path algorithm.

5.4 Simulation 3 – Base Node Location

According to [58], the location of the base node in a WSN has a direct influence on sensor node coverage, network lifetime and congestion, which ultimately influences the data throughput. Determining the ideal base node location is beyond the scope of our research. However, it is of our interest to determine whether our routing method remains effective, regardless of the base node location. In this simulation, the effect of the location of the base node (in all cases Node 1 serves as the base node) is investigated, as well as the influence our game theoretic routing scheme has on the network lifetime and the throughput.

5.4.1 Scope and Purpose

The purpose of this simulation is to determine to which extent the position of the base node influences the lifetime of the nodes in the network, specifically the nodes one hop away from the base node itself. These nodes serve as the final link between the base station and all the rest of the nodes in the network. The same network will be simulated twice, but in each iteration, the base node will be moved to an alternate location. The lifetimes of the one-hop nodes will be compared between the game theoretic routing scheme and the shortest path routing algorithm for both cases.

5.4.2 Simulation Setup

The network contains 100 randomly deployed nodes. The two cases are completely identical, except for the location of the base node. For the first, it will be placed in a central position and for the second it will be placed in a more solitary position. The nodes are randomly deployed and all further network parameters remain the same as during Simulation 1.

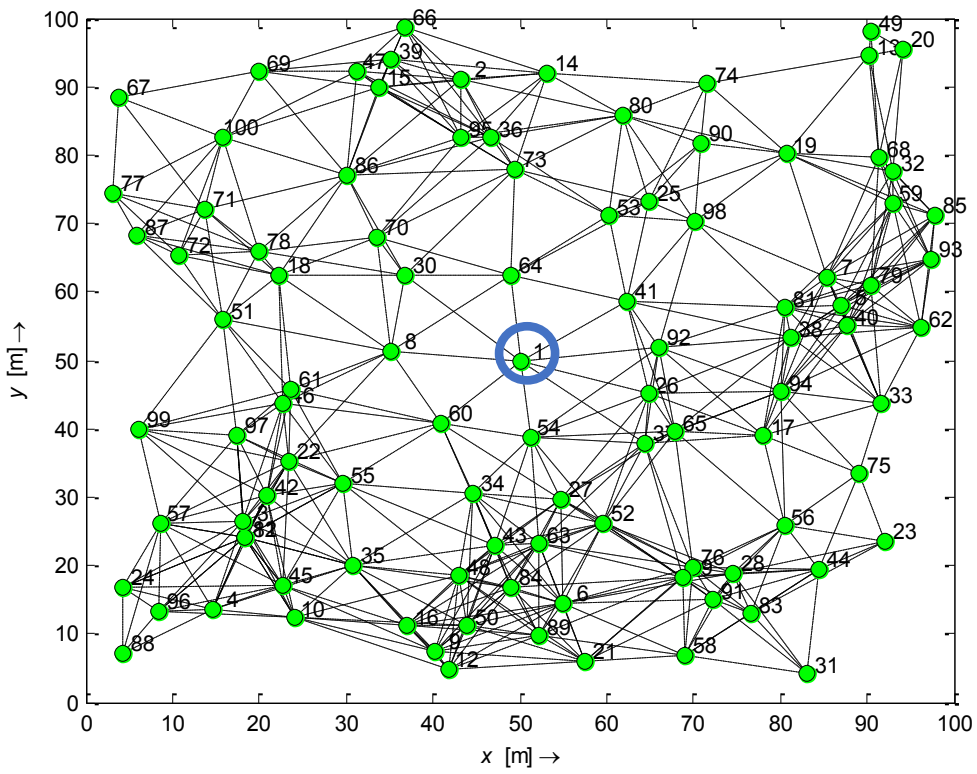


Figure 15: Case A - WSN with centrally located base node

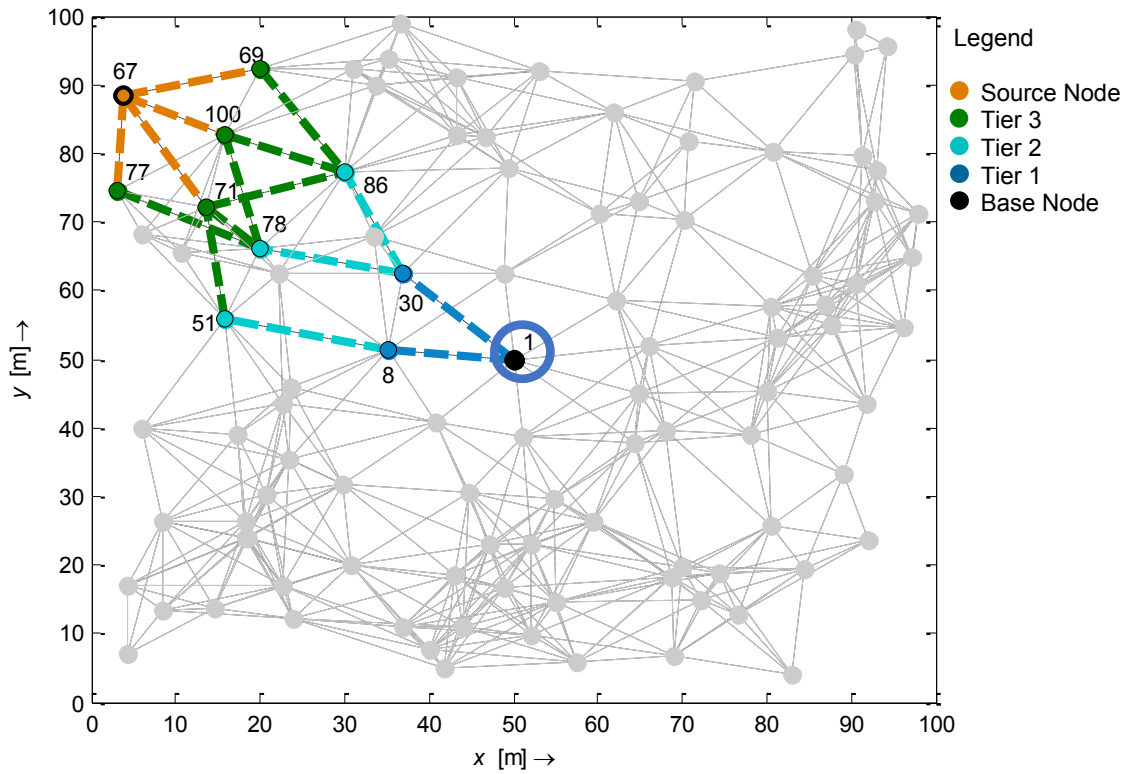


Figure 16: Case A – Least hop route options for node 67

In Figure 15, a random simulated network is given, with the base node location at the exact centre of the area (location $x = 50$; $y = 50$). This base node is ideally located, as its central position allows all outer nodes (located on the edges of the network) to be at most 5 hops away from it.

For illustration, in Figure 16, Node 67 has been selected and all the least hop routes available between Node 67 and the base node are highlighted. The relay nodes on these routes are divided into tiers, where a node three hops away from the base node falls in tier 3, and a node one hop from the base node falls in tier 1. By regarding Node 1 as the root (or terminal), and Node 67 as the parent (where the packets originate), the height of the tree is 4 (thus, the least number of hops between Node 67 and Node 1 is 4).

