The Impact of Different Propagation Environments on the Performance of Wireless Sensor Networks

Abdallah Mubark Aldosary

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The Impact of Different Propagation Environments on the Performance of Wireless Sensor Networks

By

Abdallah Aldosary

A dissertation submitted to the College of Engineering at Florida Institute of Technology in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Computer Engineering

Melbourne, Florida
May 2017
The undersigned committee, having examined the attached dissertation,

The Impact of Different Propagation Environments on the Performance of Wireless Sensor Networks

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Abstract

The Impact of Different Propagation Environments on the Performance of Wireless Sensor Networks

By

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This dissertation presents a methodology for evaluating the performance of wireless sensor network (WSN) protocols in different propagation environments. To create this methodology, practical RF propagation models that include many of the substantial features of different propagation environments are utilized, and radio energy models for different propagation environments are developed. Accurate environment-specific radio frequency (RF) propagation models should be utilized in order to improve the overall process of decision-making during pre-deployment of WSNs, to facilitate the deployment of the WSN, and to enhance the battery efficiency of sensing nodes so that the network lifetime can be prolonged.

The investigating of the impact of different propagation environments on the performance of WSNs was done based on simulating the LEACH protocol using the propagation models of sparse tree, concrete surface, sand terrain, long natural grass, short natural grass, artificial turf ground, and dense tree
environments. Also, the LEACH protocol was implemented in MATLAB using the free space and two-ray propagation models with identical setups and conditions. In addition, environment-specific radio energy models to predict energy consumption of WSNs deployed in dissimilar outdoor propagation environments were developed. These models were derived based on the usage of precise environment-specific RF propagation models. The comparison metrics that were involved in this study are the lifetime of the network and the network throughput. The network lifetime definition that was used in this study is the death of the first sensor node, while the throughput is defined as the total number of packets successfully sent to the base station node.

Moreover, the presented simulations are compared with each other so that the differences in the performance of WSNs in various propagation terrains can be identified. The results obtained through the comparison of these dissimilar outdoor propagation environments reveal significant differences in the lifetime and throughput. The differences are due to the dissimilarities existing in the wireless propagation channel of each environment. Furthermore, results generated by the developed radio energy models using these practical RF propagation models are compared with the results generated by radio energy models using free space and two-ray propagation models to demonstrate the imprecision of these theoretical
propagation models in evaluating the performance of WSN in different environments.
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Acknowledgement

I would like to express my deepest gratitude to my advisor, Dr. Ivica Kostanic, for the support, guidance, patience, and encouragement I have received from him throughout the course of my Ph.D. study at the Florida Institute of Technology. His tremendous knowledge, proficiency, and familiarity in several research areas have considerably contributed to the accomplishment of completing my doctoral dissertation. As a consequence, my understanding of research has been tremendously developed especially in the field of my research. It has been my privilege to have him as my doctoral advisor.

I would additionally like to express my thankfulness to Dr. Carlos Otero, Dr. Susan Earles, and Dr. Muzzafar Shaikh for being members of my doctoral committee. I am specifically appreciative for their support and valuable feedback and comments.

Last, yet, not least, the warmest gratefulness is given to the wonderful and distinctive people in my life. To my parents, I am very grateful for their boundless love, prayers, support, and patience throughout my journey of studying abroad. My special appreciation and gratitude go to my wife for her endless love, xiii
understanding, patience, and constant support during this long journey. To my kids, you filled my world with happiness. Finally, I would like to express my thanks to my sisters and brothers for the love, continuous encouragement, and support I have received.
Dedication

To:

My parents for their support, encouragement, prayers, and love

My wife for her endless love, encouragement, support, understanding, and patience

My kids for their love

My brothers, and sisters for their love and support
Chapter 1: Introduction

1.1 Overview

Recent advancements in the technology of micro-electro-mechanical systems (MEMS), wireless communication technologies, and digital electronics have made wireless sensor networks (WSNs) feasible. Also, they have facilitated the growth and proliferation of low-power and inexpensive wireless sensor nodes. As a result, throughout the last two decades, the utilization of WSNs has increasingly attracted the attention of research and industrial communities.

WSNs are comprised of small-scale, low-power, inexpensive, and independent sensor nodes. In addition, those nodes interact with each other wirelessly over short distances. WSNs, which are unattended computer networks, can be utilized in various environments to enable monitoring and controlling certain properties or phenomena.

Wireless sensor nodes spread packets and interact with each other in an ad hoc manner. A WSNs could be considered as a special type of ad hoc network. Ad hoc networks consist of wireless movable devices. Those devices (nodes) interact with each other without the presence of a preset network infrastructure. Nevertheless, each node is involved in providing routing services, formatting and
managing the network. Thus, every individual node can be seen as a router whereby packets are forwarded to the destination, which enables extending the size of the network to provide for wider coverage. Moreover, ad hoc networks are capable of functioning independently as stand-alone entities and can be connected to the internet via a gateway node. Ad hoc networks are easy to set up and can be utilized in numerous applications; for instance, in battlefields, rescue centers, or disaster areas [1] [2].

Although WSNs might be categorized as a special type of ad hoc network, there are several dissimilarities between traditional ad hoc networks and WSNs. Those dissimilarities comprise network density, the architecture and size of hardware, the number of sensor nodes, energy dissipation, interaction with the environment, and the design of the network [3]. The number of sensor nodes is the most distinctive attribute of WSNs and can be several times larger than the node number in other ad hoc networks. Also, the node density might be greater. While sensor networks have a great many dynamic nodes, this is not the case with ad hoc networks; thus, a global identification (ID) system is part of an ad hoc network but not of a WSN because of this large number of nodes. Furthermore, destination-addressing scheme is different between a WSN and an ad hoc network. The addressing scheme in WSNs is data-centric, where the inquiries are sent to the node that has the demanded data. On the other hand, an ad hoc network is address-centric, where the inquiries are sent to a unique ID. Moreover, there are additional dissimilarities in the case of nodes. One of the differences is that the sensor nodes
have a limitation in terms of processing resources and energy resources. Non-rechargeable batteries are usually the power source of wireless sensor nodes. Consequently, the power source is regarded as the most important of the node’s resources. Interference of radio frequency (RF), power dissipation, and physical damage cause a higher rate of node failure, which be another characteristic of WSNs. Therefore, WSNs can be differentiated from the ordinary ad hoc network by means of those characteristics.

WSNs are employed for the purpose of collecting environmental data. By using those sensor nodes, data are delivered to the base station (the sink node). In this way many benefits can be obtained, such as pre-detecting some catastrophes and enhancing the efficiency of systems [4]. The WSN is recognized as an application-dependent technology. This means that the design of the network and equipment, the methods of data processing, and the deployment patterns are constructed based on the purpose of network, and they are different among WSN applications.

In terms of the processing of gathered data, the data can be handled either internally or externally based on the nature of the application. Gathered data are sent from a sink node to a distant facility for more processing and analysis, which can be seen in Figure 1.1. Any action to be based on the provided information can be taken by the end user when applications require controlling. One example might
be an application to border security, where an intrusion detected by the wireless sensor nodes could lead to the sending of a search team to the appropriate area.

Figure 1.1: Wireless Sensor Network

WSNs can be utilized in numerous applications and in several different fields to observe various kinds of events or characteristics. For example, those fields could be habitat surveillance, battlefield monitoring, border protection, pipeline surveillance, health care monitoring, natural disaster prevention, or forest safety [4]. Data from the monitored fields are collected by sensor nodes, which can be altered to adapt to the specification other applications.

In fact, some devices can be attached to nodes, including an actuator, a Global Positioning System (GPS), a camera, or a smoke detector. There are other properties that have made WSNs adaptable so as to be workable in several applications. For example, there is the simplicity of deploying WSNs in areas that are impossible to be reached, such as forest fires. Moreover, there is the possibility of deploying large numbers of scattered nodes. Thus, a WSN provides very detailed
information about the sensing area whereby high accuracy and higher fault
tolerance can be achieved.

1.2 Architecture of Sensor Nodes

There has not been a standard design for a wireless sensor node. The basic
architecture in most cases comprises at least five units (processing unit, sensing
unit, memory, communication unit, and power supply) as illustrated in Figure 1.2
[3]. The sensing unit, consisting of the sensors as well as the Analog to Digital
Converter (ADC), is tasked with sensing the environment. Data can be gathered
periodically or whenever an event occurs, depending on the setting of the sensor.
The ADC converts the sensed data into a digital form. This can then be dealt with
by both the processor as well as the transmitter units. The sensing unit consumes
less power than either of the other two subsystems.

The collected data are delivered to the processing unit, consisting of a
processor and a memory. This unit manages the functionality of other components
and their decisions. Also, the behavior of the node within the network is controlled
by this unit, including choosing a network to join and routing the packets.
Furthermore, the processing unit is able to run local processing. For example, those
local operations could be analyzing the sensed data, aggregating the gathered data,
and generating reports.

The communication unit, which is comprised of a transmitter and receiver, is
in charge of connecting the node to the network. In addition, that unit can be set to
various functional states: transmit, receive, idle, or sleep. The power unit is necessary for the operation of the above-mentioned units. Due to the difficulty of running a main power supply to the sensor node, those units are linked to the power unit, which is usually an onboard battery. This battery could be rechargeable or non-rechargeable. Nevertheless, because the wireless sensor node is frequently deployed in hard-to-reach places, replacing the battery might be costly and difficult [2] [5].

![Figure 1.2: Basic sensor node architecture](image)

Depending on the different requirements of WSN applications, sensor nodes might contain additional hardware components. For instance, those additional components could be a position localization system, an actuator, and a power generator, such as solar panels [6]. Thus, by equipping the wireless sensor node with additional equipment, the basic architecture of a sensor node can be extended to adapt to several different requirements of WSN applications. Sensing functions that are executed by wireless sensor nodes could comprise, but not be limited to, temperature sensing, humidity sensing, and pressure sensing [5].
The size of the node is variable, and it could be as small as a grain of sand or as large as a shoebox [7]. For example, a sensor node as small as a dust particle could be utilized on battlefields, where sensor nodes are better unseen [7]. Likewise, the price of the sensor node is based on the degree of complexity of the node, where higher complexity increases the cost. Thus, the cost of the node may vary from a couple of cents to hundreds of dollars.

Indeed, in large-scale implementations, the price of sensor nodes produces major concerns. Thus, the limitations on the cost and size of sensor nodes bring further limitations on the efficiency of power resources, processing, and memory capacity. Moreover, since wireless sensor nodes are usually implemented in unreachable areas, batteries of those wireless sensor nodes are regularly irreplaceable and non-rechargeable. Thus, the wireless sensor nodes usually experience an energy shortage while functioning because of the low provided energy. Also, the power consumption has to be carefully managed to extend the lifetime of the network [4]. Essentially, expanding the network lifetime can be achieved by a longer life of the node battery. Normally, the processing and communication units are the most energy-consuming units of the sensor node battery [3].

1.3 Wireless Sensor Networks

Wireless sensor networks observe particular phenomena and several characteristics in the monitored field. The WSN in most cases is recognized as an
application-dependent technology. This means that the design of the network and equipment, the methods of data processing, and the deployment patterns are constructed based on the purpose of the network and the targeted deployment terrain. The deployment scheme is especially significant because of its substantial impact on parameters such as cost, network lifetime, and throughput. Two schemes are available for deployment of wireless sensing nodes: stochastic, where the locations of sensors are determined in random style, and deterministic, where sensors are positioned one by one [8], or by placing nodes utilizing a combination of both methods (e.g., see [9]). The distance that separates nodes is set based on the sensing functionality and sensor node capability of wireless transmission. In wireless communications, the received signal strength is often predicted by the usage of path loss models. Such models are usually created in accordance with the environmental features where the transmitting and receiving nodes operate.

Based on their sensing method, sensor networks can be categorized into two categories, reactive and proactive networks [10]. The state of the nodes in proactive networks switches repeatedly from active to sleep modes. Further, nodes during the active mode are continuously sensing neighboring objects, generating reports, and sending them. Nevertheless, proactive networks have a disadvantage, which is missing some essential data during the time in which the nodes are in sleep status. In contrast, the wireless sensor nodes in reactive networks continue sensing the neighboring objects and preparing reports once a substantial change takes place in the monitored fields, so that any change can’t be missed. Since a WSN is an
application-dependent technology, choosing which category to implement is based on the requirements of application.

The detected data are forwarded to the base station based on two mechanisms, which are single-hop or multi-hop. The single-hop mechanism forwards the data directly from each node to the base station no matter how far the base station is. Consequently, additional transmitting power is going to be consumed by faraway nodes, which makes them run out of energy faster.

The other mechanism is the multi-hop, where the data are sent from a node to the sink via a multi-hop route, which is a set of in-between neighboring nodes. Since the transmitting nodes and intermediate nodes utilize the short-range connections, much power is saved, and sent data are reduced by aggregation whereby duplicated data can be neglected. Nonetheless, using a multi-hop mechanism in large-scale networks will overload the nodes that are located near the base station. Thus, those nodes will run out of energy quicker [4] [11]. Selecting which mechanism to deploy depends on the requirements application.

By having a WSN with a large number of wireless sensor nodes, many benefits can be achieved. Among those benefits one finds expanding the coverage area, improving the fault tolerance of the network, and providing a higher degree of accuracy.
1.4 Research Problem

Since every environment is unique in the physical features that control the propagation of the signal, signal propagation of each environment is distinct from one to another. This variation in signal propagation influences the performance of the WSN. The performance evaluation studies of WSNs that have been done using simulation platforms have not taken into account the impact of different propagation environments on the performance of WSNs. In [12], a review of 151 articles shows that 76% of research articles have used network simulators, which reveals the extensive utilization of simulation in the field of wireless networks. Those simulation platforms utilize theoretical propagation models such as two-ray and free space path loss models. Also, the radio energy models that have been used in those simulation platforms were derived based on the usage of theoretical RF propagation models.

However, those simulation platforms are not able to simulate several real-world scenarios since there are various environmental difficulties that have not been taken into account in those theoretical propagation models, such as obstructions and reflections. Moreover, the free space and the two-ray propagation models have been proved to be imprecise in predicting the received signal in dissimilar WSN environments [13]. This fact motivates the need for integrating practical RF propagation models that include all known and unknown propagation factors of different propagation environments in one well-known simulation platform, such as MATLAB. In addition, there is a need to develop accurate radio
energy dissipation prediction models for WSNs deployed in dissimilar outdoor propagation environments that are derived based on the usage of precise environment-specific RF propagation models. Thus, the impact of different propagation environments on the performance of WSNs can accurately be determined. In addition, accurate evaluation of the performance of WSNs in different propagation environments leads to having a clearer and better understanding of the performance and the behaviors of wireless sensor networks and protocols.

