Reliability and Lifetime Modeling of Wireless Sensors Network

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Abstract

In this thesis, we mathematically model the lifetime of a wireless sensor network (WSN) that uses the prominent MELETE protocol for data dissemination. We first model the lifetime of an individual sensor node which is subsequently used to quantify the network's connectivity and lifetime. Using the lifetime model, we study the impact of different parameters on the network lifetime, e.g., search space around a requesting node, number of responders, transmission range, etc. In addition to providing a low-complexity analytical method for evaluating network reliability, the proposed model reveals interesting insights into the parameters governing the lifetime of a practical WSN. we compare the results inferred through the proposed lifetime model with simulation results to study the affect of the simplifying assumptions on the network lifetime model.We used Tinyos-2.1.0 TOSSIM for simulation. The comparison reveals that our mathematical model provides the upper bound for transmissions and lower bound for network lifetime. We have tightened the bounds well and given suggestions to make them further tightened.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgment has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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Signature: ________________

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Muhammad Riaz-ud-din

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Chapter 1

Introduction and Motivation

1.1 Introduction

Wireless sensor networks (WSNs) have found application in many emerging areas, including medicine, agriculture, environment monitoring, military warfare, inventory control, intrusion detection, motion tracking, machine malfunction, etc.

Due to the battery and complexity-constrained natures of sensor motes, energy efficiency is a fundamental constraint for WSN protocols, applications and services. As nodes in wireless sensor networks (WSNs) usually have limited non-rechargeable batteries, network lifetime becomes one of the most critical performance metrics of a WSN. Furthermore, most anticipated WSN deployment scenarios do not have the provision to easily replace sensor batteries. Consequently, protocols designed for sensor networks are optimized for energy efficiency to keep the network operational for an extended period of time [13].

Network reliability and lifetime are two important characteristics of a WSN. Network reliability, in the present context, is defined as probability of successfully delivering a packet from a source to a destination node in a multi-hop WSN, while a network lifetime may be defined as the time for which the network remains connected/functional. In the WSN context, reliability and lifetime are contradictory objectives. We can increase the transmission redundancy to achieve higher reliability; for instance, higher packet delivery reliability can be achieved using packet retransmissions, or by transmitting multiple redundant copies of a packets over non-overlapping paths, and/or by sending error control redundancy with every packet. All these strategies, however, incur significant energy cost due to an increased number of bit transmission/receptions. Consequently, network lifetime reduces accordingly as the nodes will deplete their energy resources at a rapid pace.

A sensor network's Lifetime and reliability depend upon a range of parameters such as network density, connectivity and coverage, traffic and event characteristics, data dissemination protocol, data delivery model, and channel characteristics. [1] [8].

In this thesis, we model the lifetime of a data disseminating WSN that uses the prominent MELETE [11] code/data dissemination protocol. We define the lifetime of the network as the expected time period for which the network remains connected. We will use reliability-theoretic concepts to model the network lifetime by incorporating the effects of critical network parameters. Reliability, as the probability that a system is functional (connected) at time t, is dependent upon the reliability or liveliness of the individual components of the system. So, we model the network lifetime using a two step approach. First, we model an individual nodes lifetime by calculating the rate at which a node receives or sends packets from/to the network. We then model the reliability of the network in term of connectivity as a function of node reliability which finally leads to the expected lifetime of the network. We also incorporate MAC layer channel contention and SNR-based physical and link layer channel error effects in the proposed lifetime model. In this context, we compare the results inferred through the proposed lifetime model with simulation results to study the affect of the simplifying assumptions on the network lifetime model.We used Tinyos-2.1.0 TOSSIM for simulation.

Using the proposed model, we study the impact of different parameters on the network lifetime, e.g., search space around a requesting node, number of responders, transmission range, node density, etc. In addition to corroborating existing empirical findings, the proposed model reveals interesting insights into the parameters governing a WSN's lifetime. For instance, we show that for lower value of search space, the number of responding nodes directly affect the lifetime. However, when the search space is increased, the number of responding nodes becomes irrelevant.