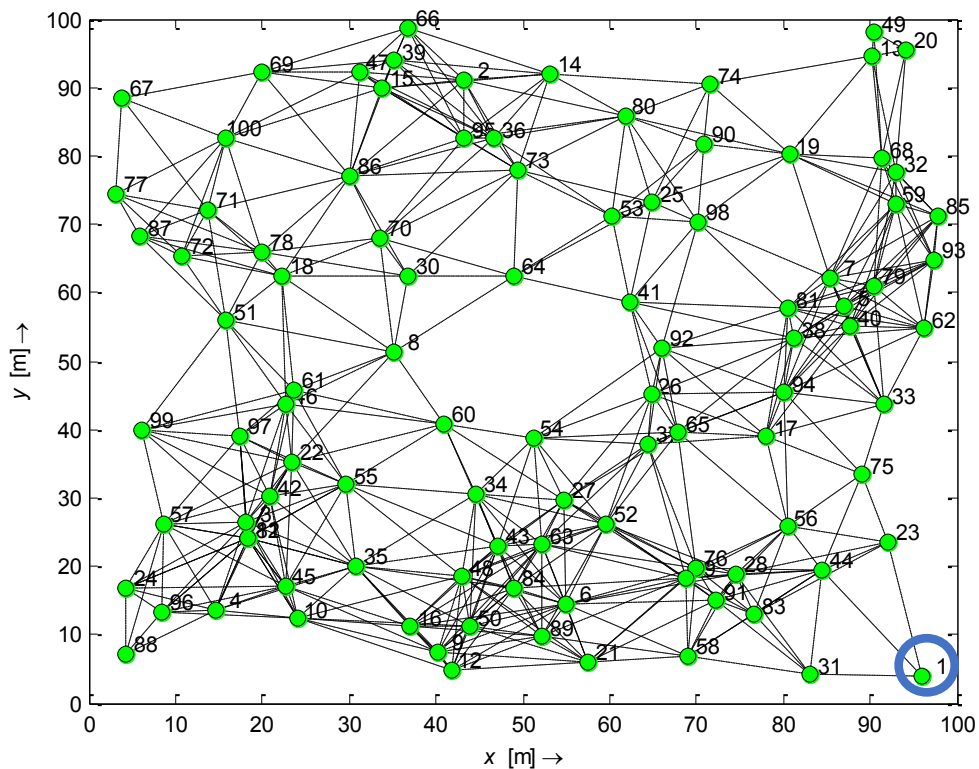


Figure 17: Case B - WSN with remotely located base node

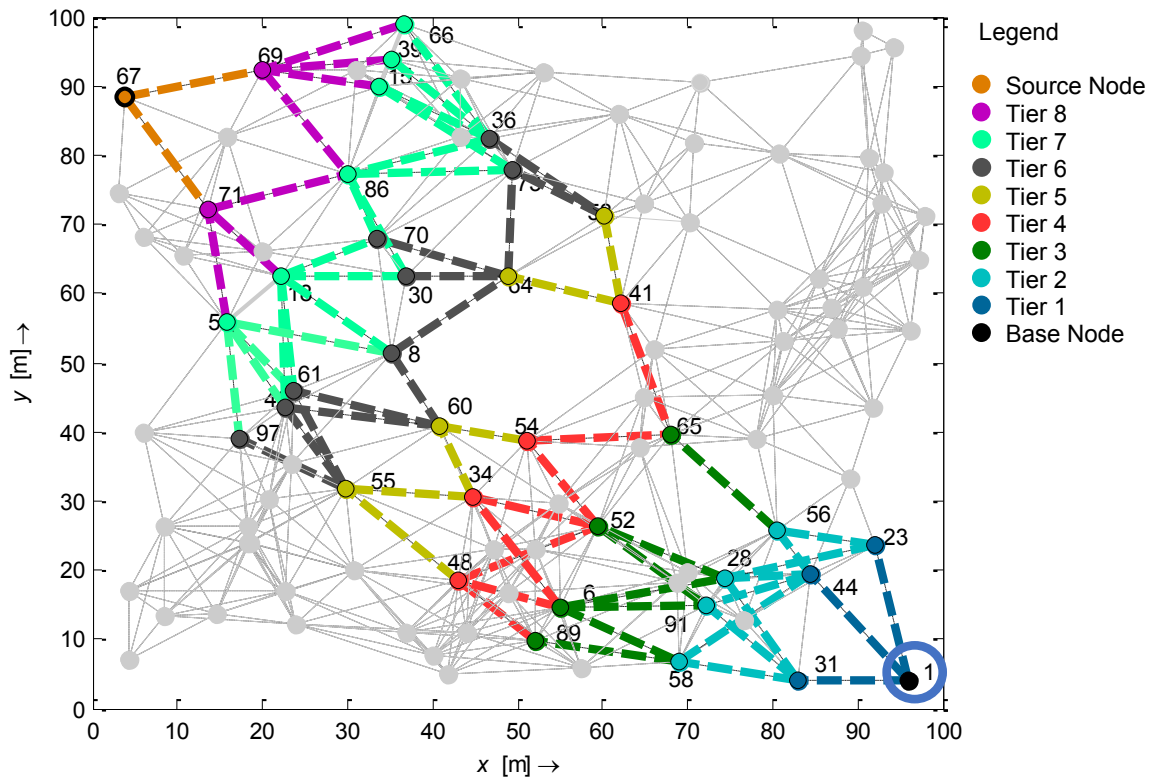


Figure 18: Case B - Least hop route options for node 67

In Figure 17, Node 1 is relocated to the edge of the network (location $x = 96$; $y = 4$). This causes the height of the tree discussed above to increase to 9. The least number of hops a packet generated by Node 67 can make to reach Node 1, is 9. If every node in the network transmits a packet to Node 1, then the sum of the least number of hops all the packets can take to reach their destination is 501 (almost double the 276 hops necessary when the base node is centrally located). Of course, this is to be expected [58], but it is interesting to note to which extent the base node location has a direct effect on the energy expended to achieve the same throughput. Below are the results for the two network scenarios discussed above.

5.4.3 Results

Table 16: Simulation 3 results

Case	Method	Rounds until First Node Death	Throughput in Lifetime (Packets)	Sum of Node Energy in Network
Case A: Node in Center	<i>Shortest Path</i>	261	42903	87.035 J after 261 rounds
	<i>Game Theory</i>	301	42950	87.051 J after 261 rounds
Case B: Node in Corner	<i>Shortest Path</i>	93	13995	90.799 J after 93 rounds
	<i>Game Theory</i>	140	14003	90.811 J after 93 rounds

5.4.4 Discussion

Note that the values of the *sum of node energy in network* in Table 16 is not taken at the end of each simulation's lifetime, but after the number of transmission rounds when the first node dies in each case. Our game theory model and the shortest path model shows a similar trend in energy usage over throughput up to a certain point, and then the two diverge and our model shows a measurable improvement over the shortest path method (for more on this, see Figure 24 in Section 6.2.4). This is why the energy values are quite similar at this stage, although the game theory method still retains a slight edge over the shortest path method.

Table 17: Simulation 3 - Model improvement

	Increase in Lifetime of First Dead Node	Increase in Throughput	Increase in Total Network Energy
Case A	15.33%	0.11%	0.018%
Case B	50.54%	0.06%	0.013%

In Case A, the base node has nine one-hop neighbours because of its centralised location. In Case B, the base node only has three one-hop neighbours. Because all of the network traffic has to move through these one-hop neighbours towards the base node, the one-hop neighbours in Case B are inundated with a much larger amount of traffic than those in Case A. This decreases their lifetime drastically, causing the base node to become isolated much quicker. This phenomenon was expected, but we can see that our model increased the lives of the base node's one hop neighbours, leading to higher throughput and better energy efficiency over the shortest path method. Since the base node (along with all the other nodes) was also randomly deployed in the Monte Carlo Simulations of Simulation 1, it stands to reason that regardless of base node location, our method consistently shows an improvement when compared to the shortest path method

5.5 Simulation 4 – Lossy Environment

In practice, packet loss is a normal occurrence in networks and happens for various reasons. We investigate the performance of our game theoretic model in networks with different packet loss rates.

5.5.1 Scope and Purpose

In this simulation, the effects of a lossy environment on the same network from Simulation 1 will be investigated by implementing our game theory routing scheme.

5.5.2 Simulation Setup

Three simulations are run: one in an environment with a 5% packet loss rate, 10% packet loss rate and a 15% packet loss rate. All further simulation parameters remain the same as those in Simulation 1.

5.5.3 Results

Table 18: Simulation 4 results

Loss Rate	Method	Average Network Lifetime (Rounds)	Average Throughput (Packets)	Average Sum of Node Energy in Network (J)
0%	Shortest Path	651	76680	57.272
	Game Theory	744	79894	60.662
5%	Shortest Path	663	72846	55.931
	Game Theory	758	75899	59.4178
10%	Shortest Path	676	69012	54.618
	Game Theory	773	71904	58.1748
15%	Shortest Path	688	65178	53.27
	Game Theory	787	67909	56.9308

5.5.4 Discussion

Table 19: Simulation 4 - Model improvement

Loss Rate	Increase in Network Lifetime	Increase in Throughput	Increase in Total Network Energy
0%	14.29%	4.19%	5.92%
5%	14.33%	4.19%	6.23%
10%	14.35%	4.19%	6.51%
15%	14.40%	4.19%	6.87%

Because of the packet loss rate, less packets are delivered to the base node than are actually intended. As the throughput of the network is decreased, node lifetime increases, as less energy is expended per round for routing when packets are lost and not routed along their complete paths. Over the entire course of the network lifetime, more energy needs to be expended to deliver the same number of packets as a network with a lower loss rate. In Table 19 we show the improvement of our model over the shortest path method in lossy networks. As expected, the lossier the network, the lower the throughput, but our model still managed to achieve a higher throughput than the shortest path method.

5.6 Simulation 5 – Isolated Nodes

Node deaths in a WSN occasionally lead to isolated nodes. The problem is that the isolated nodes are still active, but have no way of reaching the base node, because there are no routes available to relay their messages across.

5.6.1 Scope and Purpose

In this simulation, a network topology was chosen of such nature that the death of certain nodes would lead to large areas of isolated nodes, rendering them essentially useless as their path to the base node is cut off. The game theoretic routing algorithm is compared to the shortest path protocol in an attempt to discern which method would leave the largest part of the network active for the longest time.

5.6.2 Simulation Setup

The network is in a hybrid topology and is divided into three sections, with each section connected to the base node by three nodes. The network contains 100 nodes in a 100m by 100m area. Section A contains 27 nodes, Section B 23 nodes and Section C 49 nodes.