The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is a popular wireless sensor network protocol and was the first wireless sensor network protocol that is cluster-based. The generated simulation results using the free space and the two-ray ground propagation models that are shown in [14] reveal that LEACH is able to expand a system lifetime more than general-purpose multi-hop methods.

Since its first appearance, the LEACH protocol has been the most repeatedly utilized protocol in most performance evaluation studies on WSNs. Also, it began to be a key protocol and a foundation for many newly developed protocols. Most researchers claim that LEACH provides a good performance compared with the traditional WSN flat routing protocols, and it is an appropriate WSN protocol for energy efficiency. Additionally, the performance of the LEACH protocol has not been evaluated in different propagation environments. It is for these reasons that
the LEACH protocol was utilized in this study. The proposed research proposes an empirical comparative methodology for evaluating the performance of WSN protocols in different outdoor propagation environments. Additionally, the influence of different propagation environments on the performance of WSNs is investigated. The targeted environments are sparse tree, concrete surface, sand terrain, long natural grass, short natural grass, artificial turf ground, and dense tree. Since the accuracy of simulation based results of the LEACH protocol using theoretical channel models has not been completely validated, the LEACH protocol is selected for the purpose of testing our methodology. Based on our best knowledge, this proposed approach has not been attempted before. Also, this study involves the employment of several accurate outdoor RF propagation models for WSN developed by the Wireless Center of Excellence (WiCE) to develop environment-specific energy models. Then, the LEACH protocol is implemented in MATLAB using both theoretical and statistical propagation models, followed by the running of a simulator, the gathering and analyzing of the results, and the comparing of the results from each environment with both the free space and the two-ray propagation models. Thus, we can have a clearer and better understanding of the performance and the behavior of the LEACH protocol. Not only will it let us accurately anticipate the lifetime of the wireless sensor network, but it will also allow us to predict the throughput of the network and its power consumption. In addition, it can be proved whether the LEACH protocol is feasible for actual applications and if it has many prospects for real world applications on wireless
sensor networks. Also, this work will help developers in identifying the aspects that require some improvements.

1.5 Dissertation Structure

This dissertation is organized as follows. Chapter 2 describes the architecture and mechanism of the LEACH protocol and its improved versions. Additionally, a discussion of the literature review of different approaches to evaluating the performance of WSN protocols, the accuracy of simulation platforms, most popular network simulators, and an overview of the related published research on the performance of WSN are presented. Chapter 3 identifies the procedure utilized for collecting, processing, and analyzing the generated results. A wide range of topics is covered in this chapter such as utilized RF propagation models, comparison metrics, targeted environments, simulation setup, and the procedure of collecting, analyzing, and comparing the generated data. Chapter 4 develops the radio energy dissipation prediction models based on the usage of empirical path loss models. Chapter 5 presents the results generated by simulating the LEACH protocol using both the developed and the existing radio models. Chapter 6 provides a discussion of the generated results. In addition, the results of each environment are compared. The predicted network lifetime and throughput by the developed radio energy models and the commonly used radio energy models are compared to examine the adequacy of these theoretical propagation models in evaluating the performance of WSNs deployed in different propagation environments. Finally, the conclusion of this dissertation and avenues for future work are provided in Chapter 7.
Chapter 2: Literature Review

2.1 Introduction:

In this chapter, a discussion of the literature review of different approaches to evaluating the performance of WSN protocols and an overview of the related published research on the performance of WSNs are presented. The accuracy of simulation platforms is also discussed. This chapter additionally discusses most popular network simulators. Moreover, the chapter describes the architecture and mechanism of the LEACH protocol and its improved versions.

2.2 The LEACH Protocol

The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is a popular wireless sensor network protocol and was the first wireless sensor network protocol that is cluster-based. To accomplish perfect performance with regard to network lifetime and latency, LEACH incorporates the concepts of media access control (MAC) and routing protocol that is energy-efficient and cluster-based. Also, it includes data aggregation [14].

LEACH is an adaptive cluster-based self-organizing protocol [15]. The energy load is distributed equally among the network members by utilizing the randomization of cluster head election used by LEACH. The nodes are involved in formatting local clusters, with one node becoming a cluster-head. If the nodes elected to be cluster-heads were to remain as cluster-heads throughout the network
lifetime, as in traditional clustering algorithms, they would run out of energy quickly, terminating the beneficial lifetime of the non-cluster-head nodes. Therefore, LEACH utilizes the randomization of rotating the cluster-head position among the cluster members. Furthermore, local data aggregation is performed by LEACH to compress the sensed data received by the cluster-head from the cluster members thereby further minimizing energy consumption.

2.2.1 Procedure

The functioning of LEACH is divided into rounds [15]. Each round is broken up into two phases, the first of which is the set-up phase after the clusters are created. Then, the following phase is a steady-state phase, occurring once the transferring of data to the cluster-head nodes starts. The steady-state phase is longer than the set-up phase, so that overhead is reduced.

2.2.1.1 Set-Up Phase

Initially, once clusters are being formatted, every node makes its decision whether or not to be the head of the cluster. This decision is dependent on the recommended percentage of the network cluster-heads and how often the node has become a cluster-head. A node can be elected as a cluster-head by generating a random number between one and zero. This random number is compared with a threshold $T(n)$. If the generated number is less than that threshold, the node will be elected to be a cluster-head. The threshold is determined as:
\[ T(n) = \begin{cases} \frac{P}{1 - P \times \left( r \mod \frac{1}{p} \right)} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \]  

where:

- \( P \) is the required percentage of cluster-heads
- \( r \) indicates the existing round
- \( G \) determines the group of nodes which have not been chosen to be cluster-heads

in the preceding \( \frac{1}{p} \) rounds

By utilizing this threshold and throughout \( \frac{1}{p} \) rounds, every node can be a cluster-head. At round \( 0(r = 0) \), all of the nodes are eligible to be a cluster-head since they have the identical probability of being selected as a cluster-head. Every node which has already been a cluster-head will not be a cluster-head again for the remaining rounds. Consequently, the probability of being a cluster-head for the nodes that have not been cluster-heads will be increased because the number of nodes qualified to be cluster-heads is smaller. In addition, \( T \) will equal to 1 after \( \frac{1}{p} - 1 \) rounds for the set of nodes not chosen to be cluster-heads. Once \( \frac{1}{p} \) rounds are finished, all nodes can participate in electing themselves again to be cluster-heads.
An advertisement message is broadcasted by the elected cluster-head node to its neighboring nodes. During the cluster-head-advertisement phase, a CSMA MAC protocol is used by the cluster-heads. The receivers of the non-cluster-head nodes have to be ON throughout the set-up phase in order to receive the advertisements message. Once this phase is finished, every non-cluster-head node makes its decision about selecting the cluster it is going to join for the current round. Those nodes choose the cluster with higher received signal strength of the advertisement message since less transmitting energy is required for communication.

Once the decision of selecting a cluster to join is made by each node, every node has to notify the cluster-head node about its decision to join the cluster. Every sensor node broadcasts this notification to the cluster-head by the usage of a CSMA MAC protocol. All of the cluster-heads have to maintain their receivers ON throughout this phase. Those notifications are received by cluster-head nodes from nodes requesting membership in the cluster. The cluster-head nodes depend on the number of members in their cluster to generate a TDMA schedule informing every node about its transmitting slot. This TDMA schedule is sent back to the cluster members.

2.2.1.2 Steady-State Phase

After the creation of the cluster and the distribution of the TDMA schedule, the set-up phase is complete, and data transmission will be initiated. Supposing each node always has data to be sent, every node sends its data to the cluster-head
during its assigned transmitting time. All non-cluster-head members are supposed to turn off their radio modules until their given transmission time. Therefore, energy dissipation in those sensor nodes can be reduced. The receivers of cluster-heads have to be turned on in order to receive all the sensed data from the cluster members. Upon receiving all the data, the cluster-heads begin performing signal-processing processes to aggregate the received data into one signal and to forward them to the sink. Because the sink is located far away, this transmission task consumes high energy. This stage is the steady-state function of the LEACH protocol. Once this phase is over, the subsequent new round starts with the same procedure as mentioned above.

The LEACH protocol performs better than the traditional WSN protocols due to the utilization of clustering adaption, rotation of the cluster-heads, and local data fusion. Nevertheless, the LEACH protocol has its own issues and disadvantages. One of its disadvantages is the random election of cluster-heads without taking into consideration the remaining energy of the nodes. In addition, cluster-heads forward aggregated data directly to the base station based on one hop transmission. Consequently, the batteries of cluster-heads located far away from the sink drain faster than ones closer to the sink. Another issue of LEACH is the lack of reliable transmission. The transmitted packet might be lost in the case where the cluster-head runs out of energy or has difficulties connecting with the sink. In those cases, the undelivered data needs to be resent once a new round is initiated. Those issues have been investigated by researchers who developed some versions of LEACH, as
is documented in the following section.

2.3 Improved Versions of the LEACH protocol

Several optimized versions of LEACH have been proposed. They included various mechanisms to improve the performance of the standard LEACH protocol. The following is a discussion of some of those versions.

2.3.1 LEACH-C

LEACH-C, Centralized Low Energy Adaptive Clustering Hierarchy, is composed of a steady-state phase and a set-up phase. Its steady-state phase is identical to the steady-state phase of the basic LEACH protocol, but it differs in its set-up phase. The base station is responsible for choosing the cluster-head. Every sensor node forwards its location and remaining energy level to the sink. Based on that information, the sink creates clusters consuming less transmission energy. Furthermore, the sink selects nodes with higher energy level to be cluster-heads and sends this information to all of the network members.

This protocol outperforms the basic LEACH by the deterministic method of selecting number of cluster-heads in every round. LEACH-C is able to make a good distribution of cluster-heads. However, since LEACH-C demands all the current locations of the nodes, a GPS is required, leading to the consumption of more energy [14] [16].

2.3.2 LEACH-F

LEACH-F, Fixed number of cluster Low Energy Adaptive Clustering
Hierarchy, is similar to LEACH-C protocol in terms of using a centralized mechanism for cluster creation. However, the steady-state phase is identical to the standard LEACH. The creation of the clusters is applied only one time for the whole lifetime of the network, and reforming of the clusters is not repeated for the subsequent rounds. The cluster organization is fixed, while cluster-head position is rotated within each cluster [14] [17]. However, this protocol has a drawback, which is the inflexibility of joining new members to the cluster and of leaving the cluster after the formation of the clusters.

2.3.3 LEACH-B

LEACH-Balanced (LEACH-B), which stands for Balanced Low Energy Adaptive Clustering Hierarchy, depends on the usage of the residual energy of each node and the optimal number of cluster-heads [18]. In LEACH-B, the optimal cluster-head number is maintained in order to balance the dissipation of energy. This number of cluster-heads is generated through two steps. The first step is the same as the election mechanism in basic LEACH. The second step of election begins after the process of cluster-head advertisements. Within this step, the determination of the number of cluster-heads is defined by \( n \times p \), where \( p \) is the optimal percentage of cluster-heads and \( n \) is the total number of nodes. If the number of the chosen cluster-heads matches the optimal number, this election stage is over; otherwise, one of following two scenarios is employed. The first scenario is followed once the elected cluster-head number is lower than \( p \). In this case, some nodes that have not been elected to be cluster-heads are converted to become
cluster-heads. However, the other scenario is when the number of selected cluster-head is more than the optimal number. Some of those cluster-heads are converted back to non-cluster head nodes. Once the desired cluster-head number is achieved, the election stage is over. The rest of the procedures are the same as for the basic LEACH protocol.

Simulation shows that LEACH-B functions better than the standard LEACH in terms of energy efficiency. This improved performance is caused by the balancing of energy consumption that is achieved by making the number of the CH equivalent to the optimal number throughout the network lifetime. Also, including the remaining energy in the mechanism of electing the cluster-heads is another aspect of the improved performance.

2.3.4 MH-LEACH

MH-LEACH, which stands for Multihop-LEACH, is identical to the standard LEACH. The only difference is the usage of multi-hop communication instead of direct communication. The cluster-heads broadcast the data to the base station via a multi-hop route [19]. Thus, the high power consumption caused by faraway cluster-heads is reduced. The cluster-heads are responsible for determining the best multi-hop path to the sink. This route is composed of a chain of many cluster-heads, and the end of this chain is a cluster-head located near the base station. The data is passed on by intermediate cluster-heads until the end cluster-heads whereby data is delivered to the base station.

The comparison between Multihop-LEACH and the standard LEACH carried
out in [19] showed that there is less power consumption in Multihop-LEACH compared to the basic LEACH. Also, Multihop-LEACH shows more scalability than the basic LEACH.

All of those improved versions of the basic LEACH protocol employed various mechanisms. Those mechanisms handle some of the basic LEACH’s issues, such as communication techniques and residual energy.

### 2.4 Methods of Performance Evaluation

There are several different techniques of measuring the performance of protocols and networks, as every protocol and network is dissimilar in its nature and design. In [20], there are three dissimilar methods to assess the performance of protocols. The first method employs mathematical models for evaluating and analyzing the performance of several protocols. This method is often not suitable and accurate because of the limitations and complication of WSNs [21]. The second approach is conducting a simulation. The specifications of the protocols and the network as well are defined within the simulator in order to test both the protocols and the network. After running the simulator, the analysis and evaluation of gathered results are made. By this approach, comparative studies of multiple protocols can be conducted, which involves choosing a set of protocols and then comparing them with each other. The primary purpose of this kind of study is to provide a good understanding of the behavior and performance of the selected protocols in various circumstances. The results produced by the simulations of those selected protocols are mapped in a table. This comparison table demonstrates
the differences among those protocols, so that the performance evaluation of each one can be achieved.

Nevertheless, this method is not able to offer a methodology to choose a suitable protocol for a particular application’s design. Due to the disadvantages and shortages of the features of every simulator, this simulation-based method is not ideal [22]. Moreover, several real-world scenarios cannot be validated by these simulation platforms. The last approach is deploying a real network in a real-world scenario. In this method, all measurements are collected by running the network in the real world; then, the gathered results will be evaluated. By this method, real behavior of the networks can be observed. However, the number of protocols that were analyzed and evaluated through real-world deployment is relatively low. This is due to the fact that real-world deployment costs a lot of money and consumes too much time. Consequently, a simulation-based approach is currently the most commonly used approach of analyzing the performance of networks and protocols.