1.2 Background and Motivation

Most of the current performance evaluation techniques put more emphasis on increasing the transmission redundancy to achieve higher reliability in conventional manner; like packet retransmissions, or transmission of multiple redundant copies of a packets over non-overlapping paths, and/or transmission of error control redundancy with every packet. All these strategies, however, incur significant energy cost due to an increased number of bit transmission/receptions. Consequently, network lifetime reduces accordingly as the nodes will deplete their energy resources at a rapid pace. Lifetime and reliability of a WSN are dependent on many network characteristics such as network topology, traffic and event characteristics, data dissemination protocol, data delivery model, and channel characteristics. The impact of each of these parameters on network lifetime is commonly studied through simulations. Empirical analysis is found to be a tedious, inconsistent and unrepeatable process. Moreover, vast majority of WSN applications require extensive deployment of sensor nodes, scalability experiments even with few thousands of nodes may become infeasible due to the highly time consuming nature of network simulations. Therefore, we argue that simulation-based evaluation should be complemented with mathematical modeling of the key performance metrics of WSNs. Such an evaluation technique will not only be consistent and provable performance but also save significant time and efforts involved in the simulation analysis.

1.3 Contribution

To the best of the authors' knowledge, this thesis proposes the first known technique based on reliability-theoretic concepts for evaluation of lifetime of sensors network. In addition to providing a low-complexity analytical method for evaluating network reliability, the proposed model reveals interesting insights into the wide range of parameters governing the lifetime of a practical WSN.

1.3.1 Problem Statement

The problem statement of our research thesis is:

> *"Mathematically model the reliability and lifetime of a WSN, and study the impact of different network parameters on network lifetime. The main parameters to be incorporated in the model are network topology, traffic and event characteristics, data dissemination protocol, data delivery model, and channel characteristics. "*

1.4 Thesis Organization

The remainder of this thesis is structured as follows:

Chapter 2 provides discussion on some of the existing techniques for evaluation and increasing the lifetime of wireless sensors network. Chapter 3 is dedicated to the network architecture, data collection initiation and data disseminating protocol. Data dissemination protocol, mathematical equations for transmission cost and delays during data collections process have been explained. In Chapter 4, we present node lifetime model. Derivation of lifetime distribution of individual nodes is discussed in this chapter. Using node lifetime model, network lifetime model is drived in Chapter 5. Impact of different parameters on transmission cost and network lifetime, an overview of energy distribution among nodes, concluding remarks and future directions are discussed in Chapter 6.

Chapter 2

Literature Review

This chapter provides the background literature review regarding lifetime of wireless sensors networks. In this review the main aspects which we cover are coverage, connectivity, load balancing and service availability keeping the objective of maximizing lifetime of wireless sensors network in view.

2.1 Service Disruption Tolerance

After discussions of Lifetime definitions found in literature like, the time until the first sensor is drained of its energy, the time until all nodes have been drained of their energy, k-coverage, α-coverage etc., the authors come up with new lifetime definition incorporating the service disruption tolerance of the application which is the ability of the network to cope with temporary failures of one or more of its requirements.[2]. In addition, following concepts were also considered as important in calculating lifetime.

2.1.1 Time-integrated Requirement

A time-integrated requirement specifies that it does not have to be satisfied at each point in time, but rather in the course of a certain time interval.

2.1.2 Graceful Degradation

Instead of sudden death of the network, means of estimating the degree of compliance with the application demands have been pointed out for graceful degration of the network.

2.1.3 Connected Coverage

Connected coverage can be defined as a combination of coverage and connectivity, and shows that this is a different requirement than connectivity and coverage on their own. Because, the nodes covering the area could be different from those able to communicate. The difference between the two definitions is that in connectivity and coverage all active nodes are considered for communication, whereas in connected coverage only those active nodes with a path to the sink are considered in calculating the network lifetime.

All these factors, if taken into consideration while calculating the lifetime help increasing the lifetime of the network.

2.2 Load Balancing and Minimizing Total Energy Consumption

The energy consumption rate at the level of individual nodes is very critical in controlling the lifetime of a network. Uneven energy load among all the nodes increases the chances of expiring nodes very early in the operation of the network resulting application requirement failure like coverage, connectivity etc., and the network become down without utilizing its resources to their full capacity. So efforts were made to design protocols to distribute energy load evenly among nodes to keep all nodes intact for maximum possible time resulting longer lifetime of the network. In this regard, several clustering-based routing protocols have been proposed for sensor networks, like LEACH [4], TTDD [14], and LRS [15]. LEACH and LRS periodically select cluster-heads from sensors in the network. Ye et al. [16] proposed PEAS to let redundant sensors go to sleep and save energy. Tian et al. [17] proposed node-sleeping scheme based on sponsored area. Xiaojiang et al. [5] wrote that network systems are increasingly following heterogeneous design, incorporating a mixture of sensors with widely varying capabilities. Therefore, to achieve better performance, they adopt a heterogeneous sensor network model. In the HSN model, a small number of powerful High-end sensors (Hsensors) are deployed in the field in addition to a large number of Low-end sensors (L-sensors). An H-sensor has much larger transmission range (power), better computation capability, larger storage, more energy supply, and better reliability than an L-sensor. They address the UEC(Uneven energy consumption) problem by the Chessboard Clustering scheme designed for HSN. The authors design a routing protocol based on the chessboard clustering scheme, and compute the minimum node density for satisfying a given lifetime constraint. They show through simulation experiments that the chessboard clustering-based routing protocol balances node energy consumption very well and dramatically increases network lifetime, and it performs much better than two other clustering-based schemes.