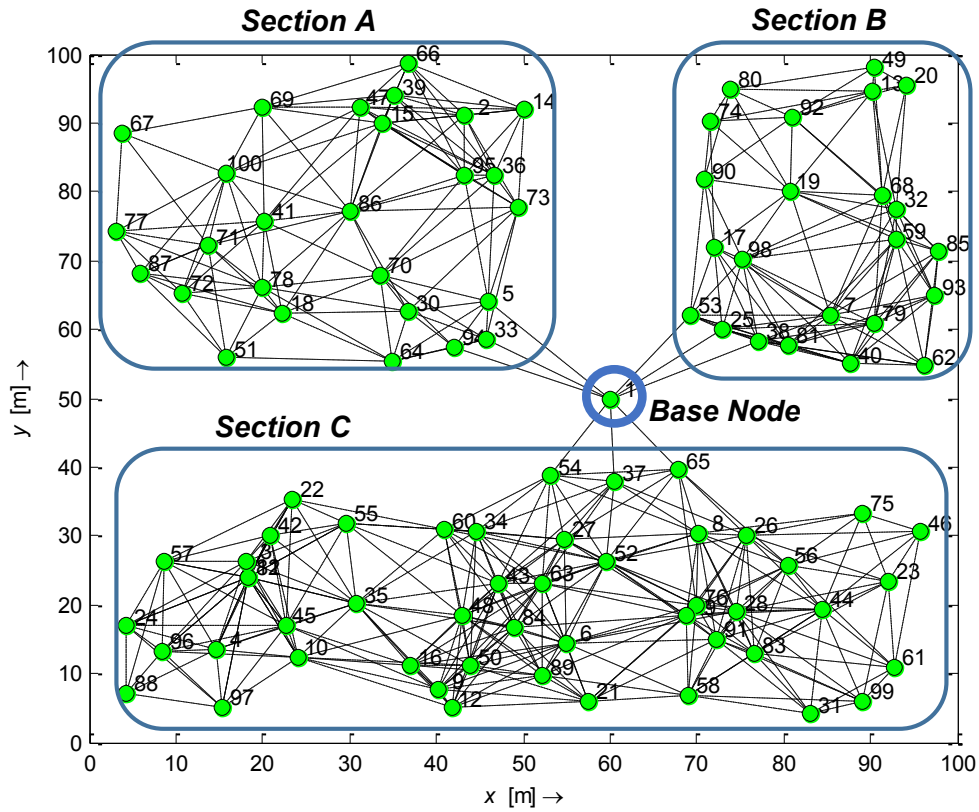


Figure 19: Network layout for Simulation 5

5.6.3 Results

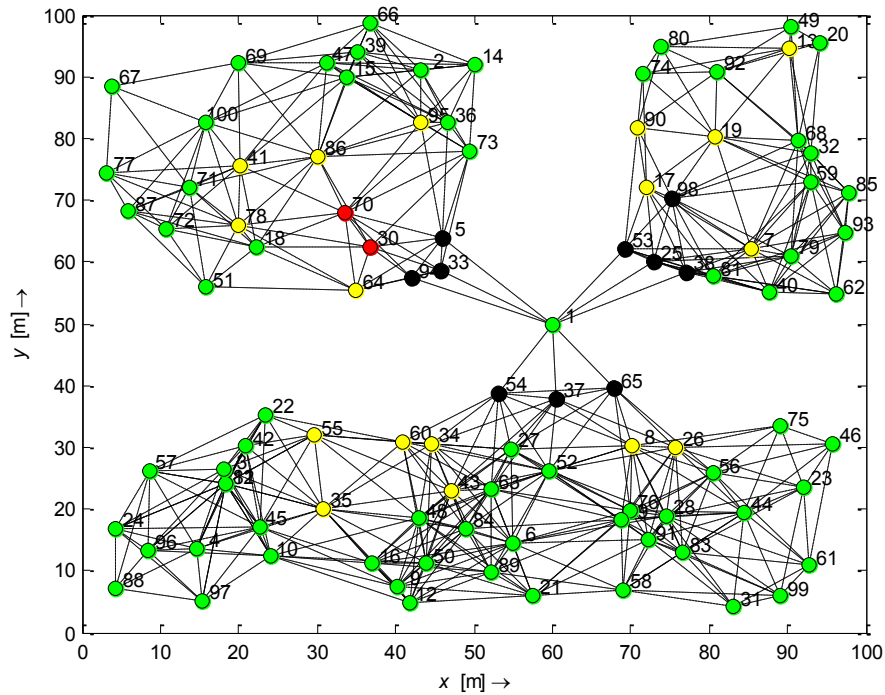


Figure 20: Shortest path - Isolated nodes

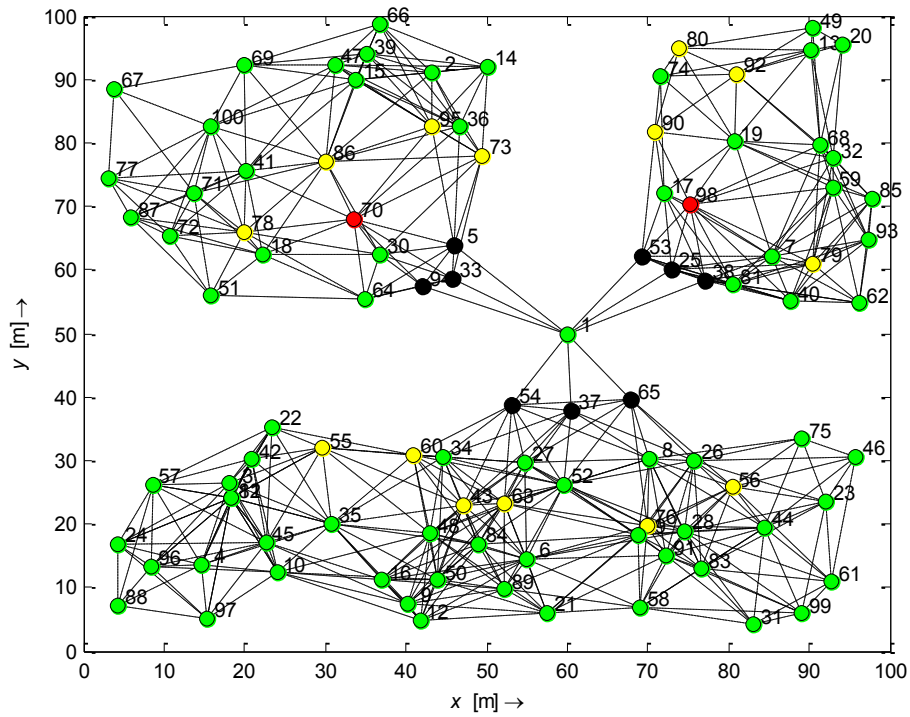


Figure 21: Game theory - Isolated nodes

Table 20: Simulation 5 results

Section	Method	First Node Death	Throughput in Lifetime (Packets)	Sum of Section Node Energy in Network (J)
A	Shortest Path	Node 5: 426 Node 33: 338 Node 94: 541	14338	19.1773
	Game Theory	Node 5: 425 Node 33: 538 Node 94: 543	14463	19.3493
B	Shortest Path	Node25: 641 Node38: 519 Node53: 365	14453	15.96354768

	Game Theory	Node 25: 647 Node 38: 642 Node 53: 434	14571	16.1099
C	Shortest Path	Node37: 290 Node54: 179 Node65: 277	14086	41.8166
	Game Theory	Node37: 295 Node54: 281 Node65: 287	14170	42.01054

5.6.4 Discussion

In Table 21 below, we show the improvement achieved by our method.

Table 21: Simulation 5 - Model improvement

Section	Increase in Lifetime of First Dead Node	Increase in Throughput	Increase in Total Network Energy
A	59.17%	0.87%	0.90%
B	18.90%	0.82%	0.92%
C	56.98%	0.6%	0.46%

Due to the star-like topology of the network, failure by the nodes leading to the base node can leave large portions of the network inoperable. In each section, the game theoretic algorithm showed a small improvement in the lifetime for most of the essential nodes that serve as bridge between the base node and the various sections.

5.7 Conclusion

In this chapter, we have tested our game theoretic algorithm in five different scenarios. Our model has proved that it offers an effective and robust solution to improving the energy efficiency of wireless sensor nodes, compared to the shortest path method.

For the validation of the results from this chapter, see Chapter 6. For a summary of the results obtained, refer to Section 7.3.

Chapter 6 – Validation

6.1 Introduction

In this chapter we will validate that we developed the correct model by comparing ours to a similar, published model. We will test our model in a scenario based on the published model simulation, and then compare both sets of results, their trends, and their network characteristics. Due to the fact that our model is original, it would not be possible to implement an existing, published simulation scenario exactly. For this reason, our model is placed in juxtaposition with the existing model, their similarities and differences are discussed and the results are compared. We will highlight several key aspects of both models to confirm our model's validity.

6.2 Validation

During the validation phase, a model is validated by comparing it to existing, validated and published models with regards to network performance and network characteristics [59].

In this section, our aim is to validate that the correct model was built. This will be done by comparing important aspects of our model to a similar, published model. Because the model we have set forth is original, we will place it in juxtaposition with a published model, discuss similar key aspects of both, and compare our results with theirs.

For the purpose of validation, a published model employing a game theoretic approach combined with their own LEACH-based protocol has been chosen [60].

6.2.1 Published Model

In the published model, a LEACH-based protocol with multi-layer clustering is compared to a network which employs the same LEACH-based protocol but with a game theoretic approach. The purpose of their comparison is to determine the effect game theory could have on a network's energy efficiency and throughput.

LEACH is considered to be one of the most popular cluster-based protocols aimed at minimizing energy consumption in a network [60]. The network is divided into groups of nodes called *clusters*, and for each cluster there is a single node called a *cluster head* to which the nodes (called *members*) in the cluster relay their data. A cluster head is responsible for propagating the data to the base node by relaying it via the other cluster heads in the network. The cluster heads are also each assigned to a level or *layer* which expresses their distance from the base node, with level 1 being the closest. Clustering improves network scalability and reduces transmission overhead [61]. A non-cooperative game theory approach was used wherein each cluster head acts selfishly to conserve its energy and increase its lifespan [60].

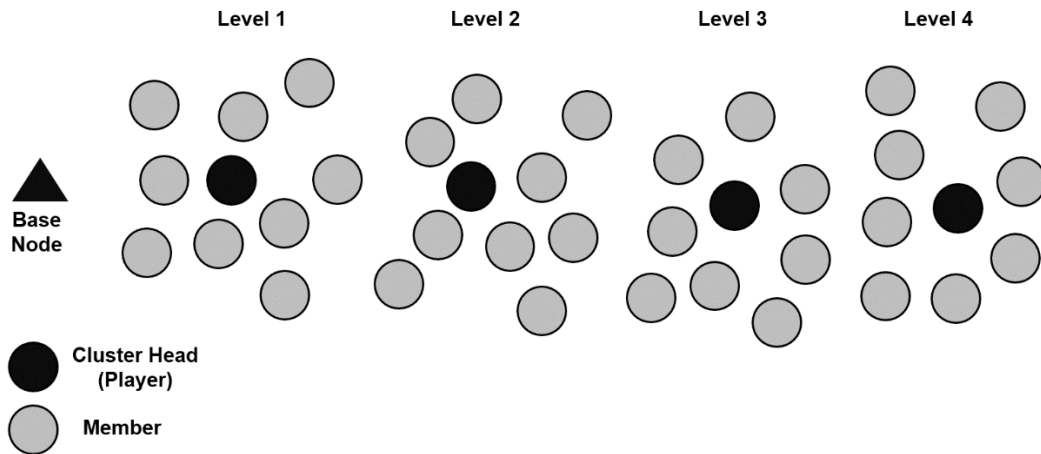


Figure 22: Published model – Multi-layer clustering

A game takes place between two cluster head nodes when a node needs to decide between relaying towards the base node for another cluster head (Forward the packet – F) or not (Drop the packet – D). The model employs an incentive method, where a node receives a reward of 1 for relaying (if the packet reaches its destination), which is translated into extra energy. The energy consumed by cluster head 1 is higher than that of cluster head 2, which is higher than cluster head 3 and so forth, as each cluster head closer to the base node has to relay both the data of the heads in higher levels, as well as its own.

6.2.2 Model Comparison

Our aim is not to duplicate and match the results obtained from the published model. Rather, we endeavour to compare aspects of our model to this similar model and make observations on the models themselves and the trends between the result sets obtained from both. In Table 22 below, we compare our model to the published model.

Table 22: Model comparison

	Published Model	Own Model
Similarities		
Network Type	WSN	WSN
Key Performance Indicators	Energy Consumption, Throughput, Network Lifetime	Energy Consumption, Throughput, Network Lifetime
Node Deployment	Random	Random
Differences		
Routing	Multi-hop forwarding via game theory-based clustering algorithm atop energy-aware LEACH-based protocol (GMLeach)	Multi-hop forwarding via game theory-based routing method
Node Energy	Cluster heads are rewarded with extra energy for cooperating	All nodes (excluding the base node) have a finite amount of energy, which is finished once depleted
Game Theory	Only Cluster Heads are players in game	All data transmitting nodes are players in game

6.2.3 Simulation Parameters

In Table 23, the parameters used in the published model to yield their results is given. For the purpose of validation, we simulated our model with the same parameters and obtained a set of results.