### 2.5 Accuracy of Simulation Based Results

Network simulation platforms are able to play a significant role in implementing and evaluating the performance of WSNs. Moreover, simulation is very useful when the scale of deployment is massive. The simulation platforms provide a high level of flexibility and control and generate results that can be repeatable. Because of the ease of implementing experiments with only one appropriately configured computer, complicated experiments can be conducted.
Thus, those simulation platforms are considered to be scalable and cost-effective [23].

However, several existing simulators cannot model many of the substantial features of different propagation environments. Simulation platforms are built on basic assumptions, and those simulators do not provide realistic results [24]. In addition, simulation platforms are abstract and deviate from the real world in many ways. For instance, EM radiation and obstacles in the propagating channel are not included in simulators. Instead, simulators use an equation to determine the received signal strength at the receivers [25]. Also, those simulators are still affected by imprecise modeling of wireless networks.

One of the most notable issues is the insufficiency of the wireless physical layer modeling [26] [27]. Certainly, assumptions included in simulators are not permanently identical to the real-world scenarios. For instance, received signal strength is modeled as a function of distance. Moreover, there has not been an ideal physical model, capturing all the factors, because of the inconsistent characteristics of the wireless physical layer. Based on the need to achieve feasibility, those abstractions are necessary, and several details could be disregarded since their influence on the simulation outcomes is limited. The simulation-based results can be valid only for the purpose of conducting research-based projects. Specifically, existing WSN simulation models are not able to capture the irregularity of radios and sensors [28].
The accuracy of wireless simulators has been studied mainly in the domain of Mobile Ad Hoc Networks (MANETs). When Ivanov compared the outcomes of a real experiment with that using the ns-2 wireless simulator, he found that while the delivery ratio from the simulator was very accurate, there was a great deal of deviation in the latency results from the real experiment. Moreover, because the study was limited to only one routing and a MAC protocol, the value of this study is also limited; it has been shown in other studies that dissimilar physical models have differing effects on a variety of routing protocols [29].

Validation of the physical layer models that are employed in the Scalable Wireless Ad-Hoc Networks (SWAN) simulator is provided by Liu et al. [30], where connectivity traces from a real-life experiment are used to drive the simulator. Based on the usage of various routing protocols, this study concentrates only on sensitivity and packet delivery ratio.

A set of assumptions that are used by several MANET network simulators and a couple of small experiments are provided by Kotz et al. [27] to demonstrate how those assumptions can cause erroneous results. Colesanti et al. [31] provides a study of the accuracy of the OMNeT++ MAC Simulator, but this study discussed solely one MAC protocol and only the packet delivery ratios. The Unit Disk Graph (UDG) model is used by the MAC Simulator. According to Colesanti et al, the results achieved by the usage of the UDG model can be optimized to approach the results of real life experiments by including probabilistic packet corruption, which is derived from real life experiments.
In [32], a performance evaluation study of test-bed instruments and simulation instruments in a wireless mesh network is provided. The primary goal of this study is to identify the differences between the generated results of those tools. The scope of this study includes the physical layer, the MAC layer, and the IP layer for both practical and simulation experiments. The metrics used in this study are the transmission rate, routing stability, interference, and path loss. Two simulators are used which are QualNet and NS2, while the actual experiment is made up of Hp nc6000 laptops provided with wireless LAN adapters and operating Linux kernel operating systems with MadWiFi drivers. The simulation-based results are provided together with test-bed results. Some of the simulation-based results are quite dissimilar to the test-bed based results. Those dissimilarities are caused mostly by imprecise channel modeling and insufficient interference in the simulators.

In [33] and [34], the importance of developing a path loss model for the WSN was acknowledged by the authors, but admittedly many of them utilize the log-normal shadowing model because of the unavailability of WSN-specific models. Use of accurate simulation models is an essential prerequisite for accurate simulation of a real-life network [35]. In order to achieve a proper evaluation and an enhancement of the performance of the network during pre-deployment phases, RF signal propagation in a WSN needs to be accurately modeled [36]. This capability has the possibility of prolonging network lifetime, maximizing
connectivity and coverage, reducing network cost, and optimizing the accuracy of simulation platforms.

2.6 Most Popular Network Simulators

Wireless network simulators have been a broadly utilized approach to improve and assess wireless networks in previous years. The advantages of those simulators are the ease of implementing and modifying network scenarios and the reproducibility of experiments. In [12], a review of 151 articles shows that 76% of research articles have used network simulators, which reveals the extensive utilization of simulation in the field of wireless networks. The following is a discussion of the most frequently used simulators.

2.6.1 NS-2

Network Simulator-2, which is a discrete event network simulator, is utilized for the purpose of simulating the network protocols with various network topologies [37]. In addition, wired and wireless networks can be simulated using NS-2. It is written in C++, and its simulation environment is created and controlled by OTcl, which is an object-oriented programming language originated from Tcl. By using OTcl, the user is able to set the network topology, and the NS-2 simulator simulates the required topology. Also, a network animator (NAM) is employed in order to display the network graphical view. NS-2 is the most widely employed network simulator in the research field with 44% usage [12].

In order to achieve detailed results, simulation is executed at the packet level.
Moreover, OSI layers are provided by NS-2 except for session and presentation layers.

### 2.6.2 OPNET Modeler

OPNET, which stands for Optimized Network Engineering Tools, [38] is employed for studying protocols, networks, and applications. Powerful user graphical support is provided by OPNET. By using the graphical editor interface, the building of a network topology and objects from the application layer to the physical layer can be achieved. Mapping to real systems implementation from the graphical design can be created by using the Object-Oriented Programming method [39]. The setting of all topologies and simulation outcomes can be visualized. The simulation parameters can be modified, and the experiments can be iterated easily via GUI. OPNET is dependent on a mechanism that is called a discrete event system. Organizing the network can be achieved by utilizing the hierarchical structure.

The advantage of using an OPNET simulator is its usefulness when using large-scale networks where a little alteration might be critical [40]. Also, before applying any modification, predicting the behavior and verifying the configurations of the devices are possible. NetDoctor, MVI, and ACE are other tools of OPNET whereby administrators are able to examine their networks and the later implementations to be made.
2.6.3 MATLAB

MATLAB, which stands for matrix laboratory, is an interactive software environment and high-level programming language. MATLAB was built in C programming language, and a cross-platform operating system is supported [41]. Some functions of MATLAB are manipulating matrices, generating measurements, analyzing data, plotting data and function, executing algorithms, and creating a graphical user interface. Also, programs that are built in different languages can be interfaced with it. Users from different backgrounds, such as engineering, science, and economics, use MATLAB and its associated toolboxes.

Even though MATLAB is utilized mainly for numerical computing, an alternative toolbox utilizes the MuPAD symbolic engine, which allows accessing the symbolic computing capabilities. Another package is Simulink, adding model-based design and graphical multi-domain simulation for both dynamic and embedded systems [42].

2.6.4 OMNET++

OMNET++ [43] was designed in September 1997, and it is currently being used by a great number of users. It is a general discrete event and component-based open architecture simulation framework. In contrast to ns-2, OMNET++ is not just designated for network simulations. It is used for several purposes, such as multiprocessor modeling and evaluating the performance of complex software systems. Nevertheless, it is one of the most widely used network simulators. Creating a robust open-source discrete event simulator that can be utilized by
research, academic, and industrial communities was the motivating reason for developing OMNET++ [44]. OMNET++ is compatible with both UNIX and Windows operating systems. A component-oriented method that supports reusable and structured models was used to develop OMNET++. Moreover, OMNET++ provides a large graphical user interface (GUI) [45].

2.6.5 NS-3

NS-3, which stands for network simulator three, is a discrete-event simulator [46]. This simulator is targeted mainly for the purpose of research and educational use. NS-3 is open-source free software, which exists publicly for the research field. Research studies on networks for both IP and non-IP are supported by NS-3 simulation. NS-3 is divided into multiple of modules where each implements one or additional models for real-life network devices and protocols like Wi-Fi, WiMax, or LTE. Nevertheless, most of its utilizations are focused on simulations of wireless/IP including models for Wi-Fi, WiMAX, and LTE. Also, it includes a set of static and dynamic routing protocols like OLSR and AODV. NS-3 was built using the C++ programming language, and it can be programmed using either the Python or C++ programming languages.
2.7 Related Work

Throughout the literature, evaluating the performance of WSNs in different propagation environments is frequently neglected in WSN research. Most of the evaluation studies of WSNs were conducted based on the usage of simulation tools with nominal and frequently unrealistic RF propagation models. For instance, the well-known network simulator ns-2 provides simulation of signal propagation utilizing the free space and the two-ray propagation models [47]. Accurate environment-specific radio frequency (RF) propagation models should be utilized in order to improve the overall process of decision-making during the pre-deployment of WSNs. Not only do accurate environment-specific RF propagation models help facilitate the deployment of the WSN, but they also help enhance the battery efficiency of sensing nodes so that the network lifetime can be prolonged [48] and [49]. Despite their importance, performance evaluation studies of WSNs that have been done using simulation platforms have not taken into account the impact of different propagation environments on the performance of WSNs.

In [50], an analysis study of WSNs using the LEACH protocol is presented. The LEACH protocol is implemented in NS-2 simulator and TOSSIM emulating the whole TinyOS applications. Then, a comparison of the NS-2 simulator results to the TinyOS results was made, which shows that the results of both simulation and emulation agree. However, the emulation still does not take into account the environmental effects of the channel propagation, such as weather and obstacles. Also, this study has not examined the impact of different propagation environments
on the performance of the LEACH protocol. Additionally, research done by [51] dealt with an evaluation study of network simulators for WSNs. A comparison was made between simulation and real life methods using a forest fire sensing application. It revealed that simulators don’t have the ability to simulate the actual situation and are not strong enough in this respect. Moreover, the influence of various propagation environments was not included in this study.

In [52], the performance of Optimized Link-State Routing (OLSR), Destination-sequenced Distance Vector (DSDV), and Ad-hoc On-demand Distance Vector (AODV) protocols have been evaluated using NS-2 simulator where two scenarios were involved, namely, sensor-based network nodes and tactical networks for ships. To evaluate the routing ability and protocol efficiency, four metrics were utilized in this study, including routing overhead, packet delivery rate, normalized routing load, and average end-to-end delay. The simulation results reveal that AODV outperforms OLSR and DSDV in the second scenario, while OLSR has emerged as the desirable protocol to be utilized for sensor network.

In [53], the performance evaluation of OLSR, Dynamic Source Routing (DSR), and AODV protocols is accomplished on the Wireless Sensor Actor Network (WSAN) for different topologies utilizing the OPNET simulator. This evaluation performance study employed stationary and mobile scenarios where the used metrics are: throughput, routing traffic, and delay. Another performance evaluation of routing protocols has been done using real-life sensor networks [54], composed of cricket motes, which were designed by the University of California –
Berkeley. Those motes were used to emphasize the subsequent metrics: routing overhead, unsuccessful multi hop sends, route length, loss of packets, and end-to-end delay. Moreover, research done by [55] dealt with performance evaluation of Better Approach To Mobile Ad Hoc Networks (B.A.T.M.A.N) and OLSR protocols where the protocols were implemented in a real-world network. The employed metrics are Ratio Traffic Overhead (RTO) and Packet Delivery Ratio (PDR), and the results indicated that B.A.T.M.A.N performs better than OLSR in terms of PDR.

The study in [56] has been done based on a real-life sensor networks utilizing Tmote Sky sensing nodes, where a weighted routing protocol for heterogeneous networks (MANET using PDA) is presented. This proposed routing protocol is compared against the modified version of AODV. The utilized metrics in this study are number of hops, time of round trip for one hop, and time of round trip for multihops. In [57], the OMR, Opportunistic Multi-Path Reliable, routing protocol is proposed, and its performance is compared to other routing protocols, e.g., the Shortest Path SP and flooding using NS-2 simulator. The performance metrics considered in this study are delivery latency, delivery ratio, and control overhead.

In [58], a methodology based on hypothesis testing is used to compare propagation loss as generated by the OPNET WSN model and a real-world WSN. In order to verify simulation results, a software tool is proposed. This comparison tool shows the need for verification of simulation by presenting cases where
experimental and simulation results do not agree. In addition, research conducted by W. Heinzelman [14] revealed that the LEACH protocol is able to expand a system lifetime more than general-purpose multi-hop methods.

Nevertheless, because of the utilization of inaccurate propagation models employed in those studies such as the two-ray and the free space propagation models, the evaluated protocols performed well on simulation platforms but may not act and reflect what is expected in real-life scenarios. Furthermore, the behavior of the evaluated protocols in various propagation environments may not be as perfect as the way they behaved in those studies where the impact of dissimilar propagation environments on the performance of WSN has not been examined. In [59] and [60], the authors present a methodology to evaluate the performance of WSNs in sparse-tree, dense-tree, sand terrain, and artificial turf environments. Also, radio energy models have been developed for WSN deployment in sparse-tree, dense-tree, sand terrain, and artificial turf environments, respectively. The work presented in this dissertation extends the work in [59] and [60] by continuing the investigation of the impact of dissimilar propagation environments on the performance of WSNs and protocols. In combination with the presented work so far, this research has the possibility to significantly enhance the quality of results generated by simulations of the WSN operating in several outdoor environments.
2.8 Conclusion

In this chapter, some of the published articles regarding the accuracy of simulation-based results were reviewed. Some of these articles are related to WSN, while others are more generally related to simulation platforms and networks. Also, a discussion of several techniques for evaluating the performance of network and protocols were provided. Besides these techniques, this chapter discussed the LEACH protocol and its architecture and mechanism. In addition, several improved versions of LEACH were presented. A review of the most used network simulators was given. Also, an overview of the related published research on the performance of WSNs was discussed.
Chapter 3: Research Methodology

3.1 Introduction

This chapter aims to identify the procedure utilized for collecting, processing, and analyzing the generated results throughout this doctoral thesis. A wide range of topics is covered in this chapter such as utilized RF propagation models, comparison metrics, targeted environments, simulation setup, and the procedure of collecting, analyzing, and comparing the generated data. The goal of this study is to examine the influence of different propagation environments on the performance of WSNs and to develop accurate radio energy dissipation prediction models of WSNs deployed in dissimilar outdoor propagation environments. Additionally, it aims to develop a methodology for evaluating the performance of WSNs in various propagation environments. The LEACH protocol, which has not been evaluated in different propagation environments, has been chosen in order to test our proposed methodology. The motivation behind choosing the LEACH protocol is the claim of most of the researchers in the field that the LEACH protocol provides a good performance compared to the traditional WSN flat routing protocols.