2.3 Channel State and Residual Energy Information

Yunxia et la. [10] list important network characteristics that affect the network lifetime and derive a formula for lifetime based on channel state and the residual energy of sensors, and Based on this formula, they propose a medium access control protocol that exploits both the channel state information and the residual energy information of individual sensors. The formula for network lifetime of wireless sensor networks holds independently of the underlying network model including network architecture and protocol, data collection initiation, lifetime definition, channel fading characteristics, and energy consumption model. Following network characteristics have been discussed in their paper and it has been proposed that network design should exploit channel status information and nodes residual energy status to maximize network lifetime.

2.3.1 Network Architecture

How the data regarding environmental phenomenon is carried by the sensors to the base stations is purely based on network architecture. The flat ad hoc, the hierarchical ad hoc, and the SEnsor Network with Mobile Access (SENMA) are the three kinds of architectures of sensors networks. Under the flat ad hoc architecture, sensors relay each others data in multiple hops to the base station. Clusters are formed in hierarchical WSNs which report their data to the cluster heads which are responsible for sending the aggregated data to the base station. In SENMA, sensors communicate directly with mobile APs moving around the sensor field.

2.3.2 Data Collection Initiation

Based on the requirements of the applications, data collections in a WSN can be initiated by three ways

- *Clock-driven:* Sensors collect and transmit data at predetermined time intervals.
- *Event-driven:* Data collections are triggered by an event of interest

- *Demand-driven:* In this case it is initiated from APs as per request of user.

2.3.3 Channel and Energy Consumption Model

Energy consumption can generally be categorized by two ways i.e. the continuous energy consumption and the reporting energy consumption. They are explained below.

- *Continuous Energy Consumption:* It is the minimum energy needed to sustain the network during its lifetime without data collection. It includes, for example, battery leakage and sensor sleeping energy.
- *Reporting energy Consumption:* It is the additional energy consumed in data collections. It depends on the rate of data collection as well as the channel model and the network architecture and protocols. It includes the energy consumed in transmission, reception, and possibly channel acquisition. Energy consumption may come from other sources such as network maintenance whose energy expenditure rate is neither continuous nor related to data collections. All these energy consumption resources can be accommodated in their derived formula.

2.3.4 Lifetime Definition

It is the time starting from deployment time of the network to the time when it stops functioning. When a network should be considered nonfunctional is, however, application-specific. It can be, for example, the instant when the first sensor dies, a percentage of sensors die, the network partitions, or the loss of coverage occurs.

They have derived the formula for network lifetime as given in equation No. 2.1

$$E[\pounds] = \frac{\varepsilon_0 - E[E_w]}{P_c + \lambda E[E_r]} \tag{2.1}$$

where P_c is the constant continuous power consumption over the whole network, $E[E_w]$ is the expected wasted energy (i.e., the total unused energy in the network when it dies), λ is the average sensor reporting rate defined as the number of data collections per unit time, and $E[E_r]$ is the expected reporting energy consumed by all sensors in a randomly chosen data collection. Based on this formula the authors proposed a MAC protocol exploiting channel status information and residual energy. In other word the protocol select the transmitting node in each round of data collection based on the maximum value of energy-efficiency index γ_i defined as

$\gamma_i = e_i - E_r(c_i)$,

where e_i is the residual energy of sensor i at the beginning of a data collection and c_i is its fading gain. The Fig. 2.1 shows four curves i.e. random, pure conservative, pure opportunistic and max-min. In random, the transmitting node is selected randomly at each data collection round, in pure conservative a node with maximum residual energy is selected, in pure opportunistic a node with maximum fading gain is selected, while in max-min a node is selected by taking under consideration both channel and residual energy status of nodes. It is obvious that consideration of both channel status and residual energy of individual node raises the lifetime maximum among all others.