Table 23: Simulation parameters - Published model vs. own model

	Published Model	Own Validation Model
Number of Nodes	100	100
Energy per Node (J)	0.5	0.5
Area (m²)	200x200	200x200
Message Size (Bytes)	500	30
Radio Range (m)	Unknown	40
Node Deployment	Random	Random

6.2.4 Result Sets

Below are the results obtained from the published model [60] as well as the results obtained from our own simulation.

Table 24: Published results

	LEACH		GMLEACH	
Transmission Rounds	Throughput (Packets)	Energy Consumption (J)	Throughput (Packets)	Energy Consumption (J)
100	1000	6.1	800	6.08
200	2000	11.84	1600	11.8
300	3000	17.5	2400	17.4
400	4000	23.6	3200	22.5
500	5000	29.2	4000	28.75

Table 25: Own model results

	Shortest Path		Game Theory	
Transmission Rounds	Throughput (Packets)	Energy Consumption (J)	Throughput (Packets)	Energy Consumption (J)
100	9900	6.043	9900	6.038
200	19603	12.18	19684	12.08
300	28423	19.38	29038	18.84
400	31570	22.10	36869	26.24
500	32990	22.41	37961	26.54

Too little is known of the published model's parameters to explicitly compare its results to our model's results. The published model did not disclose the exact network layout used, and the location of nodes is known to have an effect on results [23]. The published model also uses another energy model than our own (refer to Section 3.2.2) and different packet sizes. With this in mind, we have reproduced our simulation parameters as closely as possible to compare our models qualitatively and explore their differences and similarities (as set apart in Table 22).

There can be seen that although both models employ different methods, they are similarly designed and built. Both models are developed to evaluate the effect game theory can have on energy efficiency, with a heavy focus on the key performance indicators, i.e. energy usage and throughput.



Figure 23: Published model results – Energy vs. throughput

In both Figures 23 and 24, the dots on the graphs are the values taken at each 100 simulation round interval (the first at 0 rounds, the second at 100 rounds, etc.). In Figure 23, the GMLeach method consumes more energy per packets delivered than the Leach method does. Its energy consumption is lower per number of transmission rounds, but so is its packet delivery rate.

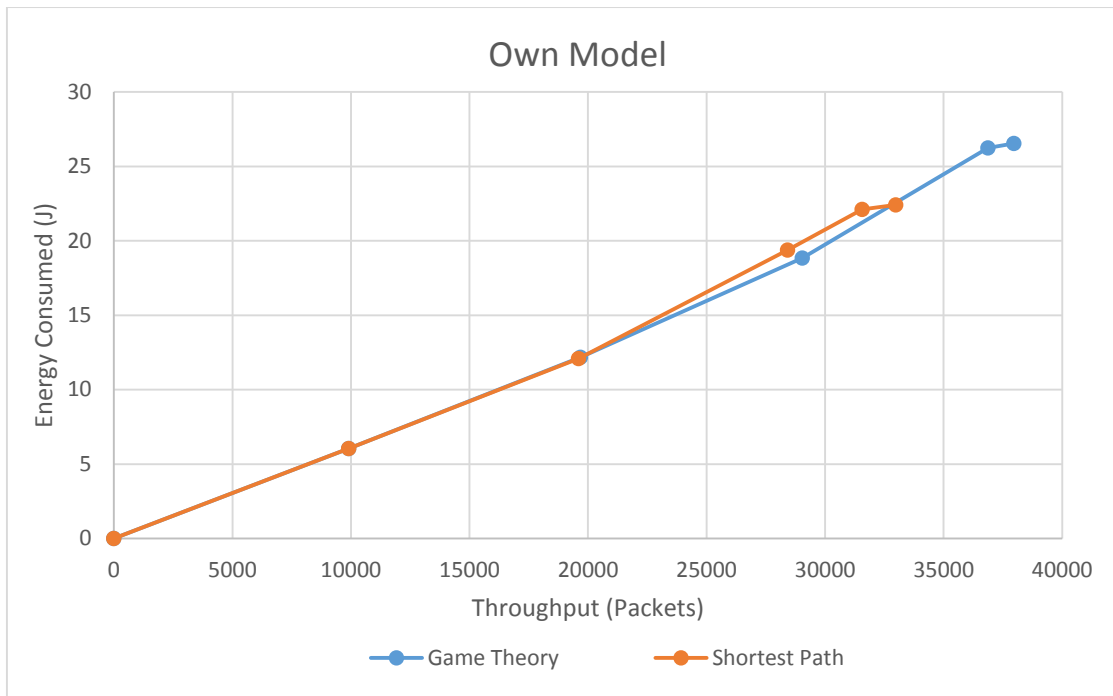


Figure 24: Own model results – Energy vs. throughput

In Figure 24, the game theory method and shortest path method manages about the same energy consumed over throughput for about 200 rounds, until nodes start dying in the shortest path simulation. This leads to a higher energy consumption needed to deliver the same number of packets than the game theory model. The shortest path method then starts to display a decline in packets delivered, leading to a decline in energy consumption, until the two graphs intersect at the point where the game theory model surpasses the energy consumption of the shortest path model, because it has more nodes that are alive and able to transmit.

6.2.5 Qualitative Model Comparison

In Table 24, the published model's GMLeach method consistently consumes less energy than the LEACH protocol, but the trade-off is a decrease in throughput. By studying Figure 23, it is evident that the GMLeach protocol is less energy efficient per packet delivered than the LEACH protocol. The reason for this is that, in order to achieve a Nash equilibrium, they introduced a selfish cluster head which regularly chooses to drop the packets of other cluster heads in order to conserve its own energy. The GMLeach network would therefore live longer, but at a cost to the throughput.

In Table 25, there can be seen that our method and the shortest path method displays almost identical throughput and energy consumption for the first 200 simulation rounds. After this, they diverge and our method displays both a higher throughput and a lower energy consumption. The reason for this is that some nodes have started dying in the shortest path simulation. This trend continues until after about 400 rounds, when shortest path method's throughput decreases fast because of base node isolation due to dead one-hop nodes. At this point, the game theory method's throughput is still linear, and more packets are delivered in the same number of rounds.

The reason our method displayed both a better throughput and lower energy consumption, is due to the fact that the same nodes are not constantly overused for routing, leading to a more balanced energy consumption over the entire network (refer to Simulation 1 in Section 5.2)

Figure 23 doesn't display the point at which nodes start dying in the published model's simulation. This is due to their using another energy model, and so their graph displays a more linear trend. There can be observed that the overall trend between our graph and theirs is similar, with the results of the published model's two scenarios diverging more rapidly than our own results and the results of the shortest path method.

It is evident that our model and methods hold up well to that followed by previously published work. Our key performance indicators are relevant and revealing, and our model setup and parameters are similar to those in the published model. Our model and simulations compare realistically to those of a previously published model.

6.2.6 Conclusion

We have compared our model to a published model. Since the published work is not described sufficiently to perform a direct quantitative comparison, we have attempted to show by means of a qualitative comparison that the results we have presented are relevant and realistic. The setup and simulation parameters for both models are similar, the key performance indicators for both models are the same and there has been observed that the curves yielded from both models have similar trends. Further, we have compared our results to a well-known routing protocol and have shown that our approach improves on an existing method. It follows that our model is validated and provides new, plausible results while building on existing knowledge.

Chapter 7 – Conclusion

7.1 Introduction

We now conclude the dissertation by reviewing the chapters and critically evaluating our research. We refer back to the original research objectives to determine if they have been reached and finally conclude with future work and recommendations.

7.2 Research Objectives

In this section we will determine if our research objectives, as stated in Section 1.5 have been met.

- **“Gain an understanding of the WSN environment, especially with regards to the energy usage of wireless sensor nodes”**
 - This goal was reached in Chapter 2 through means of a thorough literature study on the abovementioned subjects, as well as many others.

-
- **“Develop an energy efficient routing framework based on the principles of basic game theory”**
 - In Chapter 3 we developed a game theoretic routing model as applicable to WSNs

 - **“Implement this framework on a model of a WSN and obtain quantifiable results”**
 - This objective was reached in Chapter 5, where the routing model of the previous objective was implemented in a WSN simulation and yielded results. See Section 7.3 for a summary of the results.
 - **“*Improve the energy efficiency of wireless sensor nodes*”**
 - Our model results in Section 5.2 show an improvement in energy usage over the shortest path protocol.
 - **“*Increase overall network lifetime*”**
 - In Section 5.2, our model also shows an improvement in network lifetime over the shortest path protocol.
 - **“*Increase throughput*”**
 - The longer network lifetime that our model has achieved, directly leads to an increase in the throughput, compared to the shortest path protocol.

 - **“Compare our results to a basic routing scheme to ascertain any improvement”**
 - In Chapter 4, every simulation yielded two sets of results – one where the WSN employed our game theoretic routing scheme, and one where the *shortest* path routing protocol was used. These results were juxtaposed to prove that the game theoretic model did in fact, offer an improvement over the shortest path protocol.

 - **“Verify our model by proving it is mathematically accurate”**
 - Section 4.2 in Chapter 4 offers a comparison between a subset of our simulated results and results obtained through calculations done by hand to show that our model is mathematically accurate and realistic.

- **“Validate our model with an existing model”**
 - In Section 6.2 our model is also validated through comparison with an existing, published model.

7.3 Results

In Chapter 5, our model repeatedly proved that it could significantly improve the energy efficiency of nodes in a WSN under different circumstances and scenarios. The best results were obtained in smaller networks, but larger networks also showed significant improvement. Below is a summary of the results obtained:

Table 26: Summary of results

Simulation	Increase in Network Lifetime (%)	Increase in Lifetime of First Dead Node (%)	Increase in Throughput (Packets)	Increase in Total Network Energy (%)
1 – Network with Randomly Placed Nodes	14.29%	-	4.19%	5.92%
2 – Small Network	35.28%	-	9.20%	7.78%
3 – Base Node Location (Case B)	-	50.54%	0.06%	0.013%
4 – Lossy Environment (15% Loss Rate)	14.40%	-	4.19%	6.87%
5 – Isolated Nodes (Section C)	-	56.98%	0.6%	0.46%

7.4 Conclusions

In Chapter 1, we discussed a research problem and set research goals, which, as we have shown, have all been reached throughout the course of this research project. Our aim was to improve the energy efficiency of wireless sensor nodes by applying basic game theoretic principles to the way they packets are routed. Our results from Chapter 5 have proven that these goals have been satisfied by showing an improvement in the energy efficiency, overall network lifetime and throughput when compared to the shortest path routing protocol.