The performance of the LEACH protocol in various propagation environments was evaluated using the developed radio energy models. Then, the results of each implementation were compared with the results generated using the existing radio energy models that were derived using free space and two-ray propagation models. The dissimilarities of the performance of the LEACH protocol
when using the developed radio energy models and the existing radio energy models were identified. Also, this study provides a methodology for investigating the accuracy of the existing physical layer modeling of network simulators.

The rest of this chapter is structured as follows. Section 3.2 provides details on the theoretical and empirical RF propagation models that were used to develop the radio energy models. Section 3.3 highlights the employed metrics of comparison. The network topology is provided in Section 3.4. Section 3.5 describes the simulated environments and simulation setup. Section 3.6 covers the process of analyzing and comparing the generated results. Section 3.7 concludes this chapter.

3.2 Utilized Propagation Models

Due to the difficulties involved in conducting real life experiments, simulation platforms are utilized very often. Among many other critical characteristics that have to be designed into simulation platforms, the RF propagation model has to be modeled precisely. It has a strong influence on the performance of WSNs such as in the performance of routing protocols. The RF propagation models utilized in wireless network simulators use simple channel propagation models that neglect some of propagation factors of different propagation environments. For example, the NS–3 simulator contains 11 different theoretical propagation models including a free space propagation model and two-ray model [61]. The free space propagation model and two-ray propagation model were used in this study as the theoretical propagation models.
3.2.1 Free Space Propagation Model

The free space propagation model is a theoretical RF propagation model, which is employed to anticipate received signal strength when there is a clear and unobstructed path between the transmitter and the receiver [62]. In FSPL, the strength of the signals decreases as a function of the distance that separates the transmitter and the receiver.

Since FSPL does not consider obstructions and reflections located between the transmitter and receiver, it is a very optimistic propagation model. In the applications of outdoor WSN, an obstruction that can be avoided in the propagation channel is the earth surface. Therefore, FSPL might not be considered a practical propagation model. The following equation is the Friis free space model that calculates the received power:

\[
P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}
\]

(3.1)

where:

- \(P_t\) is the transmitted power
- \(P_r\) is the received power
- \(d\) is the space separating the transmitter and receiver
- \(G_r\) is the gain of the receiver antenna
- \(G_t\) is the gain of the transmitter antenna
\( \lambda \) is the wave length

\( L \) is the losses of the system

The following equation is FSPL expressed in \( \text{dB} \):

\[
\text{PL[\text{dB}]} = 32.44 + 20\log(d) + 20\log(f)
\]  

(3.2)

where:

\( d \) is the distance in km

\( f \) is the carrier frequency in MHz

3.2.2 Two Ray Ground Reflection Model (Two-Ray)

It is uncommon in WSN to have one direct path that arrives at the receiver. Thus, considering only one direct path, as seen in the free space propagation model is inaccurate. In various outdoor terrains, there are two paths that exist between a transmitter and a receiver. The well-known Two-Ray Ground Reflection model takes into account two waves which are direct and ground-reflected waves. The two-ray propagation model assumes that the separating distance between the transmitting node and receiving node is much greater than antenna heights [62]. Moreover, it characterizes the ground as a flat conducting surface. Due to the unique properties of different grounds that rule the reflection of incident waves, a simplistic method leads to inaccurate predictions which are not reflected in most real-life scenarios [62]. The following equation is the Two-Ray model that calculates the path loss.
PL\left[\text{dB}\right] = 40\log (d) - 20\log \left( h_t \right) - 20\log \left( h_r \right) \quad (3.3)

where:

\( d \) is the separating distance between the transmitter and the receiver in meters

\( h_t \) is the height of the transmitting antenna in meters

\( h_r \) is height of the receiving antenna in meters

In this research, empirical RF propagation models that include all known and unknown propagation factors of different propagation environments were employed to determine the impact of various propagation environments on the performance of WSNs. Also, those accurate practical outdoor RF propagation models for WSN developed by WiCE were utilized in order to derive environment-specific radio energy models for several propagation environments. Those practical propagation models are discussed in the following subsection.

### 3.2.3 Utilized Outdoor Propagation Models

Propagation modeling is categorized into two types, empirical (statistical) and analytical (physical) methods. The empirical method is developed based on the collecting of in-field measurements of different propagation terrains. One of the advantages of the empirical method is that it takes into account all known and unknown propagation factors through real measurements [62]. Statistical models that have been developed by WiCE were utilized for deriving radio energy models
for WSNs deployed in various propagation environments. Each of these statistical models has been developed for a specific propagation environment. These statistical models representing seven different outdoor propagation environments of WSNs are discussed below.

### 3.2.3.1 Concrete Surface Environment

The empirical path loss model for the RF propagation of concrete surface terrain is given in the following equation [63]:

\[
L_p = 64.84 + 32.1 \log \left( \frac{d}{d_0} \right)
\]  

(3.4)

where:

- \( L_p \) is the path loss at a provided distance \( d \)
- \( d_0 \) is the reference distance in meters

### 3.2.3.2 Artificial Turf Environment

The empirical path loss model for the RF propagation of artificial turf terrain is given in the following equation [13]:

\[
L_p = 67.68 + 27.52 \log \left( \frac{d}{d_0} \right)
\]  

(3.5)
where:

\( L_p \) is the path loss at a provided distance \( d \)
\( d_0 \) is the reference distance in meters

### 3.2.3.3 Short Natural Grass Environment

The empirical path loss model for the RF propagation of short natural grass terrain is given in the following equation [64]:

\[
L_p = 57.97 + 29.6 \log \left( \frac{d}{d_0} \right)
\]  

(3.6)

where:

\( L_p \) is the path loss at a provided distance \( d \)
\( d_0 \) is the reference distance in meters

### 3.2.3.4 Long Natural Grass Environment

The empirical path loss model for the RF propagation of long natural grass terrain is given in the following equation [65]:

\[
L_p = 59.44 + 25.5 \log \left( \frac{d}{d_0} \right)
\]  

(3.7)
where:

\( L_p \) is the path loss at a provided distance \( d \)

\( d_0 \) is the reference distance in meters

### 3.2.3.5 Sand Environment

The empirical path loss model for the RF propagation of sand terrain is given in the following equation [66]:

\[
L_p = 60.97 + 34.2 \log \left( \frac{d}{d_0} \right) \tag{3.8}
\]

where:

\( L_p \) is the path loss at a provided distance \( d \)

\( d_0 \) is the reference distance in meters

### 3.2.3.6 Sparse Tree Environment

The empirical path loss model for the RF propagation of sparse tree terrain is given in the following equation [65]:

\[
L_p = 60.844 + 33.363 \log \left( \frac{d}{d_0} \right) \tag{3.9}
\]
where:

\( L_p \) is the path loss at a provided distance \( d \)

\( d_0 \) is the reference distance in meters

### 3.2.3.7 Dense Tree Environment

The empirical path loss model for the RF propagation of dense tree terrain is given in the following equation [67]:

\[
L_p = 52.14 + 40.2 \log \left( \frac{d}{d_0} \right)
\]  
\[ (3.10) \]

where:

\( L_p \) is the path loss at a provided distance \( d \)

\( d_0 \) is the reference distance in meters
3.3 Metrics of Comparison

The comparison metrics that were involved in this study for examining the impact of different propagation environments on the performance of WSNs and protocols are discussed below.

**Network lifetime:** prolonging the network lifetime is the primary target of most WSN protocols and a necessity for several WSN applications. Nevertheless, the definition of network lifetime differs in many published articles. Some authors have used the time until the first death of any node, while others have used the time of the death of a predefined percentage of nodes, or waited until the disconnection of the network. The network lifetime definition that was used in this study is the death of the first sensor node, which is the most commonly used criterion.

**Throughput:** Throughput is defined as the total number of packets successfully sent to the base station per unit of time. This contains the total data rate broadcasted over the network, which are forwarded by the cluster-heads toward the sink. Thus, knowing the throughput of the LEACH protocol in several propagation environments is necessary to evaluate the impact on the performance of WSNs.
3.4 Network Topology

The topology of WSN that was applied in this work is a grid with two dimensions where sensor nodes were placed at each intersection of the grid. Therefore, the distance between any two nodes is identical. Also, covering the sensing field can be managed easily by the usage of grid topology. Based on already known distances between any two nodes, the range of sensing and transmitting of each node can be regulated.

For the sake of providing a fair comparison between the results generated by MATLAB using existing radio energy models and the developed environment-specific radio energy models, all of the experimental settings throughout this study were identical. The setting of the simulated network in this work for all simulation experiments was a 10 x10 grid network as illustrated in Figure 3.1. The number of nodes in this network was 100 nodes plus the base station. The base station was positioned at location (x=50, y=175). The assumptions that were used throughout this work are that all nodes are equivalent in their abilities, having equivalent initial power, and the distance between nodes is consistent within the whole network. Also, various environmental propagation models discussed in Section 3.2.3 were employed to develop environment-specific radio energy models for WSNs deployed in several outdoor environments.
3.5 Simulation Experiments

Since a WSN is application-dependent, various applications might be deployed in several different environments. Thus, in order to have a broader understanding of the performance of WSNs, the LEACH protocol was simulated in seven different terrains. The radio energy models using free space and two-ray propagation models and one of the developed radio energy models using the empirical RF models reviewed in Section 3.2.3 were utilized in each experiment. For the purpose of having a fair comparison, the LEACH protocol was implemented in MATLAB using the existing radio energy models and the developed radio energy models under exactly the same conditions. The measurements of network lifetime and throughput were taken for every experiment. Also, an average of ten measurements was taken for every experiment.
The environments that have been examined can be categorized into two main classes, which are discussed below. Also, the simulation setup details are summarized in Table 3.1.

### 3.5.1 Deployment Environments

The performance of the LEACH protocol has been evaluated in seven different environments. The setting that was used in each simulated environment is identical to the presented setting in Section 3.4. The measurements of network lifetime and throughput were taken in each environment. The environments that have been examined can be categorized into two main classes.

#### 3.5.1.1 Open Space, Unobstructed Environments:

In this research, five terrains that are unobstructed, flat, and open space were targeted to examine their impact on the performance of a WSN. These terrains, which are artificial turf, sand terrain, long grass, short grass, and concrete surface, have dissimilar sorts of grounds. Since every ground has a different response to electromagnetic waves, it is essential to develop an environment-specific radio energy model that is derived based on the usage of an environment-specific RF propagation model. Additional environments might be included in future work.
3.5.1.2 Tree-obstructed Environments:

Since WSN is usually deployed in areas where there is an existence of obstructions, it is essential to observe the performance of WSNs deployed in areas where trees exist. Thus, two deployment scenarios where trees exist were included. The sparse tree and dense tree environments were thus part of this research.

The lifetime of the network and throughput were measured for every deployment scenario and then compared with the generated results using the existing radio energy models. Thus, the impact of various propagation environments on the performance of WSNs can be known. Moreover, having a better understanding of the behavior of the LEACH protocol in different outdoor environments can be achieved.

3.5.2 Simulation Setup

MATLAB was used to carry out experiments throughout this study. MATLAB was installed on a MacBook Pro laptop that has a processor of 2.6 GHz Intel Core i5 and a memory of 8 GB. Also, the implementation of the LEACH protocol that is explained in [15] was done based on the flowchart illustrated in Figure 3.2. The simulation setup details are summarized in Table 3.1.
Table 3.1: The set-up parameters of the simulated WSN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Rounds</td>
<td>10000 rounds</td>
</tr>
<tr>
<td>Number of Cluster-heads</td>
<td>5</td>
</tr>
<tr>
<td>Number of Sinks</td>
<td>1</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>100 nodes</td>
</tr>
<tr>
<td>Simulation Area</td>
<td>100 m x 100 m</td>
</tr>
<tr>
<td>Base Station Position</td>
<td>50 X 175</td>
</tr>
<tr>
<td>Packet Size</td>
<td>200 bytes</td>
</tr>
<tr>
<td>Data Rate</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Initial Energy</td>
<td>2 Joule</td>
</tr>
<tr>
<td>Antenna Height</td>
<td>5 centimeters</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>1925 MHz</td>
</tr>
<tr>
<td>KT</td>
<td>$4 \times 10^{-18}$ mW/Hz</td>
</tr>
<tr>
<td>Signal Bandwidth</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Receiver Noise Figure</td>
<td>10 dB</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>1.86 dB</td>
</tr>
<tr>
<td>Signal-Noise Ratio</td>
<td>10 dB</td>
</tr>
<tr>
<td>Topology</td>
<td>Grid</td>
</tr>
</tbody>
</table>
Figure 3.2: Flowchart of the distributed cluster formation algorithm for LEACH protocol

3.6 Procedure

The performance evaluation of WSNs has been done based on simulating the LEACH protocol in seven different propagation environments. Each empirical RF propagation model of each propagation environment has been employed in order to develop an accurate environment-specific radio energy model. Then, the LEACH protocol was implemented in MATLAB using both the existing radio energy
models derived based on the usage of theoretical propagation models and each of the developed radio energy models with identical setups and conditions. After the gathering of results, results were compared with each other. Then, the analysis of the results was made and demonstrated so that the differences in the performance of the LEACH protocol in various propagation environments can be identified. The following is a demonstration of the procedures of data collection and data comparison.

3.6.1 Theoretical Model Measurements

The LEACH protocol was implemented in MATLAB using the existing radio energy models developed based on the usage of theoretical propagation models. The network lifetime and total amount of data sent to the base station were measured. The generated results were used for comparison with the results of the developed models. Moreover, the outcomes generated by simulating the LEACH protocol under these scenarios are compared to the results produced by other implementations of the LEACH protocol using other empirical RF propagation models. Thus, the accuracy of using these theoretical propagation models to evaluate the performance of WSN can be validated. The simulation setting in these scenarios was 100 nodes distributed over a 10x10 grid network, including the sink node. The base station was positioned at location (x=50, y=175).
3.6.2 Practical Model Measurements

In order to know the impact of various propagation environments on the performance of WSNs, the empirical propagation models of various propagation environments that are discussed in Section 3.2.3 were utilized to develop radio energy models representing seven different outdoor propagation environments for a WSN. The LEACH protocol was simulated using each developed radio energy model. Then, the results of each implementation were compared with the generated results using the existing radio energy models. The network lifetime and the number of sent packets to the sink node were considered in every test. These comparisons are shown as a percentage of differences of network lifetime and total sent packets to the sink. In this test, the network sizes of all implementations were 10 x 10 nodes. Thus, the performance of the LEACH protocol in different propagation environments and how the performance of the LEACH protocol differs with different environment deployments can be recognized. Also, the influence of those propagation environments on WSN performance can be determined. Moreover, the accuracy of existing radio energy models that were developed using theoretical propagation models and utilized in most simulation platforms can be validated.
3.7 Conclusion

This chapter discussed the comparison metrics and simulation setup that were used for examining the influence of various propagation environments on WSN performance. In addition, the utilized RF propagation models and the targeted environments were discussed. Also, the procedure and techniques of carrying out the experiments of evaluating LEACH in different propagation environments were provided. The process of collecting, processing, and analyzing the data were presented.
Chapter 4: Development of Empirical Radio Energy Models

4.1 Introduction

This chapter derives the radio energy dissipation prediction models based on the usage of the empirical path loss models discussed in Section 3.2.3. Throughout this chapter, several radio energy dissipation prediction models have been developed for WSNs deployed in seven environments, namely sparse tree, concrete surface, sand terrain, long natural grass, short natural grass, artificial turf ground, and dense tree.