2.4 Random Data Generation Process

In [6], the authors assume that nodes are randomly placed and the occurrence of every event is both temporally and spatially independent of all the other events in the network. So, the data generation process at individual sensor nodes is Poisson and

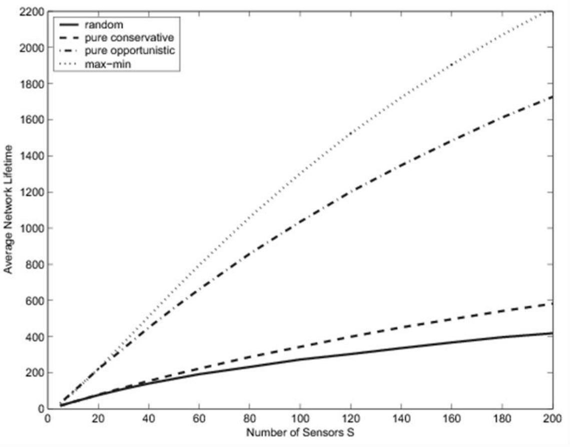

Figure 2.1: Comparison of the network lifetime. $E_0 = 5$, $E_c = 0.01$, $E_{es} = 0.01$

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hence the time interval between two successive data generation events is an exponentially distributed random variable. They have assumed a circular field of n annular rings. Under these assumptions, they have derived expected network lifetime i.e. $E[T]$, and CDF for network lifetime as shown in equation 2.2 and 2.3.

$$E[T] = \frac{2P}{n(n+1)\omega\lambda} \tag{2.2}$$

and

$$Pr(T < x) = G(x) = 1 - \sum_{j=0}^{\frac{\omega_n P}{\gamma}-1} \frac{e^{-\lambda_n x}(\lambda_n x)^j}{j!} \tag{2.3}$$

where $\lambda_n = \lambda$ and $\omega_n = \frac{2}{n(n+1)}$ for a linear network; and for a planar network $\lambda_n = (2n-1)\lambda$ and $\omega = \frac{6(2n-1)}{n(n+1)(4n-1)}$. Here γ is energy dissipated per data transmission, λ is the data forwarding rate, n is total number of annular rings and P is total initial energy of the network.

Fig. 2.2 and 2.3 show that simulation results support the model results.

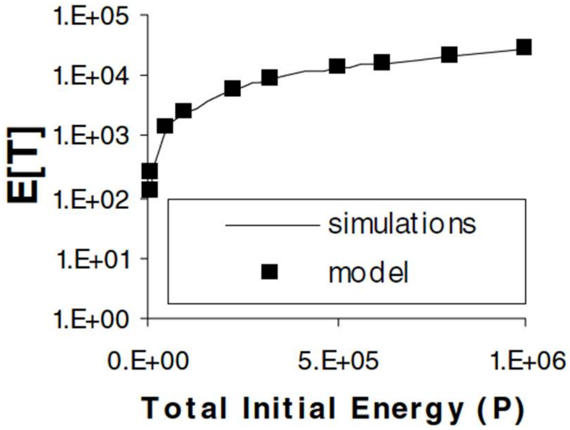

Figure 2.2: Comparison of analytical model with simulation results of expected lifetime

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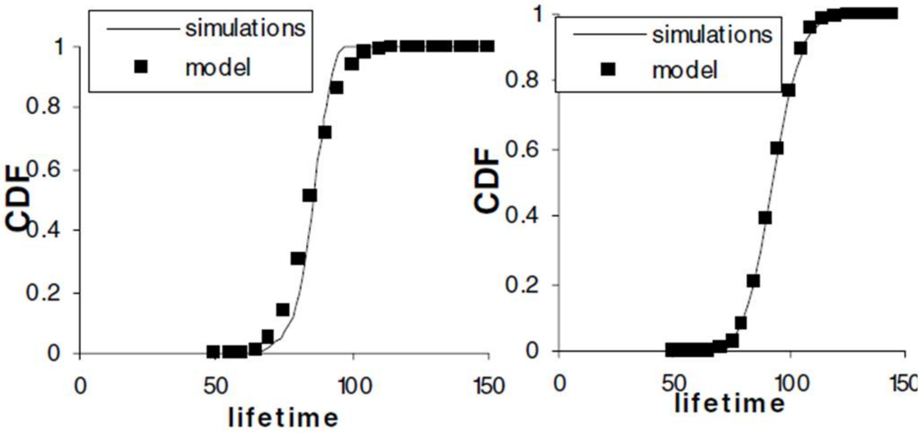