A peer-reviewed conference article was published and presented through the course of this research and is available in Appendix B.

7.5 Future Work

There are areas where our research can be elaborated upon in future.

- The effects of a wide range of network conditions and errors can be investigated further.
- The application of our model on a wider range of network types, topologies and scenarios.
- A more in-depth study on the influence of the tuning of the PRI parameters can be determined.
- More research can be done on how our model performs against a wider range of energy aware routing schemes and protocols (e.g. EAR [33] and LEACH [34]).
- The practical application of our model in real-life WSNs.

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Appendix A – Simulation Setup

We found some of the existing simulation packages too constraining for the purposes of our research, and opted to create our own simulation package from the ground up using MATLAB. Refer to the Verification section in Chapter 4 where we confirm the accuracy of our model and simulation software.

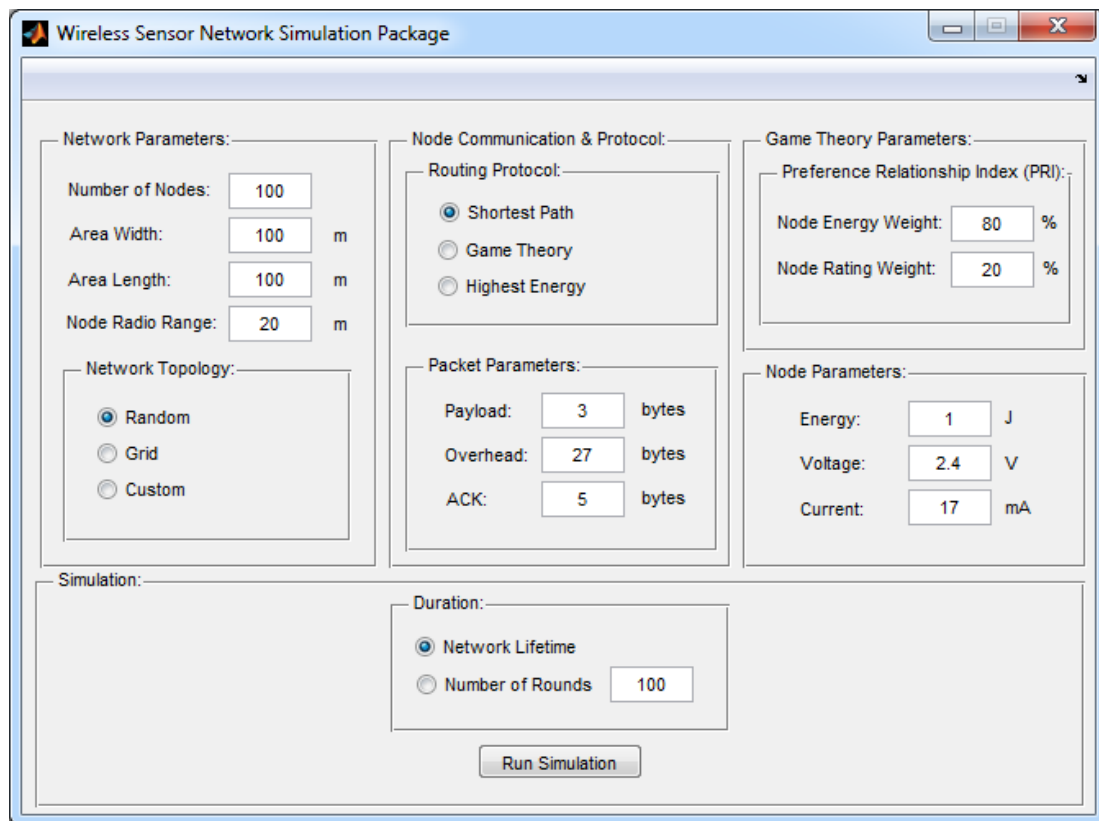


Figure 25: Screenshot of WSN simulation package GUI

Before the simulation can be run, the user needs to input certain parameters into the simulation software (see *Figure 25*). These parameters include the number of nodes, the dimensions of the area, the radio range of the nodes (as calculated in Section 3.2.3), the type of node deployment (if custom, the user can define the location of each node), packet parameters and the initial energy characteristics for each node. The weights of the node energy and node rating can be adjusted for the preference relationship index, the type of routing protocol can be chosen, and finally the duration of the simulation needs to be defined before the simulation can be run.

Once the relevant inputs have been entered into the GUI and the *Run Simulation* button is selected, the following occurs:

- 1) From the inputs the total package sizes are calculated.
- 2) The total energy needed to send and receive a package, as well as an acknowledge message (ACK) is calculated based on the package parameters.
- 3) Depending on the option selected at *Network Topology*, a network matrix of node positions is generated.
- 4) A calculation is done on this array using the *Node Radio Range* to determine the one hop neighbours for each node, as well as the tier of each node
- 5) One simulation round of transmission is completed at a time. During each round the following happens:
 - a. Each node generates its own packet to send to the base node via a certain path, depending on the routing method chosen.
 - b. Nodes also choose to relay or drop packets for one another by using the PRI which is stored in an array and updated
 - c. The total of packets sent and received by each node is updated in an array, and according to this the amount of energy expended per node is calculated and subtracted from the total node energy
 - d. If the transmission energy of a node is depleted, it is immediately marked as 'dead' and removed as a feasible routing option
 - e. At the death of each node, the network matrix, one hop neighbours and tier of each node is updated to reflect this change
- 6) A finite number of simulation rounds are run, depending on the end conditions. In the case of running the simulation for the entire network lifetime, the simulation ends when there are no one-hop nodes from the base node

The nodes are modelled as Zigbee devices [54], so the calculations of the energy calculation in Section 3.2.2.2 are completed in a software module and done with the inputs received from the GUI.

Once the simulation has been completed, there are various results and data sets as output.

	63	64	65	66	67	68
Node	63	64	65	66	67	68
Voltage	2.4000	2.4000	2.4000	2.4000	2.4000	2.4000
Current	0.0170	0.0170	0.0170	0.0170	0.0170	0.0170
Energy	0.7678	0	0.7399	0.6673	0.9561	0.9562
Messages Received	859	4392	986	1317	0	0
Own Messages Sent	399	339	400	400	400	399
All Messages Sent	1258	4731	1386	1717	400	399
Messages Processed	2117	9123	2372	3034	400	399
Energy Expended Receiving	0.0942	0.4817	0.1081	0.1444	0	0
Energy Expended Transmitting	0.1380	0.5189	0.1520	0.1883	0.0439	0.0438
Rounds Alive	0	339	0	0	0	0
Live Status	1	0	1	1	1	1
Tier	6	-1	3	2	4	7
	74.4262	0.0592	60.1890	62.2808	76.4005	76.4002

Figure 26: Node data output by our simulation software

In Figure 26, an output from the simulation can be seen where information on each individual node is given. This information includes the amount of energy each node has left, the number of messages each node sent, received and processed, the energy expended, the current tier of the node (-1 if the node is dead), the number of rounds the node lasted (a zero indicates it is still active) and the status of the node indicating if it is dead or alive (a one being alive and a zero dead).

In addition to this, the total energy used in the entire system is given, as well as the total number of messages received by the base node.

Various graphs and charts are also part of the output for a visual interpretation of the results:

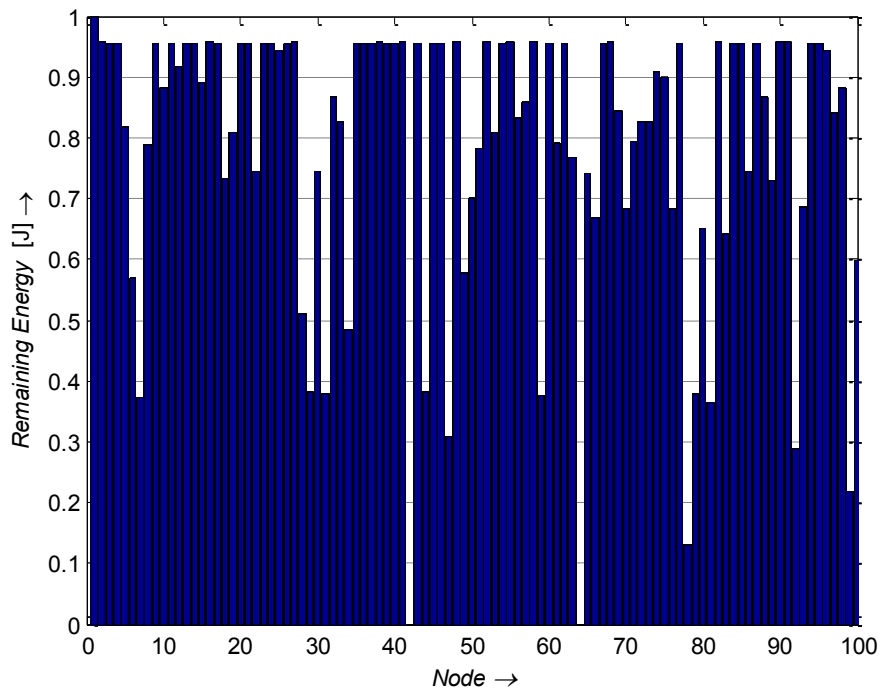


Figure 27: Remaining node energy

Figure 27 graphically displays the amount of energy remaining in each node after the simulation has been complete.