Much research has been done in the field of low-energy radios. Different protocols will have different advantages depending on different assumptions with regard to the characteristics of the radio, such as the amount of energy dissipated during transmission and reception. In this study, a model in which energy is dissipated by the transmitter and by both the power amplifier and receiver to run the radio electronics is assumed [68]. In order to transmit a message of l-bit for a distance d, the radio expenditure takes the following form:

\[ E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) \]  \hspace{1cm} (4.1)

and, in order to receive the message, the radio expenditure takes the following form:
\[ E_{Rx}(l) = E_{Rx-elec}(l) \]

\[ E_{Rx}(l) = lE_{elec} \quad (4.2) \]

Figure 4.1: Radio energy dissipation model

as illustrated in Figure 4.1. Among the factors upon which the electronics energy \( E_{elec} \) is dependent are digital coding, filtering of the signal prior to sending it to the transmit amplifier, and modulation. Also, the spreading of data during transmission and the correlating of data with the spreading code during reception consume electronics energy when utilizing DS-SS. The relationship between the path loss, the received power, and the transmit power is generally expressed by

\[ L_p[dB] = P_t[dBm] - P_t[dBm] + G_t[dB] + G_r[dB] \quad (4.3) \]
where:

$L_P$ is the path loss

$P_t$ is the transmitted power

$P_r$ is the received power

$G_r$ is the gain of the receiver antenna

$G_t$ is the gain of the transmitter antenna

Adjustment of the transmitted power is needed in order to maintain the power level higher than a set threshold $P_{r\text{-thresh}}$ at the receiver. Thus, the required sensitivity of the receiver and the noise figure of the receiver will determine the parameter $E_{\text{Tx-amp}}$. The minimum transmit power can be determined by working backwards from this threshold. If $R_b$ is the radio bitrate, the transmitted power, $P_t$, equals the transmitted energy per bit $E_{\text{Tx-amp}}(l,d)$ multiplied by the bitrate [69]:

$$P_t = E_{\text{Tx-amp}}(l,d)R_b$$  \hspace{1cm} (4.4)

In addition, the receiver threshold $P_{r\text{-thresh}}$ can be determined [70]:

$$P_{r\text{-thresh}}[\text{dBm}] = 10\log(KTB) + F[\text{dB}] + C/N[\text{dB}]$$  \hspace{1cm} (4.5)
where:

\[ K \] is Boltzmann's constant

\[ T \] is the absolute temperature expressed in K

\[ B \] is the bandwidth of the signal expressed in Hz

\[ F \] is the noise figure of the receiver

\[ C/N \] is the signal-to-noise ratio

For the rest of this chapter, Section 4.2 through Section 4.8 present the radio energy dissipation prediction models for the deployment environments being targeted in this dissertation. Section 4.9 concludes the chapter.

4.2 Artificial Turf Environment

In the artificial turf terrain, the transmitted power is attenuated in accordance with the empirical path loss model for the RF propagation of artificial turf terrain as follows:

By combining (3.5) and (4.3) one obtains:

\[
P_r[\text{dBm}] = P_t[\text{dBm}] + G_t[\text{dB}] + G_r[\text{dB}] - \left(67.68 + 27.52\log\left(\frac{d}{d_0}\right)\right) \quad (4.6)
\]

or

58
Simplifying (4.7):

\[
P_r = \frac{P_t * G_t * G_r}{0.1(67.68 + 27.5 \log(d))}
\]

(4.7)

As shown above, the distance that separates the transmitter and the receiver determines the attenuation of the power. The model for the propagation loss is inversely related to \(d^{2.75}\) for deploying a WSN in the artificial turf terrain. This loss may be inverted by using power control if the power amplifier is set appropriately, so that a particular power is assured at the receiver. Therefore, in order to transmit a message of \(l\)-bit for a distance \(d\) for a WSN deployed in the artificial turf environment, the radio would expend:

\[
E_{Tx}(l, d) = lE_{-\text{elec}} + lE_{\text{artificial_turf_amp}}d^{2.75}
\]

(4.9)

Substituting the value of \(E_{\text{Tx-amp}}(l, d)\) in (4.4), the transmitted power would be:

\[
P_t = E_{\text{artificial_turf_amp}}R_t d^{2.75}
\]

(4.10)
By combining (4.10) and (4.8), the received power would be:

\[ P_r = \frac{E_{\text{artificial\_turf\_amp}} \cdot R_b \cdot G_t \cdot G_r}{5.861 \cdot 10^6} \quad (4.11) \]

If the previous (4.11) is set equal to \( P_{r\text{-thresh}} \), the parameter \( E_{\text{artificial\_turf\_amp}} \) can be found:

\[ E_{\text{artificial\_turf\_amp}} = \frac{P_{r\text{-thresh}} \cdot 5.861 \cdot 10^6}{R_b \cdot G_t \cdot G_r} \quad (4.12) \]

Thus, the required transmitted power for a WSN deployed in the artificial turf environment, \( P_t \), as a function of the separation between the receiver and the transmitter and the receiver threshold is:

\[ P_t = \alpha \cdot P_{r\text{-thresh}} \cdot d^{2.75} \quad (4.13) \]

where \( \alpha = \frac{5.861 \cdot 10^6}{G_t \cdot G_r} \)
4.3 Concrete Surface Environment

In the concrete surface environment, the transmitted power is attenuated in accordance with the empirical path loss model for the RF propagation of the concrete surface environment as follows:

By combining (3.4) and (4.3) one obtains:

\[
\begin{align*}
P_T[\text{dBm}] &= P_t[\text{dBm}] + G_t[\text{dB}] + G_r[\text{dB}] - \left(64.84 + 32.1 \log\left(\frac{d}{d_0}\right)\right) \quad (4.14) \\
\text{or} \\
P_T &= \frac{P_t \cdot G_t \cdot G_r}{10^{0.1 \left(64.84 + 32.1 \log(d)\right)}} \quad (4.15) \\
\end{align*}
\]

Simplifying (4.15):

\[
P_T = \frac{P_t \cdot G_t \cdot G_r}{3.047 \cdot 10^6 \cdot d^{3.21}} \quad (4.16)
\]

As shown above, the distance that separates the transmitter and the receiver determines the attenuation of the power. The model for the propagation loss is inversely related to \(d^{3.21}\) for deploying a WSN in the concrete surface environment. This loss may be inverted by using power control if the power amplifier is set appropriately, so that a particular power is assured at the receiver.
Therefore, in order to transmit a message of l-bit for a distance d for a WSN the deployed in concrete surface environment, the radio would expend:

$$E_{Tx}(l, d) = lE_{Tx-elec} + lE_{concrete_amp}d^{3.21} \tag{4.17}$$

Substituting the value of $E_{Tx-amp}(l, d)$ in (4.4), the transmitted power would be:

$$P_t = E_{concrete_amp}R_b d^{3.21} \tag{4.18}$$

By combining (4.18) and (4.16), the received power would be:

$$P_r = \frac{E_{concrete_amp}R_b G_t G_r}{3.047 \times 10^6} \tag{4.19}$$

If the previous (4.19) is set equal to $P_{r-thresh}$, the parameter $E_{concrete_amp}$ can be found:

$$E_{concrete_amp} = \frac{P_{r-thresh} \times 3.047 \times 10^6}{R_b G_t G_r} \tag{4.20}$$
Thus, the required transmitted power for a WSN deployed in the concrete surface environment, $P_t$, as a function of the separation between the receiver and the transmitter and the receiver threshold is:

$$P_t = \alpha^*P_{r-thresh}^*d^{3.21}$$

(4.21)

where $\alpha = \frac{3.047 * 10^6}{G_t * G_r}$
4.4 Short Natural Grass Environment

In the short grass environment, the transmitted power is attenuated in accordance with the empirical path loss model for the RF propagation of the short grass environment as follows:

By combining (3.6) and (4.3) one obtains:

$$P_r[\text{dBm}] = P_t[\text{dBm}] + G_t[\text{dB}] + G_r[\text{dB}] - \left( 57.97 + 29.6 \log \left( \frac{d}{d_0} \right) \right)$$

or

$$P_r = \frac{P_t \cdot G_t \cdot G_r}{10^{\left( 0.1 \cdot \left( 57.97 + 29.6 \log(d) \right) \right) / 10}}$$

Simplifying (4.23):

$$P_r = \frac{P_t \cdot G_t \cdot G_r}{0.626 \cdot 10^6 \cdot d^{2.96}}$$

As shown above, the distance that separates the transmitter and the receiver determines the attenuation of the power. The model for the propagation loss is inversely related to $d^{2.96}$ for deploying a WSN in the short grass environment. This loss may be inverted by using power control if the power amplifier is set appropriately, so that a particular power is assured at the receiver. Therefore, in
order to transmit a message of l-bit for a distance d for a WSN deployed in the short grass environment, the radio would expend:

\[ E_{\text{Tx}}(l, d) = lE_{\text{Tx-elec}} + lE_{\text{short_grass_amp}}d^{2.96} \]  \hspace{1cm} (4.25)

Substituting the value of \( E_{\text{Tx-amp}}(l, d) \) in (4.4), the transmitted power would be:

\[ P_t = E_{\text{short_grass_amp}}R_b d^{2.96} \]  \hspace{1cm} (4.26)

By combining (4.26) and (4.24), the received power would be:

\[ P_r = \frac{E_{\text{short_grass_amp}}R_b G_t G_r}{0.626 \times 10^6} \]  \hspace{1cm} (4.27)

If the previous (4.27) is set equal to \( P_{r\text{-thresh}} \), the parameter \( E_{\text{short_grass_amp}} \) can be found:

\[ E_{\text{short_grass_amp}} = \frac{P_{r\text{-thresh}}0.626 \times 10^6}{R_b G_t G_r} \]  \hspace{1cm} (4.28)
Thus, the required transmitted power for a WSN deployed in the short grass environment, $P_t$, as a function of the separation between the receiver and the transmitter and the receiver threshold is:

$$P_t = \alpha^{*P_{\text{r-thresh}}} * d^{2.96}$$

(4.29)

Where $\alpha = \frac{0.626 * 10^6}{G_t * G_r}$
4.5 Long Natural Grass Environment

In the long grass environment, the transmitted power is attenuated in accordance with the empirical path loss model for the RF propagation of the long grass environment as follows:

By combining (3.7) and (4.3) one obtains:

\[ P_r[dBm] = P_t[dBm] + G_t[dB] + G_r[dB] - \left( 59.44 + 25.5 \log\left( \frac{d}{d_0} \right) \right) \]  \hspace{1cm} (4.30)

or

\[ P_r = \frac{P_t \cdot G_t \cdot G_r}{0.1 \cdot (59.44 + 25.5 \log(d))} \]  \hspace{1cm} (4.31)

Simplifying (4.31):

\[ P_r = \frac{P_t \cdot G_t \cdot G_r}{0.879 \cdot 10^6 \cdot d^{2.55}} \]  \hspace{1cm} (4.32)

As shown above, the distance that separates the transmitter and the receiver determines the attenuation of the power. The model for the propagation loss is inversely related to \( d^{2.55} \) for deploying a WSN in the long grass environment. This loss may be inverted by using power control if the power amplifier is set appropriately, so that a particular power is assured at the receiver. Therefore, in
order to transmit a message of $1$-bit for a distance $d$ for a WSN deployed in the long
grass environment, the radio would expend:

$$E_{Tx}(l, d) = lE_{Tx-elec} + lE_{long\_grass\_amp}d^{2.55} \quad (4.33)$$

Substituting the value of $E_{Tx-amp}(l, d)$ in (4.4), the transmitted power
would be:

$$P_t = E_{long\_grass\_amp}R_b d^{2.55} \quad (4.34)$$

By combining (4.34) and (4.32), the received power would be:

$$P_r = \frac{E_{long\_grass\_amp}R_b G_t G_r}{0.879 \times 10^6} \quad (4.35)$$

If the previous (4.35) is set equal to $P_{r-thresh}$, the parameter
$E_{long\_grass\_amp}$ can be found:

$$E_{long\_grass\_amp} = \frac{P_{r-thresh} \times 0.879 \times 10^6}{R_b G_t G_r} \quad (4.36)$$
Thus, the required transmitted power for a WSN deployed in the long grass environment, $P_t$, as a function of the separation between the receiver and the transmitter and the receiver threshold is:

$$P_t = \alpha P_{\text{r-thresh}} d^{2.55}$$

where $\alpha = \frac{0.879 \times 10^6}{G_t \cdot G_r}$
4.6 Sand Terrain Environment

In the sand terrain environment, the transmitted power is attenuated in accordance with the empirical path loss model for the RF propagation of the sand terrain environment as follows:

By combining (3.8) and (4.3) one obtains:

\[
P_r [\text{dBm}] = P_t [\text{dBm}] + G_t [\text{dB}] + G_r [\text{dB}] - \left( 60.97 + 34.2 \log \left( \frac{d}{d_0} \right) \right) \quad (4.38)
\]

or

\[
P_r = \frac{P_t * G_t * G_r}{10^{(60.97 + 34.2 \log(d))/10}} \quad (4.39)
\]

Simplifying (4.39):

\[
P_r = \frac{P_t * G_t * G_r}{1.250 \times 10^6 \times d^{3.42}} \quad (4.40)
\]

As shown above, the distance that separates the transmitter and the receiver determines the attenuation of the power. The model for the propagation loss is inversely related to \(d^{3.42}\) for deploying a WSN in the sand terrain environment. This loss may be inverted by using power control if the power amplifier is set appropriately, so that a particular power is assured at the receiver. Therefore, in
order to transmit a message of l-bit for a distance d for a WSN deployed in the sand terrain environment, the radio would expend:

$$E_{Tx}(l, d) = \|E_{Tx-elec} + \|E_{\text{sand\_terrain\_amp}}d^{3.42}$$ (4.41)