Figure 2.3: Comparison of simulation results with model of CDF and $G(x)$ of lifetime in a linear(left) and in a planner network(right)

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2.5 Achievable Distortion in Data Reconstruction

In [8] , the authors have trade-off between fidelity and lifetime. For example, in sensor network of wireless cameras, high quality image of the scene is generally not required, and flexibility in fidelity can be exploited to increase the lifetime of the network. Using a technique of multiple rate allocation among correlated nodes, required distortion is achieved at the point of reconstruction data. These rate allocations would typically have different energy cost in routing depending on the network topology resulting in the interplay between these two considerations of distortion and energy. *Choice of sensors*, *choice of routes*, *protocol overheads* and *In-network Aggregation* are very important factors to determine the distortion performance of the network. For instance, a sensor sensing at high SNR may be needed to generate low data transmission rate and follow a longer rout as compared to a sensor at low SNR which needs higher data transmission rate and follow short rout. Similarly other factors help in consuming minimum possible energy resources.

2.6 Related Work

Chen and Zhao propose a generic lifetime model based on the channel state and the remaining energy levels of the nodes in [10]. Based on this model, they also propose a MAC layer protocol for sensor networks that exploits two parameters to maximize the remaining energy level across the network. Dietrich and Dressler propose a formal definition of sensor network lifetime that incorporates the service disruption tolerance of the network and time integration [2]. Given a network with some energy availability, routing mechanism and communication energy model, Kansal *et al.* model the sensor network lifetime to reproduce a phenomenon at required level of data distortion [8]. All proposed models involving evaluation and the techniques to increase the lifetime of a wireless sensor network exploit some of the basic parameters or requirement to control the energy consumption among nodes. They also define lifetime for evaluation purpose. Specially their evaluation techniques do not cover all the underlying network parameters as compared to our model. In addition, our model does not restrict the network to be nonfunctional at the time of first node failure or at the time of all node failure. In other words our definition for network lifetime is very comprehensive. It follows the realistic approach i.e.the network will become nonfunctional when it partitions. One node or even many nodes failure may or may not cause the network nonfunctional. All underlying characteristics of the network like, Network architecture, data collection initiation, data dissemination protocol, channel characteristics etc. can be studied and optimized in the light of our model.

Chapter 3

Data Disseminating Protocol

MELETE[11] is a system that supports concurrent execution of multiple applications deployed in a WSN. MELETE uses a modified version of Trickle [12] for code dissemination. State transitions in Trickle are shown in Fig. 3.1. Each application is deployed and executed on a group of sensor nodes and a node may be running multiple applications. Applications may be upgraded or the new ones deployed which in turn requires code migration and dissemination mechanism. An application code is divided into capsules which is further divided into chunks (packets).

Nodes keep exchanging code / application version information with their neighbors. When a node detects a newer version of an associated application, it switches to $REQUEST$ state (see Fig. 3.1) and advertises (broadcasts) the request with $TTL = 0$ to upgrade its application. One hop neighbors of the requester forward the request with probability p_f which is given by

$$p_f = \min(1, 0.33\sqrt{q}), \tag{3.1}$$

where q is the number of received requests by the node. This is known as *lazy forwarding.* The requester advertises request with highest rate initially and slows down exponentially to a pre-specified rate.

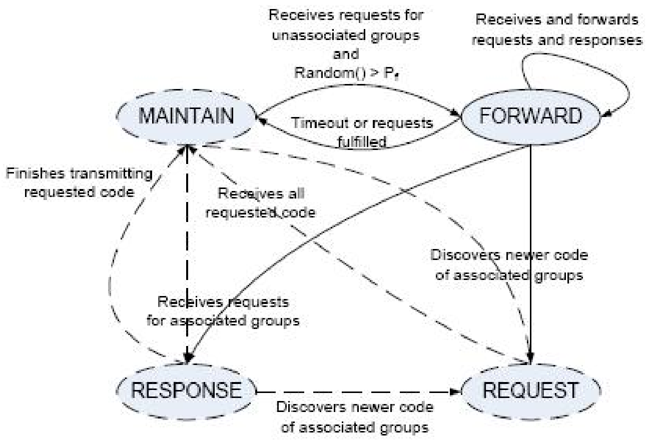

Figure 3.1: State transitions in MELETE; states and transitions in dotted line are from the original *Trickle* [11]

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When a 1-hop neighbor decides to forward the request, it switches to *FORWARD* state with probability p_f and forwards the request with $TTL = H - 1$ hops. This is known as *progressive forwarding*. A node receiving the request with $TTL > 0$, immediately switches to *FORWARD* state and forwards the request. In this way, a H hops wide forwarded region is formed. If no responder is found within H hops, the nodes at H hops again perform lazy forwarding and the forwarding process repeats until a responder is found. Probabilistic forwarding or lazy forwarding gives enough time to a responder located in the searched area to respond to avoid unnecessary expansion of the forwarded region.