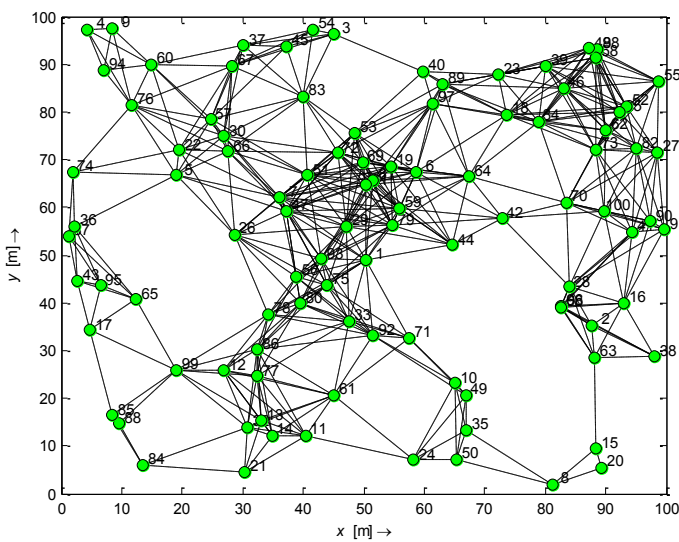


Figure 29: Randomly deployed node network before simulation

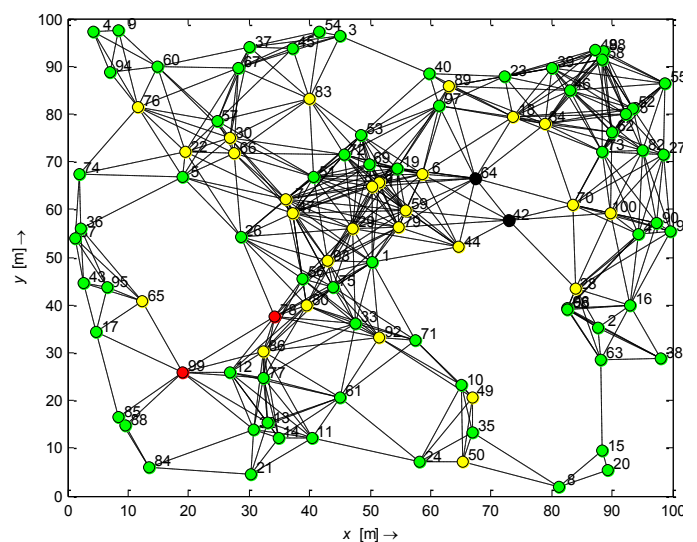


Figure 28: Randomly deployed node network after simulation

In Figures 28 and 29 the network layout, node placement, and energy status of each node can be seen before and after the simulation has completed.

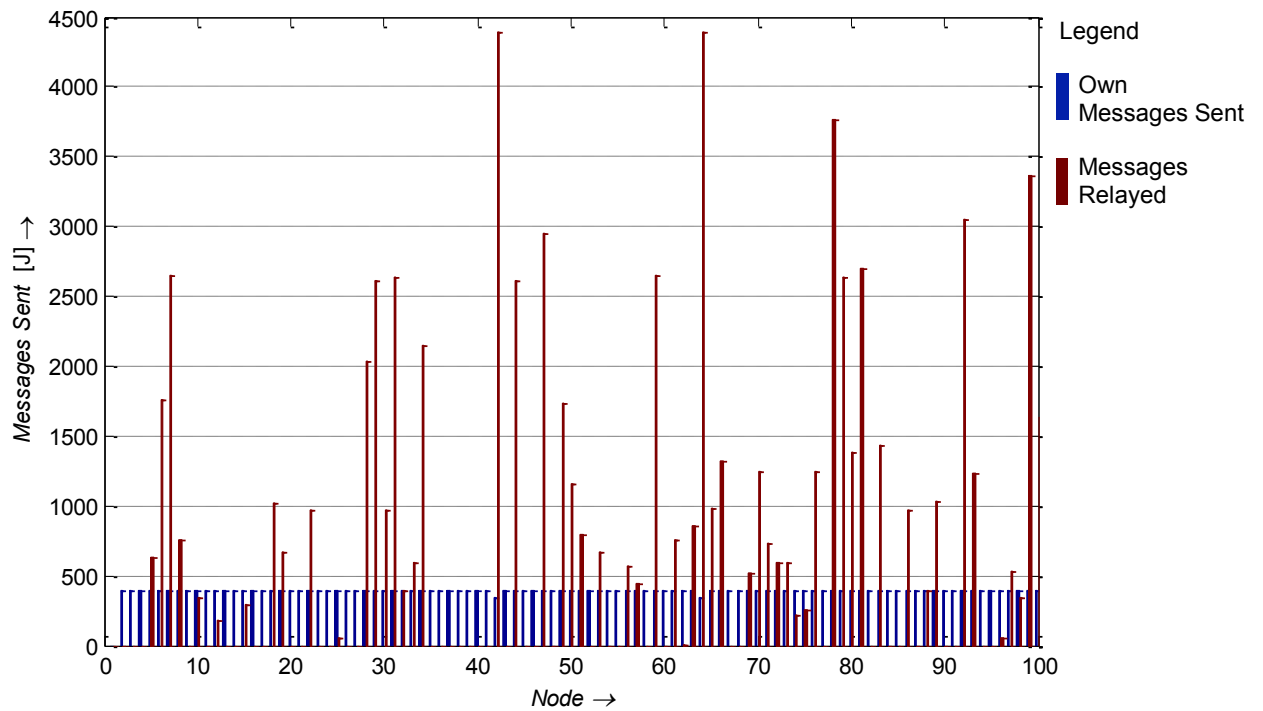


Figure 30: Messages sent vs. messages relayed per node

Other visual tools help us interpret the data, such as the graph in Figure 30, where the number of own messages each node sends is compared to the number of messages relayed by each node for other nodes. This makes it possible to easily see which nodes have to handle the most traffic in the network.

Appendix B – Conference Contributions from this Dissertation

An Application of Game Theory for Energy Saving in a Model of a Real World WSN

Presented at:

Southern African Telecommunication Networks and Applications Conference (SATNAC)

September 2013

Spier Wine Estate, Stellenbosch, South Africa

An Application of Game Theory for Energy Saving in a Model of a Real World WSN

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Abstract- Due to the nature of a wireless sensor network, one of its biggest constraints is limited node energy. As wireless sensor networks are growing in popularity, an increasing number of studies are being dedicated to developing protocols and algorithms to curb the energy expenditure of wireless sensor nodes. In this paper, the aim is to investigate if game theory is a feasible solution for improving the energy efficiency and reliability of a wireless sensor network. The aim is also to improve the lifetime of a network and contribute to more even energy distribution, to prevent nodes from becoming flooded with traffic whilst others remain less affected. Game theory operates on the premise that all entities that are capable of making rational decisions are inherently selfish by nature, and will exercise all of their decisions in such a manner that they receive the best possible payoff available. This can also be said of nodes in a wireless sensor network, and by exploiting this inherently selfish nature, this paper aims to show that by coercing the nodes through a game theoretical model, they can make energy- and network efficient decisions.

Index Terms— wireless sensor networks, game theory, selfish nodes, energy efficiency

I. INTRODUCTION

Wireless sensor network (WSN) technology is increasingly becoming more popular, with a legion of applications that include military, security and smart home technologies [1]. Due to the wireless nature of the devices (henceforth referred to as nodes in this paper), an extended battery life and optimum energy efficiency is part of the core concerns when designing and deploying a wireless sensor network [2][3]. The problem that arises with ineffective energy expenditure is not only that energy is wasted, but also the fact that it can lead to downtime and an unreliable network, and intermediate dead nodes can leave other still-active nodes stranded, preventing their data from being relayed to the destination node.

Various protocols and methods have been developed to address this problem, such as energy-aware forwarding schemes [4] and physical layer-driven protocols [5], but some still display drawbacks such as unreliable data delivery, higher latency and ineffective scalability [6]. While the approach of employing game theory doesn't necessarily claim to address all of the above mentioned problems, it could serve as a more elegant, simple solution for improving the energy efficiency of wireless sensor

networks and the network lifetime.

Game theory alters the way the nodes perceive each other by providing a set of rules according to which the nodes can base their relaying decisions, dependent on the specific payoffs available for the nodes in question. It is assumed that nodes are essentially selfish entities, meaning that each node will only exercise its decisions in such a manner as to gain the maximum benefit possible. This can be exploited by playing the nodes off against each other, and in doing so, force them to make their decisions in such a manner that benefits both themselves and the entire network.

Similar research has been done where game theory was employed to improve network efficiency, node cooperation [7] [8] and energy efficiency [9], but the novelty of this research is that it actively implements a mathematical game theoretic model in a simulation based on a real-life application of a wireless sensor network. Game theory allows for better, prompt interpretation of the current status of a network's energy distribution and for this reason leads to more efficient decisions being made.

In Section II, a concise background is provided on game theory, wireless sensor networks, energy efficiency and the applicability of implementing game theory in a WSN. This is followed by Section III which elaborates on the system model designed for the simulation, how game theory is implemented in this model, the process of communication between the nodes, the calculation of packet sizes and how energy expenditure is determined. The simulation is explained in Section IV and the results obtained are interpreted in Section V.

II. BACKGROUND

A. Wireless Sensor Networks

A wireless sensor network is a network which consists of wireless devices, or wireless sensor nodes, distributed in a certain environment. These nodes can be used to monitor their surroundings and record useful information which can be passed along to a base station or base node. In many cases, the nodes are autonomous, so each node essentially governs its own operation independently. However, these nodes work cooperatively to propagate their data through the network via multiple hops towards the base node [1].

B. Energy Efficiency

From [1] it is evident that the limited energy budget of wireless sensor nodes are a big constraint on WSNs. Sensor nodes are usually battery-powered, which have to be

replaced or recharged once depleted [1]. For some nodes this is not possible and the nodes are then discarded when their energy is fully depleted. In all cases, a depleted battery leads to a dead node, which is inefficient, can disrupt network communication and even cause network downtime.

C. WSN Model

For the purpose of the wireless sensor network simulation, an existing wireless sensor network has been chosen to base the simulated network model's architecture upon. The Torre Aquila is a medieval tower located in Trento, Italy, which is both a heritage building and houses a series of internationally renowned murals [15]. Due to the age of the building, a team of researchers have deemed it necessary to deploy a wireless sensor network in the tower to continuously monitor the structural integrity and stability of the tower.