Substituting the value of $E_{Tx-amp}(l, d)$ in (4.4), the transmitted power would be:

$$P_t = E_{\text{sand\_terrain\_amp}}R_b d^{3.42}$$ (4.42)

By combining (4.42) and (4.40), the received power would be:

$$P_r = \frac{E_{\text{sand\_terrain\_amp}} * R_b * G_t * G_r}{1.250 \times 10^6}$$ (4.43)

If the previous (4.43) is set equal to $P_r\text{-thresh}$, the parameter $E_{\text{sand\_terrain\_amp}}$ can be found:

$$E_{\text{sand\_terrain\_amp}} = \frac{P_r\text{-thresh} * 1.250 \times 10^6}{R_b * G_t * G_r}$$ (4.44)
Thus, the required transmitted power for a WSN deployed in the sand terrain environment, $P_t$, as a function of the separation between the receiver and the transmitter and the receiver threshold is:

$$P_t = \alpha P_{r-thresh} \cdot d^{3.42}$$

where $\alpha = \frac{1.250 \cdot 10^6}{G_t \cdot G_r}$
4.7 Sparse Tree Environment

In the sparse tree environment, the transmitted power is attenuated in accordance with the empirical path loss model for the RF propagation of the sparse tree environment as follows:

By combining (3.9) and (4.3) one obtains:

$$P_r[dBm] = P_t[dBm] + G_t[dB] + G_r[dB] - \left(60.844 + 33.363 \log \left(\frac{d}{d_0}\right)\right)$$  (4.46)

or

$$P_r = \frac{P_t \cdot G_t \cdot G_r}{10^{0.1(60.844 + 33.363 \log(d))}}$$  (4.47)

Simplifying (4.47):

$$P_r = \frac{P_t \cdot G_t \cdot G_r}{1.21 \cdot 10^6 \cdot d^{3.33}}$$  (4.48)

As shown above, the distance that separates the transmitter and the receiver determines the attenuation of the power. The model for the propagation loss is inversely related to $d^{3.33}$ for deploying a WSN in the sparse tree environment. This loss may be inverted by using power control if the power amplifier is set appropriately, so that a particular power is assured at the receiver. Therefore, in
order to transmit a message of l-bit for a distance d for a WSN deployed in the sparse tree environment, the radio would expend:

$$E_{Tx}(l, d) = lE_{Tx-elec} + lE_{sparse\_tree\_amp}d^{3.33}$$

(4.49)

Substituting the value of \(E_{Tx-amp}(l, d)\) in (4.4), the transmitted power would be:

$$P_t = E_{sparse\_tree\_amp}R_b^{d^{3.33}}$$

(4.50)

By combining (4.50) and (4.48), the received power would be:

$$P_r = \frac{E_{sparse\_tree\_amp}R_bG_tG_r}{1.21 \times 10^6}$$

(4.51)

If the previous (4.51) is set equal to \(P_{r-thresh}\), the parameter \(E_{sparse\_tree\_amp}\) can be found:

$$E_{sparse\_tree\_amp} = \frac{P_{r-thresh} \times 1.21 \times 10^6}{R_bG_tG_r}$$

(4.52)
Thus, the required transmitted power for a WSN deployed in the sparse tree environment, $P_t$, as a function of the separation between the receiver and the transmitter and the receiver threshold is:

$$P_t = \alpha P_{r-thresh} d^{3.33}$$

(4.53)

where $\alpha = \frac{1.21 \times 10^6}{G_t G_r}$
4.8 Dense Tree Environment

In the dense tree environment, the transmitted power is attenuated in accordance with the empirical path loss model for the RF propagation of the dense tree environment as follows:

By combining (3.10) and (4.3) one obtains:

\[
P_T[dBm] = P_t[dBm] + G_t[dB] + G_r[dB] - \left(52.14 + 40.2 \log\left(\frac{d}{d_0}\right)\right) \quad (4.54)
\]

or

\[
P_r = \frac{P_t \cdot G_t \cdot G_r}{10 \left(52.14 + 40.2 \log(d)\right)} \quad (4.55)
\]

Simplifying (4.55):

\[
P_r = \frac{P_t \cdot G_t \cdot G_r}{0.163 \cdot 10^6 \cdot d^{4.02}} \quad (4.56)
\]

As shown above, the distance that separates the transmitter and the receiver determines the attenuation of the power. The model for the propagation loss is inversely related to \(d^{4.02}\) for deploying a WSN in the dense tree environment. This loss may be inverted by using power control if the power amplifier is set appropriately, so that a particular power is assured at the receiver. Therefore, in
order to transmit a message of l-bit for a distance d for a WSN deployed in the dense tree environment, the radio would expend:

$$E_{Tx}(l,d) = I_{Tx-elec} + I_{\text{dense}_\text{tree}_\text{amp}} d^{4.02}$$  \hspace{1cm} (4.57)

Substituting the value of \(E_{\text{Tx-amp}}(l,d)\) in (4.4), the transmitted power would be:

$$P_t = E_{\text{dense}_\text{tree}_\text{amp}} R_b d^{4.02}$$  \hspace{1cm} (4.58)

By combining (4.58) and (4.56), the received power would be:

$$P_r = \frac{E_{\text{dense}_\text{tree}_\text{amp}} * R_b * G_t * G_r}{0.163 * 10^6}$$  \hspace{1cm} (4.59)

If the previous (4.59) is set equal to \(P_r\text{-thresh}\), the parameter \(E_{\text{dense}_\text{tree}_\text{amp}}\) can be found:

$$E_{\text{dense}_\text{tree}_\text{amp}} = \frac{P_r\text{-thresh} * 0.163 * 10^6}{R_b * G_t * G_r}$$  \hspace{1cm} (4.60)
Thus, the required transmitted power for a WSN deployed in the dense tree environment, $P_t$, as a function of the separation between the receiver and the transmitter and the receiver threshold is:

$$P_t = \alpha \cdot P_{\text{r-thresh}} \cdot d^{4.02}$$  \hspace{1cm} (4.61)

where $\alpha = \frac{0.163 \times 10^6}{G_t \cdot G_r}$
4.9 Conclusion

This chapter derived the radio energy dissipation prediction models based on the usage of the empirical path loss models discussed in Section 3.2.3. These radio energy models were utilized for the simulations provided in this work to determine the impact of different propagation models on the performance of WSNs. Throughout this chapter, several radio energy dissipation prediction models were developed for WSNs deployed in seven environments, namely sparse tree, concrete surface, sand terrain, long natural grass, short natural grass, artificial turf ground, and dense tree.
Chapter 5: Experimental Results

5.1 Introduction

This chapter presents the results of simulating WSNs using the developed radio energy dissipation prediction models presented in Chapter 4. The results of simulating WSNs using the existing radio energy models is also presented. Throughout this chapter, the generated results are provided using several radio energy models derived from the usage of free space, two-ray, sparse tree, concrete surface, sand terrain, long natural grass, short natural grass, artificial turf ground, and dense tree propagation models.

The investigating of the impact of different propagation environments on the performance of WSNs was done based on simulating the LEACH protocol using the developed radio energy dissipation prediction models for WSNs deployed in seven different propagation environments. Also, the LEACH protocol was implemented in MATLAB using the existing radio energy models utilizing the free space and two-ray propagation models with identical setups and conditions. Once more, the LEACH protocol has been implemented in these experiments according to [15]. The comparison metrics that were involved in this study are the lifetime of the network and the network throughput. The network lifetime definition that was used in this study is the death of the first sensor node, while the throughput is defined as the total number of packets successfully sent to the base station node. An average of ten measurements was taken for every experiment. Simulating the
LEACH protocol using several radio energy models showed a significant change in the network lifetime and throughput.

In the experiments performed to support this work, the energy to be dissipated per each bit in the transceiver electronics is set to be 50 nJ/bit in the 1 Mbps transceiver used. Thus, 50 mW are dissipated by the radio electronics during operation, whether transmitting or receiving. Also, the receiver threshold \( P_{r-thresh} \) can be determined if estimates for the receiver noise are used. For successful reception, a minimum receiver power \( P_{r-thresh} \) must be larger or equal to -94 dBm when the thermal noise floor is 114 dBm [70] and the noise figure of the receiver is 10 dB, and the required signal-noise ratio (SNR) is a minimum of 10 dB in order to receive an error-free signal:

\[
P_{r-thresh} \geq 20 + (-114) = -94 \text{ dBm}
\]

Consequently, in order to successfully receive the packet a minimum of -94 dBm or 0.000398 nW of received power is necessary.

For the rest of this chapter, Section 5.2 through Section 5.10 present the generated results using several radio energy models derived from the usage of free space, two-ray, sparse tree, concrete surface, sand terrain, long natural grass, short natural grass, artificial turf ground, and dense tree propagation models. Section 5.11 concludes the chapter.
5.2 Free Space Propagation Model

In [69], the radio energy model using the free space propagation model was derived and energy dissipation of the radio transmitter amplifier was calculated using the same parameters used in this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

\[ E_{\text{friss amp}} = 1.10 \text{ fJ/bit/} \ d^2 \]  \hspace{1cm} (5.2)

In all iterations of this experiment, the free space propagation model is used as the standard against which to compare each of the empirical propagation models to examine the adequacy of this theoretical propagation model in evaluating the performance of a WSN in different propagation environments.

The first death of the network members using the free space propagation model was at round 4152. Figure 5.1 illustrates the lifetime result of implementing the LEACH protocol using the free space propagation model. The number of packets successfully sent to the sink node was 73758. Figure 5.2 demonstrates the throughput result of implementing the LEACH protocol using the free space propagation model.
Figure 5.1: Lifetime result using free space propagation model

Figure 5.2: Throughput result using free space propagation model
5.3 Two Ray Ground Reflection Model (Two-Ray)

In [69], the radio energy model using the two-ray propagation model was derived and energy dissipation of the radio transmitter amplifier was calculated using the same parameters used in this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

\[ E_{\text{two-ray\_amp}} = 0.027 \text{ pJ/\text{bit} \ d^4} \] (5.3)

In all iterations of this experiment, the two-ray propagation model is used as the standard against which to compare each of the empirical propagation models to examine the adequacy of this theoretical propagation model in evaluating the performance of WSNs in different propagation environments.

The first death of the network members using the two-ray propagation model was at round 69. Figure 5.3 illustrates the lifetime result of implementing the LEACH protocol using the two-ray propagation model. The number of packets successfully sent to the sink node was 1135. Figure 5.4 demonstrates the throughput result of implementing the LEACH protocol using the two-ray propagation model.
Figure 5.3: Lifetime result using two-ray propagation model

Figure 5.4: Throughput result using two-ray propagation model
5.4 Artificial Turf Environment

In [60], the radio energy model using the artificial turf propagation model was derived and energy dissipation of the radio transmitter amplifier was calculated using the same parameters used in this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

$$E_{\text{artificial\_turf\_amp}} = 0.9915 \ \text{pJ/bit/} \ d^{2.75}$$  \hspace{1cm} (5.4)

The first death of the network members using the artificial turf propagation model was at round 1041. Figure 5.5 illustrates the lifetime result of implementing the LEACH protocol using the artificial turf propagation model. The number of packets successfully sent to the sink node was 18560. Figure 5.6 demonstrates the throughput result of implementing the LEACH protocol using the artificial turf propagation model.
Figure 5.5: Lifetime result using artificial turf propagation model

Figure 5.6: Throughput result using artificial turf propagation model
5.5 Concrete Surface Environment

In Section 4.3, the radio energy model using the concrete surface propagation model was derived. The energy dissipation of the radio transmitter amplifier was calculated using the same parameters used throughout this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

\[ E_{\text{concrete_amp}} = 0.5154 \text{ pJ/bit/} d^{3.21} \]  

(5.5)

The first death of the network members using the concrete surface propagation model was at round 207. Figure 5.7 illustrates the lifetime result of implementing the LEACH protocol using the concrete surface propagation model. The number of packets successfully sent to the sink node was 3601. Figure 5.8 demonstrates the throughput result of implementing the LEACH protocol using the concrete surface propagation model.
Figure 5.7: Lifetime result using concrete surface propagation model

Figure 5.8: Throughput result using concrete surface propagation model
5.6 Short Natural Grass Environment

In Section 4.4, the radio energy model using the short grass propagation model was derived. The energy dissipation of the radio transmitter amplifier was calculated using the same parameters throughout this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

\[ E_{\text{short\_grass\_amp}} = 0.1059 \text{ pJ/bit/ } d^{2.96} \]  

(5.6)

The first death of the network members using the short grass propagation model was at round 2343. Figure 5.9 illustrates the lifetime result of implementing the LEACH protocol using the short grass propagation model. The number of packets successfully sent to the sink node was 41823. Figure 5.10 demonstrates the throughput result of implementing the LEACH protocol using the short grass propagation model.
Figure 5.9: Lifetime result using short grass propagation model

Figure 5.10: Throughput result using short grass propagation model
5.7 Long Natural Grass Environment

In Section 4.5, the radio energy model using the long grass propagation model was derived. The energy dissipation of the radio transmitter amplifier was calculated using the same parameters used throughout this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

$$E_{\text{long\_grass\_amp}} = 0.1487 \text{ pJ/bit/} d^{2.55} \tag{5.7}$$

The first death of the network members using the long grass propagation model was at round 3729. Figure 5.11 illustrates the lifetime result of implementing the LEACH protocol using the long grass propagation model. The number of packets successfully sent to the sink node was 66435. Figure 5.12 demonstrates the throughput result of implementing the LEACH protocol using the long grass propagation model.
**Figure 5.11**: Lifetime result using long grass propagation model

**Figure 5.12**: Throughput result using long grass propagation model
5.8 Sand Terrain Environment

In [60], the radio energy model using the sand terrain propagation model was derived and energy dissipation of the radio transmitter amplifier was calculated using the same parameters used in this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

\[
E_{\text{sand\_terrain\_amp}} = 0.2114 \text{ pJ/bit/} d^{3.42} \tag{5.8}
\]

The first death of the network members using the sand terrain propagation model was at round 172. Figure 5.13 illustrates the lifetime result of implementing the LEACH protocol using the sand terrain propagation model. The number of packets successfully sent to the sink node was 2947. Figure 5.14 demonstrates the throughput result of implementing the LEACH protocol using the sand terrain propagation model.
Figure 5.13: Lifetime result using sand terrain propagation model

Figure 5.14: Throughput result using sand terrain propagation model
5.9 Sparse Tree Environment

In [59], the radio energy model using the sparse tree propagation model was derived and energy dissipation of the radio transmitter amplifier was calculated using the same parameters used in this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

\[ E_{\text{sparse_tree_amp}} = 0.2047 \text{ pJ/bit/} \ d^{3.33} \]  \hspace{1cm} (5.9)

The first death of the network members using the sparse tree propagation model was at round 270. Figure 5.15 illustrates the lifetime result of implementing the LEACH protocol using the sparse tree propagation model. The number of packets successfully sent to the sink node was 4748. Figure 5.16 demonstrates the throughput result of implementing the LEACH protocol using the sparse tree propagation model.
Figure 5.15: Lifetime result using sparse tree terrain propagation model

Figure 5.16: Throughput result using sparse tree terrain propagation model
5.10 Dense Tree Environment

In [59], the radio energy model using the dense tree propagation model was derived and energy dissipation of the radio transmitter amplifier was calculated using the same parameters used in this dissertation. Thus, the energy dissipation of the radio transmitter amplifier would be:

\[
E_{\text{dense\_tree\_amp}} = 0.0275 \text{ pJ/} \text{bit/ } d^{4.02}
\]  \hspace{1cm} (5.10)

The first death of the network members using the dense tree propagation model was at round 57. Figure 5.17 illustrates the lifetime result of implementing the LEACH protocol using the dense tree propagation model. The number of packets successfully sent to the sink node was 971. Figure 5.18 demonstrates the throughput result of implementing the LEACH protocol using the dense tree propagation model.
Figure 5.17: Lifetime result using dense tree terrain propagation model

Figure 5.18: Throughput result using dense tree terrain propagation model
5.11 Conclusion

The results of simulating WSNs using the developed radio energy dissipation prediction models presented in Chapter 4 have been presented in this chapter. Also, the results of simulating WSNs using the existing radio energy models have been provided. These results represent nine radio energy models derived based on the usage of free space, two-ray, sparse tree, concrete surface, sand terrain, long natural grass, short natural grass, artificial turf ground, and dense tree propagation models. In Chapter 6, discussions and analysis of the generated results are provided. In addition, comparisons between the generated results are given.
Chapter 6: Results Discussion

6.1 Introduction

The outdoor deployment scenarios for WSNs that have been simulated in this work have significant differences in their lifetime and throughput. Five of these simulated environments are unobstructed (i.e., sand terrain, concrete surface, long natural grass, short natural grass, and artificial turf), while two of them comprise obstructions (i.e., dense tree and sparse tree environments). This chapter discusses the physical influences of each environment on the performance of WSNs by discussing the parameters of the utilized empirical RF propagation models. Following are discussions of the results of each simulated environment. Additionally, the predicted network lifetime and throughput by the developed radio energy models and commonly used radio energy models are compared. Also, statistical methods are utilized to demonstrate the differences in WSN performance when using the developed radio energy models and commonly used radio energy models.

This chapter is structured as follows: In Section 6.2 through Section 6.8, discussions of generated results using the developed radio energy models are provided. Illustrations of the developed radio energy models and summary of the findings are presented in Section 6.9. Meanwhile, Section 6.10 compares the developed radio energy models with existing radio energy models using theoretical models. Finally, Section 6.11 concludes this chapter.
6.2 Artificial Turf Environment

In the artificial turf environment, the lifetime of the simulated WSN lasted for 1041 rounds before the first death of the network members, whereas the first death of the network members when using the free space propagation model was at round 4152 and at round 69 when using the two-ray propagation model. This is because of the path loss exponent (PLE) value of the artificial turf propagation environment that is smaller than that of the two-ray propagation model and larger than that of the free space propagation model. The PLE value in the artificial turf environment is 2.75, while it is equal to 2 in the free space propagation model and 4 in the two-ray propagation model.

In the artificial turf terrain, where there are no obstacles between the transmitting node and the receiving node, the transmitting node and the receiving node always have a LOS propagation [64]. However, the RSS is frequently influenced by multipath fading, which is caused mainly by waves that reflect from the ground. Furthermore, the electrical characteristics of artificial turf ground are dissimilar to the other propagation environments being examined in this study. This means that the ground reflected part differed in these examined environments. Since the PLE value of the artificial turf terrain is lower than that of the two-ray propagation model, the RSS is always stronger, making the transmitting node battery drain slower and thus prolonging network lifetime with larger throughput.
A comparison of the generated results using artificial turf, free space, and two-ray propagation models is shown in Figure 6.1 and Figure 6.2. Comparing the generated results with the results using free space and two-ray propagation models demonstrates the inadequacy of using these theoretical propagation models in evaluating the performance of a WSN in the artificial turf propagation environment.

**Figure 6.1**: Lifetime comparison between the results using artificial turf, free space, and two-ray propagation models

**Figure 6.2**: Throughput comparison between the results using artificial turf, free space, and two-ray propagation models
6.3 Concrete Surface Environment

In the concrete surface environment, the lifetime of the simulated WSN lasted for 207 rounds before the first death of the network members, whereas the first death of the network members when using the free space propagation model was at round 4152 and at round 69 when using the two-ray propagation model. This is because of the path loss exponent (PLE) value of the concrete surface propagation environment that is smaller than that of the two-ray propagation model and larger than that of the free space propagation model. The PLE value in the concrete surface environment is 3.21, while it is equal to 2 in the free space propagation model and 4 in the two-ray propagation model.

The concrete surface environment has the second shortest network lifetime among the five unobstructed environments. In this environment, there are two signal paths existing between the transmitting node and receiving node [64]. However, the PLE value in the concrete surface environment is higher than in the previous environment because of the greater ground reflection coefficient than that for the artificial turf environment. Since the PLE value of the concrete surface environment is larger than that of the artificial turf and free space propagation models, the RSS is always weaker, making the battery of the transmitting node drain faster, which in turn results in a shorter lifetime of the network with smaller throughput.

A comparison of the generated results using concrete surface, free space, and
two-ray propagation models is shown in Figure 6.3 and Figure 6.4. Therefore, comparing the generated results with the results using free space and two-ray propagation models demonstrated the inadequacy of using these theoretical propagation models in evaluating the performance of a WSN in the concrete surface propagation environment.

**Figure 6.3**: Lifetime comparison between the results using concrete, free space, and two-ray propagation models

**Figure 6.4**: Throughput comparison between the results using concrete, free space, and two-ray propagation models
6.4 Short Natural Grass Environment

In the short grass environment, the lifetime of the simulated WSN lasted for 2343 rounds before the first death of the network members, whereas the first death of the network members when using the free space propagation model was at round 4152 and at round 69 when using the two-ray propagation model. This is because of the path loss exponent (PLE) value of the short grass propagation environment that is smaller than that of the two-ray propagation model and larger than that of free space propagation model. The PLE value in the short grass environment is 2.96, while it is equal to 2 in the free space propagation model and 4 in the two-ray propagation model.

The short grass environment has the second longest network lifetime among the seven environments being examined in this work. This environment is similar to the two preceding environments in the sense that there are two waves existing between the transmitting node and receiving node [64]. However, the PLE value in the short grass environment is different than the previous environments because of the dissimilar ground reflection coefficient among these propagation environments. Since the PLE value of the short grass environment is larger than that of the artificial turf and free space propagation models, the RSS is always weaker, making the battery of the transmitting node drain faster, which in turn results in a shorter lifetime of the network with smaller throughput.
A comparison of the generated results using short grass, free space, and two-ray propagation models is shown in Figure 6.5 and Figure 6.6. Therefore, comparing the generated results with the results using free space and two-ray propagation models demonstrated the inadequacy of using these theoretical propagation models in evaluating the performance of a WSN in the short grass propagation environment.

**Figure 6.5:** Lifetime comparison between the results using short grass, free space, and two-ray propagation models

**Figure 6.6:** Throughput comparison between the results using short grass, free space, and two-ray propagation models
6.5 Long Natural Grass Environment

In the long grass environment, the lifetime of the simulated WSN lasted for 3729 rounds before the first death of the network members, whereas the first death of the network members when using the free space propagation model was at round 4152 and at round 69 when using the two-ray propagation model. This is because of the path loss exponent (PLE) value of the long grass propagation environment that is smaller than that of the two-ray propagation model and larger than that of free space propagation model. The PLE value in the long grass environment is 2.55, while it is equal to 2 in the free space propagation model and 4 in the two-ray propagation model. This environment has the lowest PLE value among the seven outdoor environments being studied in this work.

The long grass environment has the longest network lifetime among the seven environments being examined in this work. The WSN lifetime in this environment is the closest to the WSN lifetime when using the free space propagation model. Also, the PLE of this environment is the closest one to the PLE of the free space propagation model. This is due to the fact that the length of long weeds is similar to the length of the antennas of the transmitting and receiving nodes [64]. Thus, reflected rays are prevented from arriving at the receiving node which allows only direct communication between the transmitting and receiving nodes. Since the PLE value of the long grass environment is lower than that of the artificial turf, short grass, concrete surface, and two-ray propagation models, the RSS is always stronger, making the battery of the transmitting node drain slower,
which in turn results in a longer network lifetime and larger throughput.

A comparison of the generated results using long grass, free space, and two-ray propagation models is shown in Figure 6.7 and Figure 6.8. Therefore, comparing the generated results with the results using free space and two-ray propagation models demonstrated the inadequacy of using these theoretical propagation models in evaluating the performance of a WSN in the long grass propagation environment.

**Figure 6.7:** Lifetime comparison between the results using long grass, free space, and two-ray propagation models
In the sand terrain environment, the lifetime of the simulated WSN lasted for 172 rounds before the first death of the network members, whereas the first death of the network members when using the free space propagation model was at round 4152 and at round 69 when using the two-ray propagation model. This is because of the path loss exponent (PLE) value of the sand terrain environment that is smaller than that of the two-ray propagation model and larger than that of the free space propagation model. The PLE value in sand terrain environment is 3.42, while it is equal to 2 in the free space propagation model and 4 in the two-ray propagation model.

The sand terrain environment has the second shortest network lifetime among the seven environments being examined in this work. In the sand terrain environment, there is always a line of sight (LOS) between the transmitting node
and the receiving node [64], but the received signal strength (RSS) is often influenced by a large number of ground reflected waves, which are caused by the corrugated and uneven surface of the sand terrain. This could be the cause of the higher PLE value for the sand terrain than that of the artificial turf, concrete surface, short grass, long grass and free space propagation models. Therefore, the RSS becomes weaker, which makes the battery of the transmitting node drain faster, which in turn results in a shorter network lifetime and smaller throughput.

A comparison of the generated results using sand terrain, free space, and two-ray propagation models is shown in Figure 6.9 and Figure 6.10. Therefore, comparing the generated results with the results using free space and two-ray propagation models demonstrated the inadequacy of using these theoretical propagation models in evaluating the performance of a WSN in the sand terrain propagation environment.

Figure 6.9: Lifetime comparison between the results using sand terrain, free space, and two-ray propagation models
Sparse Tree Environment

In the sparse tree environment, the lifetime of the simulated WSN lasted for 270 rounds before the first death of the network members, whereas the first death of the network members when using the free space propagation model was at round 4152 and at round 69 when using the two-ray propagation model. This is because of the path loss exponent (PLE) value of the sparse tree environment propagation environment that is smaller than that of the two-ray propagation model and larger than that of free space propagation model. The PLE value in the sparse tree environment is 3.33, while it is equal to 2 in the free space propagation model and 4 in the two-ray propagation model.

In the sparse tree environment, the transmitting and receiving nodes do not always have line of sight propagation. This means that the communication between the transmitter and the receiver could be LOS or non-line of sight (NLOS) [64].

**Figure 6.10**: Throughput comparison between the results using sand terrain, free space, and two-ray propagation models.
the LOS case, the received signal might be a combination of reflected and direct waves due to the ground reflection presence or due to the presence of weeds that block the ground reflected parts. However, in the NLOS case the received signal is dependent on indirect waves reflected or scattered from foliage or channel objects. Such a combination results in a larger PLE value than that of the artificial turf, short grass, long grass and free space propagation models. Therefore, the RSS becomes weaker, which makes the battery of the transmitting node drain faster, which in turn results in a shorter network lifetime and smaller throughput.

A comparison of the generated results using sparse tree, free space, and two-ray propagation models is shown in Figure 6.11 and Figure 6.12. Therefore, comparing the generated results with the results using free space and two-ray propagation models demonstrated the inadequacy of using these theoretical propagation models in evaluating the performance of a WSN in the sparse tree propagation environment.
Figure 6.11: Lifetime comparison between the results using sparse tree, free space, and two-ray propagation models

Figure 6.12: Throughput comparison between the results using sparse tree, free space, and two-ray propagation models

6.8 Dense Tree environment

In the dense tree environment, the lifetime of the simulated WSN lasted for 57 rounds before the first death of the network members, whereas the first death of the network members when using the free space propagation model was at round 4152 and at round 69 when using the two-ray propagation model. Because the path
loss exponent (PLE) value of the dense tree propagation environment is larger than that of the free space and the two-ray propagation models, the WSN exhausts its resources faster under dense tree conditions. The PLE value in the dense tree environment is 4.02, while it is equal to 2 in the free space propagation model and 4 in the two-ray propagation model.

The dense tree environment has the shortest network lifetime and highest PLE value among the seven environments being examined in this work. The higher value of the PLE in the dense-tree environment is caused by the lack of line-of-sight (LOS) in almost all instances due to the dense existence of foliage, bushes, and trees, which results in a greater fading rate [64]. Also, because of the presence of many objects such as leaves, branches, and tree trunks, the propagation of the signal in such a forest-linked environment is subject to various reflections, scattering, absorptions, and diffractions [71]. In some cases, multiple transmitted signal waves might arrive at the receiving node, while in other cases, only a small scattered part of that transmit signal is received because of the heavy blockage when the receiver is positioned inside bushes and far away from the transmitter. Therefore, the strength of the received signal becomes weaker due to the larger path loss, which makes the battery of the transmitting node drain faster, which in turn results in a shorter lifetime of the network and smaller throughput.

A comparison of the generated results using dense tree, free space, and two-ray propagation models is shown in Figure 6.13 and Figure 6.14. Therefore,
comparing the generated results with the results using free space and two-ray propagation models demonstrated the inadequacy of using these theoretical propagation models in evaluating the performance of a WSN in the dense tree propagation environment.