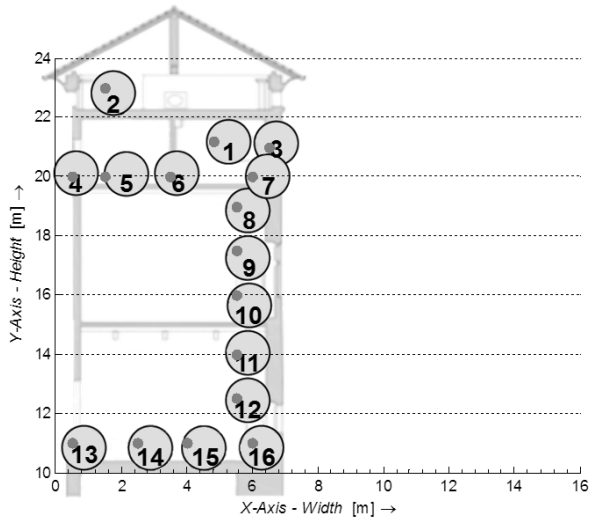


Figure 1: Node Deployment in the Torre Aquila-Based Simulation

The Torre Aquila is outfitted with 16 nodes, distributed throughout three floors. Nodes 2-16 are all sensor nodes, which monitor the building and regularly forward their collected data to the base node, node 1. In the real world application, the nodes are naturally deployed in three dimensions, but for the sake of simplicity, the simulation has been done in two dimensions. In *figure 1*, the deployment of nodes in a simulation of the Torre Aquila wireless sensor network can be seen.

D. Game Theory

Game theory is a study of the mathematical models derived from the conflict and cooperation that arises between entities capable of making rational, intelligent decisions [11] [12]. In the context of game theory, these entities are referred to as *players* and game theory operates under the assumption that these players are inherently selfish and will make all their decisions in such a manner that they will benefit the most themselves, even if it means adversely affecting other players [10].

It is proposed that this inherent selfish trait can be exploited so that nodes in a wireless sensor network can apply their decisions regarding relaying data for one another in such a manner that the lifetime of the wireless sensor network can be increased, leading to a more reliable network and increased energy efficiency.

1) Critical Components of a Game

In accordance with the requirements for a player [11] [12], wireless sensor nodes are entities capable of rational, selfish decisions [9], and the wireless sensor network environment is a competitive playing field for these nodes where each decision made by a node can affect the other nodes in the network as well.

The following three components are always necessary and form the basis of a game [13]:

- A set of two or more nodes as players: $N = \{1, 2, \dots, i, j, \dots, n\}$
- An action set of possible actions available for every node: where A_i is the set of possible actions for node i (and $1 \leq i \leq n$) and A is the action space formed from $A = A_1 \times A_2 \times \dots \times A_n$. Furthermore, a_i denotes a particular action chosen by node i , where $a_i \in A_i$
- A set of preference relationships for each node which expresses a node's desirability of one outcome over another for every possible action $\{u_i\} = \{u_1, \dots, u_n\}$

With the abovementioned mathematical model, a game can be created with the nodes as the *players*, and the possible choices the nodes have available as *actions*, and a framework can be deduced on which the nodes can base their decisions [13] when taking their one-hop neighbours into account to make the most energy efficient decisions for the benefit of the entire network.

III. SYSTEM MODEL

A. Node Communication

For the purpose of simulation, nodes are modeled as Zigbee devices.

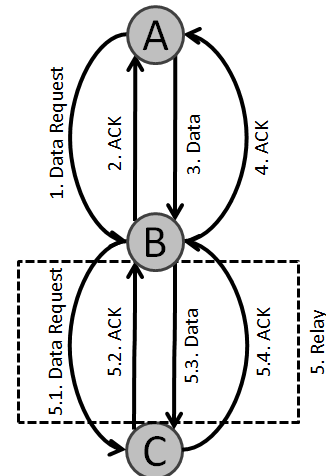


Figure 2: Data Communication in WSN

Consider *figure 2*, where *node A* attempts to communicate with *node C* but because it is too far to communicate directly, it needs *node B* to relay the message for it. Communication between the nodes occurs as follows:

1. Node A sends a *data request* to node B.
2. Node B decides if it will relay the message for node A by applying the principles of *game theory*. If node B concedes, it sends an acknowledge message back

- to node A, signaling that the data can be sent.
3. Node A transmits the data.
 4. Once node B receives the data, it sends another acknowledge message to node A that it has successfully received all data
 5. The entire handshaking process described in steps 1 to 4 is then repeated between node B and node C. If node C returns a positive acknowledgement, node B can relay the message to its final intended destination, node C.

The example above illustrates the case where the source node (A) is two hops away from the destination node (C). In actual wireless sensor networks, source nodes can be multiple hops away from their destination nodes. For the entire journey of a message from source to destination, the abovementioned handshaking process occurs between every pair of nodes between which the message is exchanged.

B. Packets & Routing

Consider *figure 3*. It is evident that node 9 is at best two hops away from the base node, node 1. Nodes 3, 6, 7 and 8 are all transit nodes for node 9 to relay messages across as they are all only one hop away from the destination node, node 1. The stage is now set where all of the nodes are set to be players in a round of basic game theory.

Nodes can choose to either relay messages for each other, or refuse to, depending on the possible payoff available for the node in question. The catch is, initially all of the nodes receive an identical rating of 0. This rating tells other nodes how reliable the node is with regards to relaying data, basically serving as a measure of the trustworthiness of a node. The more a node relays data for other nodes, the higher its rating will be, even though it will expend more energy to relay. The less a node chooses to relay for other nodes, the lower its rating will be. If a node already has a low rating, other nodes may choose to refuse relaying for that node, at less of a penalty to themselves because the credibility of the node in question is so low (see *table 2*). Conversely, the higher the node rating is, the higher the penalty if refusing to help that node, but if a node has a low rating, it has less credibility and other nodes are not penalized as much for refusing to relay. A node also loses less rating points if its energy is already low and it refuses to relay for others in order to conserve its own energy. It is important that a compromise is struck in the trade-off between maintaining a good rating and preserving energy.

Node 9 has a decision to make regarding which of the one-hop neighbour nodes would be the best option to relay its message to destination node 1. It is assumed that each node knows the energy levels, ratings and distances of all its one-hop neighbours.

Table 1: Node Relay Game Theory Table for Node 9

Node	Energy	Distance	Rating
9	E_9	-	R_9
3	E_3	D_3	R_3
6	E_6	D_6	R_6
7	E_7	D_7	R_7
8	E_8	D_8	R_8

By considering these factors through a game theoretic viewpoint, node 9 makes a decision regarding which node to

approach for relaying its data to destination node 1.

By considering the set of nodes in the game, $N = \{3, 6, 7, 8, 9\}$ and the action set available for node 9, $A_9 = \{RR, DNRR\}$ where *RR* denotes the *Request Relay* [9] and *DNRR* denotes the *Do Not Request Relay* actions available for node 9.

Node 9 now takes into account the energy levels of nodes 3, 6, 7 and 8, as well as their ratings and distances. Energy level has the highest credence above the other factors and bears the most weight in node 9's decision; the rating second most weight and distance almost none, only being the deciding factor if the energy and rating are the same for two or more nodes. So, node 9 creates a *preference relationship index* in which it calculates an aggregate for each potential relay node, consisting of 80% energy and 20% rating of the node in question.

$$\left(\frac{E_{node}}{E_{max}}\right)(80) + \left(\frac{Rating_{node}}{Rating_{max}}\right)(20) = 40\% \quad (1)$$

A node with 50% of its energy left (where 1 J is the maximum) and a rating of 0 (where 0 is neutral, -100 is the minimum and 100 is the maximum) will have an aggregate of 40%.

Node 9 selects the node with the highest aggregate in the preference relationship index as the first node to request relaying from. For argument's sake, assume that node 9 has chosen node 8 as the best relay node and sends a *data request* to node 8. Node 8 then creates its own game by taking its own energy into account, as well as the energy and rating of node 9 and decides whether to relay or not. *Table 2* below shows the penalty a node receives if it refuses to relay for another node with a rating between certain boundary values, as well as the reward it will receive if it does choose to relay. If the relay node's energy is below 25%, it can refuse relaying at a fixed penalty of 1, regardless of the rating of the sender node. For an energy level above 25%, the *Rating Table* (*table 2*) is used.

Table 2: Rating Penalties vs. Rewards

Sender Node Rating	Relay Node Penalty	Relay Node Reward
$-100 \leq R \leq -50$	1	3
$-50 < R < 50$	2	2
$50 \leq R \leq 100$	3	1

Consider the set of nodes in the game case of node 8, $N = \{8, 9\}$ and the action set available for node 8 $A_8 = \{R, DNR\}$ where *R* denotes the *Relay* and *DNR* denotes the *Do Not Relay* [9] actions available. A utility function of the preference relationships is then created for node 8 [13]:

$$u_8 = \begin{cases} a_8 = R \rightarrow \text{Expend } X \text{ Energy, Rating Increase } Y \\ a_8 = DNR \rightarrow \text{Save } X \text{ Energy, Rating Decrease } Y \end{cases} \quad (1)$$

If node 8 has an energy level above 25%, it will want to relay for node 9, as it still has a relatively healthy energy level and does not want to be penalized by not relaying. If node 8 has an energy level lower than 25% and a rating greater than -50, it will not relay for node 9. However, if its rating has dropped below -50, and node 9 has a rating above -50, node 8 will relay for node 9 to increase its rating, despite its own low energy.

If node 8 relays, it sends an *acknowledgement* message to node 9 and the complete process in *figure 2* takes place. Alternatively, if node 8 refuses to relay, node 9 then

approaches the second best node in its preference relationship index for data relaying.

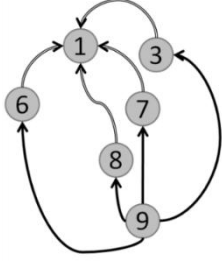


Figure 3: Possible Relaying Options for Node 9

C. Energy Model

In order to determine the energy expended by a node, the size of the messages it transmits is needed. According to the IEEE 802.15.4 [14] standard and the protocol for Zigbee devices, the size of a message can be calculated with equation 2:

$$\begin{aligned} \text{Data} &= \text{Payload} + \text{Overhead} & (2) \\ \text{Data} &= \text{Payload} + (\text{APS} + \text{NWK} + \text{MAC} + \text{PHY}) \end{aligned}$$

Where the *payload* is the size of the actual message and *overhead* consists of the headers of the APS, NWK, MAC and PHY layers, where their sizes are defined by the IEEE 805.15.4 and Zigbee protocols [15]. The time it takes for a message to be processed is the time the device spends in $R_x T_x$ mode and is calculated with equation 3 [15]:

$$R_x T_x = \frac{(k)(8)}{(b)} \quad (3)$$

where k is the size of the message in bytes and b is the bitrate of the radio chip in kbps [15].