**Figure 6.13**: Lifetime comparison between the results using dense tree, free space, and two-ray propagation models

**Figure 6.14**: Throughput comparison between the results using dense tree, free space, and two-ray propagation models
6.9 Summary of the Developed Radio Energy Models

In Chapter 4, empirical radio energy models and their associated parameters have been developed for WSNs deployed in seven outdoor environments. The parameters of the developed radio energy models are summarized in Table 6.1 and Table 6.2.

Table 6.1: Summary of the parameters of the developed radio energy models

<table>
<thead>
<tr>
<th>Environment</th>
<th>Transmit Power</th>
<th>Receive Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial turf</td>
<td>$P_t = E_{\text{artificial_turf_amp}} R_b d^{2.75}$</td>
<td>$P_r = \frac{P_t G_t G_r}{5.861 \times 10^6 \times d^{2.75}}$</td>
</tr>
<tr>
<td>Concrete surface</td>
<td>$P_t = E_{\text{concrete_amp}} R_b d^{3.21}$</td>
<td>$P_r = \frac{P_t G_t G_r}{3.047 \times 10^6 \times d^{3.21}}$</td>
</tr>
<tr>
<td>Short grass</td>
<td>$P_t = E_{\text{short_grass_amp}} R_b d^{2.96}$</td>
<td>$P_r = \frac{P_t G_t G_r}{0.626 \times 10^6 \times d^{2.96}}$</td>
</tr>
<tr>
<td>Long grass</td>
<td>$P_t = E_{\text{long_grass_amp}} R_b d^{2.55}$</td>
<td>$P_r = \frac{P_t G_t G_r}{0.879 \times 10^6 \times d^{2.55}}$</td>
</tr>
<tr>
<td>Sand terrain</td>
<td>$P_t = E_{\text{sand_terrain_amp}} R_b d^{3.42}$</td>
<td>$P_r = \frac{P_t G_t G_r}{1.250 \times 10^6 \times d^{3.42}}$</td>
</tr>
<tr>
<td>Sparse tree</td>
<td>$P_t = E_{\text{sparse_tree_amp}} R_b d^{3.33}$</td>
<td>$P_r = \frac{P_t G_t G_r}{1.21 \times 10^6 \times d^{3.33}}$</td>
</tr>
<tr>
<td>Dense tree</td>
<td>$P_t = E_{\text{dense_tree_amp}} R_b d^{4.02}$</td>
<td>$P_r = \frac{P_t G_t G_r}{0.163 \times 10^6 \times d^{4.02}}$</td>
</tr>
</tbody>
</table>
Table 6.2: Summary of the parameters of the developed radio amplifier energy models

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial turf</td>
<td>$E_{\text{artificial turf amp}} = \frac{P_{t-\text{thresh}} \times 5.861 \times 10^6}{R_b \times G_t \times G_r}$</td>
<td>0.9915 pJ/bit/d$^{2.75}$</td>
</tr>
<tr>
<td>Concrete</td>
<td>$E_{\text{concrete amp}} = \frac{P_{t-\text{thresh}} \times 3.047 \times 10^6}{R_b \times G_t \times G_r}$</td>
<td>0.5154 pJ/bit/d$^{3.21}$</td>
</tr>
<tr>
<td>Short grass</td>
<td>$E_{\text{short grass amp}} = \frac{P_{t-\text{thresh}} \times 0.626 \times 10^6}{R_b \times G_t \times G_r}$</td>
<td>0.1059 pJ/bit/d$^{2.96}$</td>
</tr>
<tr>
<td>Long grass</td>
<td>$E_{\text{long grass amp}} = \frac{P_{t-\text{thresh}} \times 0.879 \times 10^6}{R_b \times G_t \times G_r}$</td>
<td>0.1487 pJ/bit/d$^{2.55}$</td>
</tr>
<tr>
<td>Sand terrain</td>
<td>$E_{\text{sand terrain amp}} = \frac{P_{t-\text{thresh}} \times 1.250 \times 10^6}{R_b \times G_t \times G_r}$</td>
<td>0.2114 pJ/bit/d$^{3.42}$</td>
</tr>
<tr>
<td>Sparse tree</td>
<td>$E_{\text{sparse tree amp}} = \frac{P_{t-\text{thresh}} \times 1.21 \times 10^6}{R_b \times G_t \times G_r}$</td>
<td>0.2047 pJ/bit/d$^{3.33}$</td>
</tr>
<tr>
<td>Dense tree</td>
<td>$E_{\text{dense tree amp}} = \frac{P_{t-\text{thresh}} \times 0.163 \times 10^6}{R_b \times G_t \times G_r}$</td>
<td>0.0275 pJ/bit/d$^{4.02}$</td>
</tr>
</tbody>
</table>

From Table 6.2, the radio amplifier energy per bit for the dissimilar environments range from 0.0275 pJ in the dense tree environment to 0.9915 pJ in the artificial turf environment. Such values show significant variation when comparing them to radio amplifier energy computed using the free space and two-ray propagation models. Table 6.3 provides the values of network lifetime and throughput predicted by these developed radio energy models for WSNs deployed in different propagation environments.
Table 6.3: Network lifetime and throughput values predicted by the developed radio energy models

<table>
<thead>
<tr>
<th>Model</th>
<th>Network Lifetime</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial turf</td>
<td>1041</td>
<td>18560</td>
</tr>
<tr>
<td>Concrete surface</td>
<td>207</td>
<td>3601</td>
</tr>
<tr>
<td>Short grass</td>
<td>2343</td>
<td>41823</td>
</tr>
<tr>
<td>Long grass</td>
<td>3729</td>
<td>66435</td>
</tr>
<tr>
<td>Sand terrain</td>
<td>172</td>
<td>2947</td>
</tr>
<tr>
<td>Sparse tree</td>
<td>270</td>
<td>4748</td>
</tr>
<tr>
<td>Dense tree</td>
<td>57</td>
<td>971</td>
</tr>
</tbody>
</table>

A comparison of the generated results using the developed radio energy models is shown in Figure 6.15 and Figure 6.16.

Figure 6.15: Lifetime comparison of the generated results using the developed radio energy models
6.10 Empirical and Theoretical Models Comparisons

As was pointed out in Chapter 2, commonly utilized theoretical propagation models such as the two-ray and free space are less likely to provide precise lifetime and throughput predictions for WSNs deployed in different outdoor environments. Such an assumption is based on the comparisons between the generated results using the both the theoretical and practical propagation models, and the fact that these propagation models are not fully able to characterize WSN physical channels. Table 6.4 presents the values of network lifetime, throughput, and radio amplifier energy predicted by the existing radio energy models using the two-ray and free space propagation models with the same simulation settings.
Table 6.4: Values of network lifetime, throughput, and radio amplifier energy predicted by the existing radio energy models

<table>
<thead>
<tr>
<th>Model</th>
<th>Network Lifetime</th>
<th>Throughput</th>
<th>Radio Amplifier Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSPL</td>
<td>4152</td>
<td>73758</td>
<td>1.10 fJ/bit/d²</td>
</tr>
<tr>
<td>Two-Ray</td>
<td>69</td>
<td>1135</td>
<td>0.027 pJ/bit/d⁴</td>
</tr>
</tbody>
</table>

The differences between the predicted results using the developed radio energy models and the predicted results using the existing radio energy models were calculated utilizing the percentage increase or decrease of the predicted network lifetime and throughput. Positive values show a percentage increase in network lifetime and throughput whereas negative values show percentage decrease in network lifetime and throughput [72]. The differences in percentage between the predicted results using the developed radio energy models and the predicted results using existing radio energy are illustrated in Table 6.5.
Table 6.5: Differences in percentage between the predicted results using the developed and the existing radio energy models

<table>
<thead>
<tr>
<th>Model</th>
<th>FSPL Lifetime (%)</th>
<th>FSPL Throughput (%)</th>
<th>Two-Ray Lifetime (%)</th>
<th>Two-Ray Throughput (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial Turf</td>
<td>-74.93</td>
<td>-74.84</td>
<td>1408.7</td>
<td>1535.24</td>
</tr>
<tr>
<td>Concrete Surface</td>
<td>-95.01</td>
<td>-95.12</td>
<td>200</td>
<td>217.27</td>
</tr>
<tr>
<td>Short Grass</td>
<td>-43.57</td>
<td>-43.3</td>
<td>3295.65</td>
<td>3584.85</td>
</tr>
<tr>
<td>Long Grass</td>
<td>-10.19</td>
<td>-9.93</td>
<td>5304.35</td>
<td>5753.3</td>
</tr>
<tr>
<td>Sand Terrain</td>
<td>-95.86</td>
<td>-96</td>
<td>149.28</td>
<td>159.65</td>
</tr>
<tr>
<td>Sparse Tree</td>
<td>-93.5</td>
<td>-93.56</td>
<td>291.3</td>
<td>318.33</td>
</tr>
<tr>
<td>Dense Tree</td>
<td>-98.63</td>
<td>-98.68</td>
<td>-17.39</td>
<td>-14.45</td>
</tr>
</tbody>
</table>

The comparisons presented in Table 6.5 reveal that the existing radio energy model that was derived based on the usage of free space propagation model is very optimistic and inaccurate in predicting the network lifetime and throughput of WSNs deployed in outdoor environments. However, the presented comparisons indicate the pessimism and inaccuracy of the existing radio energy model that was derived based on the two-ray propagation model in predicting the network lifetime and throughput of WSNs deployed in outdoor environments.

A comparison of the generated results using both the developed and the existing radio energy models is shown in Figure 6.17 and Figure 6.18.
Figure 6.17: Lifetime comparison of the generated results using both the developed and the existing radio energy models

Figure 6.18: Throughput comparison of the generated results using both the developed and the existing radio energy models
6.11 Conclusion

This chapter provided discussions of generated results using the developed radio energy models. Also, illustrations of the developed radio energy models and a summary of the findings were presented. Moreover, the presented simulations were compared. In fact, the results obtained through the comparison of these dissimilar propagation environments revealed significant differences in the lifetime and throughput. The differences are due to the dissimilarities existing in the wireless propagation channel of every environment. A comparison between the predicted results using the developed radio energy models and the predicted results using the existing radio energy models developed based on the usage of theoretical propagation models was given. Such comparison demonstrated the inadequacy of using these theoretical propagation models in predicting the network lifetime and throughput of WSNs deployed in outdoor environments. This observation shows the importance of utilizing accurate environment-specific radio energy dissipation prediction models of WSNs deployed in dissimilar outdoor propagation environments.
Chapter 7: Conclusion and Future Work

7.1 Summary of Dissertation

This dissertation addresses the shortages in the literature on radio energy models for WSNs by developing radio energy models for seven outdoor propagation environments. This dissertation also presented a methodology for evaluating the performance of wireless sensor network (WSN) protocols in different propagation environments. To create this methodology, practical RF propagation models that include many of the substantial features of different propagation environments were utilized, and radio energy models for different propagation environments were developed. Accurate environment-specific radio frequency (RF) propagation models were utilized for the purpose of developing accurate radio energy models for different outdoor propagation environments. The purpose of developing these environment-specific radio energy models is to have an accurate prediction of network lifetime and throughput of WSN deployed in different outdoor environments.

The investigating of the impact of different propagation environments on the performance of WSNs was done based on simulating the LEACH protocol using the developed radio energy models derived based on the usage of the propagation models of sparse tree, concrete surface, sand terrain, long natural grass, short natural grass, artificial turf ground, and dense tree environments. Also, the LEACH protocol was implemented in MATLAB using the existing radio energy models
developed based on the usage of the free space and two-ray propagation models with identical setups and conditions. The comparison metrics that were involved in this study are the lifetime of the network and the network throughput. The network lifetime definition that was used in this study is the death of the first sensor node, while the throughput is defined as the total number of packets successfully sent to the base station node.

Moreover, the presented simulations were compared with each other so that the differences in the performance of WSNs in various propagation terrains can be identified. The results obtained through the comparison of these dissimilar outdoor propagation environments revealed significant differences in the lifetime and throughput. The differences are due to the dissimilarities existing in the wireless propagation channel of every environment. Furthermore, results generated by the developed radio energy models using these practical RF propagation models were compared with the results generated by radio energy models using free space and two-ray propagation models to demonstrate the imprecision of these theoretical propagation models in evaluating the performance of WSNs in different environments. Such comparison revealed the inadequacy of using these theoretical models in predicting network lifetime and throughput of WSNs deployed outdoors.

In addition to the imprecision of currently used radio energy models, this observation showed the significance of developing radio energy models based on
the utilization of empirical RF propagation models. In WSNs, accurate radio energy models have several advantages. These models are expected should aid in:

- Facilitating the process of WSN planning and deployment.
- Increasing the battery efficiency of sensing nodes so that network lifetime can be prolonged.
- Optimizing the accuracy of simulation platforms.
- Providing a better understanding of the performance and the behavior of WSN protocols.
- Proving the feasibility of WSN protocols for real world applications.

Based on the observations obtained from the investigation of the impact of different propagation environments on the performance of WSNs accomplished in this dissertation, the subsequent conclusion remarks are achieved:

- WSN performance differs from one environment to another due to the dissimilar features of each environment’s wireless channel.
- The LEACH protocol behaves differently in every different environment.
- Utilizing empirical RF propagation models for developing radio energy models for different outdoor environments is essential for the accurate prediction of WSN lifetime and throughput.
- Developing accurate environment-specific radio energy models is important for understanding the behavior of WSN protocols in different outdoor environments.
• In the outdoor deployment of WSNs, the energy expenditure of the transmit amplifier is dependent on the type of environment and objects existing in that environment.
• The utilization of the commonly used radio energy models that are derived based on the usage of theoretical propagation models such as the two-ray and free space models is unrealistic and impracticable because of the different characteristics of WSNs as opposed to those of traditional wireless networks.
• It is very essential to continue examining the impact of more potential propagation environments on the performance of WSNs and WSN protocols.
7.2 Future Work

There are several potential ways to enhance and extend the work provided throughout this study. For example:

- Even though the investigation of WSN performance was done using several empirical RF propagation models, other empirical RF propagation models of other outdoor environments still have not been utilized. Thus, it is possible to extend the work accomplished in this study to the further examination of the impact of more propagation environments on the performance of WSNs.

- Duplicating the work completed in this study with additional different metrics such as network goodput and overhead would be of value.

- Additional improved versions of the LEACH protocol such as, LEACH-B, TEEN, and APTEEN, should be evaluated using the developed radio energy models. Therefore, deep understanding of the behavior of these protocols in different outdoor environments can be accomplished.

- Validating the accuracy of currently used simulation platforms using the developed radio energy models would be another possible extension of this work.
References