The energy consumption model for the simulation is based on the IEEE 802.15.4 [14] standard. The energy expended by a node is calculated by determining the time it spends in active mode. The total time can be calculated with equation 4:

$$\begin{aligned} t_{total} &= (CCA) + (T_x \text{datarequest}) + \\ &(R_x T_x \text{receiver}) + (R_x ACK) + (R_x T_x \text{sender}) + \\ &(T_x \text{data}) + (R_x T_x \text{receiver}) + (R_x ACK) \end{aligned} \quad (4)$$

where $T_x \text{datarequest}$ is the time a node takes to transmit the data request message, $R_x T_x \text{receiver}$ and $R_x T_x \text{sender}$ the time the device takes to transit between R_x and T_x mode, $R_x ACK$ is the time it takes to transmit the acknowledge message and $T_x \text{data}$ is the time it takes for the message to be transmitted.

The energy dissipated by the sender node can then be calculated as follows [15]:

$$E_{sender} = (2.4V)(17mA)(t_{total}) \quad (5)$$

IV. SIMULATION

A simulation of the proposed wireless sensor network was created in the numerical computing environment, MATLAB. Refer to figure 1 for a layout of the node distribution in the MATLAB environment. For the purpose of simulation, rounds of data transmission take place, where it is assumed that each node sends a message to the base node per round. Each node selects the best one-hop neighbour to relay its data through, all the way to node 1, where all the data is collected. Most of the nodes do not only transmit their own messages, but also relay messages for their neighbours. The default routing protocol is the Shortest Path method, where messages are relayed along the least

hop path to the base node. The results of this will be placed in juxtaposition with the results of the same network where game theory is applied

A. Simulation Parameters

The nodes in the simulation are distributed identically to the node deployment in the Torre Aquila building [10]. The nodes each have a maximum radio distance of $R = 3.7m$, meaning that any nodes further apart than this are too far away for direct transmission and are not one-hop neighbours. For the simulation, the nodes were divided into tiers, depending on the number of hops they are away from the source node. A tier 1 node would then be one hop away from the base node, a tier 3 node three hops away and so on.

For every round of transmission, all of the nodes send their own data and relay data for others towards the base node, expending their energy while doing so. All of the nodes are assumed to be battery operated, except for the base node, which is connected to a power supply and for this reason cannot run out of power. Furthermore, each node is equipped with an initial 1J of energy, some of which is drained with each round of transmission if the node is active.

V. RESULTS

Consider the results for the node energy levels obtained after running the simulation for 1000 transmission rounds.

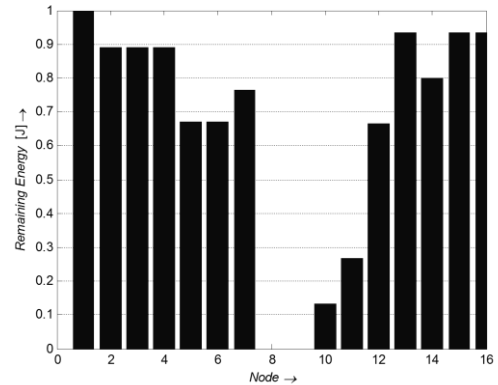


Figure 4: Node Energy Status After 1000 Transmission Rounds (Shortest Path)

Figure 4 illustrates the results for the node energy levels after 1000 rounds of transmission with the shortest path method. It is evident that nodes 8 and 9 are both dead after the complete depletion of their batteries. Figure 5 illustrates the results after 1000 rounds of transmission where the game theoretic model was implemented. At this stage, all nodes in the network are still active. Some of the nodes have a higher energy level and some lower than in the shortest path case, but all nodes are still active and the energy distribution is more uniform.

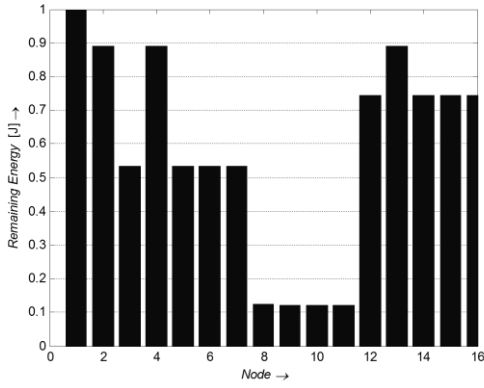


Figure 5: Node Energy Status After 1000 Transmission Rounds (Game Theory)

Consider the number of messages sent or relayed per node after 1000 rounds of transmission in figures 6 and 7.

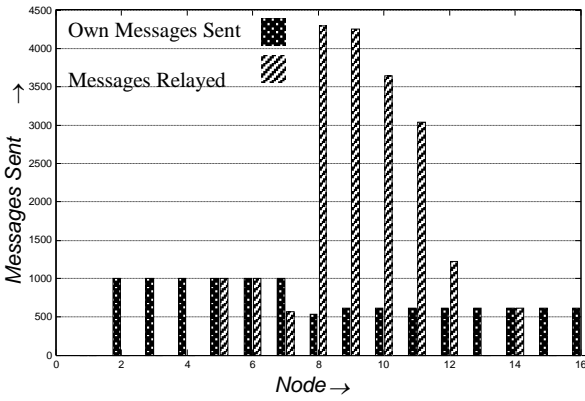


Figure 6: Own messages vs. Messages relayed (Shortest Path)

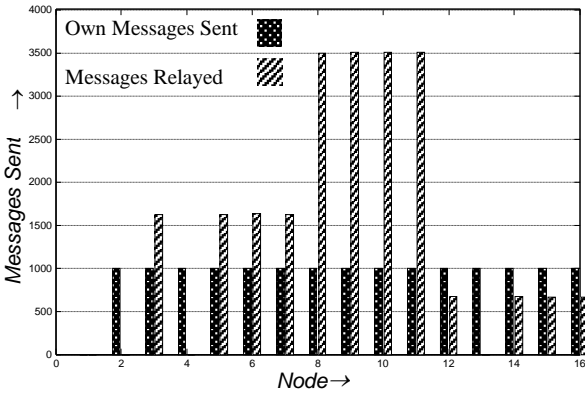


Figure 7: Own messages vs. Messages relayed (Game Theory)

By comparing figures 6 and 7, where the number of own messages sent by each node is juxtaposed with the number of messages the node relays for other nodes, there can be seen that the distribution of messages is more uniform in the case where game theory was applied and a total of 15000 messages were sent, but in the case of the shortest path method, the distribution is less uniform and only a total of 11401 messages were sent.

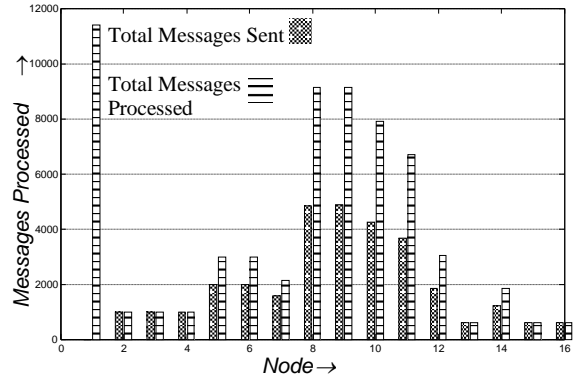


Figure 8: Processed Messages per Node (Shortest Path)

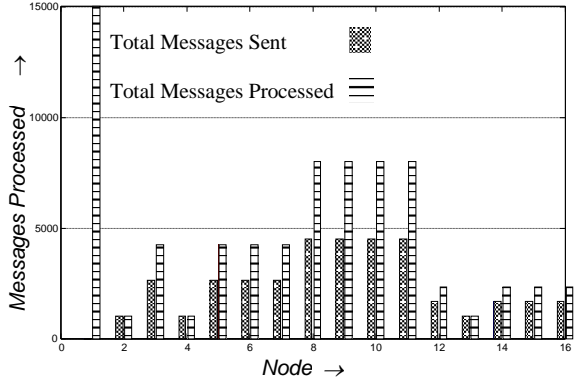


Figure 9: Processed Messages per Node (Game Theory)

In figures 8 and 9, the total number of messages sent is compared to the total number of messages sent and received (total traffic) per node. Once again, in the case of game theory, the amount of traffic through each node is more uniform, where some nodes experience more traffic and some less than in the case of Shortest Path protocol, but overall the traffic through the nodes is more uniform. This shows that the energy expenditure in the entire network is also more uniform and that the traffic is distributed more uniformly. This leads to a longer network lifetime, as crucial one-hop-to-base nodes are no longer drained first.

Table 3: Simulation Results

Shortest Path			Game Theory		
Total of Dead Nodes	Rounds to first failures	Dead node(s)	Total of Dead Nodes	Rounds to first failures	Dead node(s)
1	537	8	4	1142	8, 9, 10, 11
2	608	9			

By inspecting table 3 it can be seen that when implementing the normal, Shortest Path protocol, nodes 8 and 9 are both dead after 608 rounds of transmission. This results in nodes 10-16 also becoming inactive, or a total of 8/15 nodes, as they still have energy left but are unable to communicate with the base node (1), as they have no one-hop-to-base nodes left to relay through. With the game theoretic model implemented, a larger number of nodes died at the same time (8, 9, 10, 11), but only after 1142 rounds, leaving 8/15 nodes either dead or desolate.

Thus, without game theory, the network had only 47% functionality after 608 rounds, but with the game theoretic model implemented, the network stayed 100% functional for almost twice as long, only falling to 47% functional after

1142 rounds of data transmission.

The nodes closest to the base node receive more traffic than nodes further away, as they must relay more messages for other nodes towards the base node. Subsequently their energy is drained much faster, causing them to fail quicker. The problem is that the death of a node which is one hop away from the base node can cut off an entire group of nodes from the base node, rendering them essentially useless.

VI. CONCLUSION

It is evident that game theory can be implemented effectively to not only increase the lifetime of a wireless sensor network, but also contribute to the increased overall energy efficiency of a network. A real world application for wireless sensor networks was taken as a basis to model a WSN simulation upon. The results reflect that, with the implementation of game theory, the lifetime of the simulated network was almost doubled, with an increase of 534 additional transmission rounds before only 47% of the network remained functional. Furthermore, the throughput of the network was seen to be increased by an additional 3599 messages being transmitted.

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