Once a responder is discovered, the forwarder sets $TTL = -1$ for all requests before forwarding and switches to highest advertising rate. Each receiving node behaves in a similar way and thus the information is quickly disseminated in the network. Responder then generates replies which is finally delivered through the forwarding region to the requesting node. Forwarding nodes keep track of the chunks being exchanged between the nodes which helps in reducing the overall network traffic to serve a request.

Table 3.1: Description of Modeling Variables

Symbols	**Description**
MELETE parameters	
p_f	Probability to switch to *FORWARD* state
q	# of received request packets
H	Time to live (TTL) in hops
r/U	Transmission range / Sensor field radius in unit of r
p/z	Chunks in a capsule / responders
Q	Time to switch to *FORWARD* state
m, m_1, m_2	Trickle parameters
C/T	Number of packets / time to serve a request
Lifetime parameters	
q_c/q_e	Collision / Channel error probability
n_r	Requests rate (requests/sec)
d_{avg}/ρ	Average node degree / node density
E	Initial node energy
e_t/e_r	Transmission / reception energy (pJ/bit)
b/e_{th}	Bits per packet / threshold energy level
M/e	Exp. node lifetime/energy consumption rate(pJ/sec)
T_x/R_x	Transmission / reception rate of a node ($Pkts/sec$)
p_s	Packet (request / response) forwarding probability
m_{red}	# of packets broadcast in one interval of Trickle
$P_L(t)$	Probability that a node is live at time t
$d_f[i]$	Expected forward degree of nodes in ring R_i

3.1 Transmission Cost and Time Delay

In [11], the authors also derived an expression to compute the total number of packets C generated to serve a single request. C is the sum of packets generated to locate a responder C_d and the number of packets generated in response to the request C_f.

Mathematically, C_d is given by [11]:

$$C_d(H) = m_1U(\frac{U(\log Q + 1)}{z+1} + \frac{H\sqrt{\pi}(\log Q - 1)\Gamma(z+1)}{2\Gamma(z+\frac{3}{2})}), \tag{3.2}$$

where m_1 is Trickle redundancy parameter, U is the size (hops) of circular field, Q is the time required to switch into *FORWARD* state and z represents the number of responders. Similarly, C_f is given by

$$C_f(H) = m_2pU(\frac{U}{z+1} + \frac{H\sqrt{\pi}\Gamma(z+1)}{2\Gamma(z+\frac{1}{2})}), \tag{3.3}$$

where m_2 represents the trickle redundancy parameter for code forwarding and p is number of chunks in one capsule. The authors also derived expression for the total time T required to serve a request which is again the sum of the time taken to locate a responder and the time taken to forward the response back to the requesting node. Specifically, T is given by

$$T = \frac{QU\sqrt{\pi}\Gamma(z+1)}{H2\Gamma(z+\frac{3}{2})}(1 + \frac{pH}{Q}) \tag{3.4}$$

where p represents number of chunks in a capsule.

We now extend the above model to characterize the lifetime of a WSN assuming MELETE as an underlying dissemination protocol.

Chapter 4

Lifetime Modal of Individual Nodes

4.1 System Architecture and Definitions

We assume that links between the nodes are symmetric and transmission radius of each node is r meters. Nodes transmit at a single uniform rate only. We model a circular field of radius $r \times U$ containing a total number of N homogeneous sensor nodes with average node density of ρ which are randomly deployed in the field. We also assume that each node has an average number of neighbors or average degree of d_{avg}. Node degrees are allowed to deviate from the average degree through a Poisson random variable with parameter ρ. We also allow for the possibility of a transmitted packet being dropped due to collisions at the MAC layer or channel errors.

We now define the key terms used in the thesis:

- *Broadcast Forwarding Probability:* p_s is the probability that a rebroadcast packet will be delivered successfully to the next hop nodes.
- *Expected Forward Degree of a Node:* It is the average (or mean) number of neighbors of a node that, after receiving a packet, forward it to the next hop. Expected forward

degree of nodes located at i hops from the requesting node is denoted by $d_f[i]$.

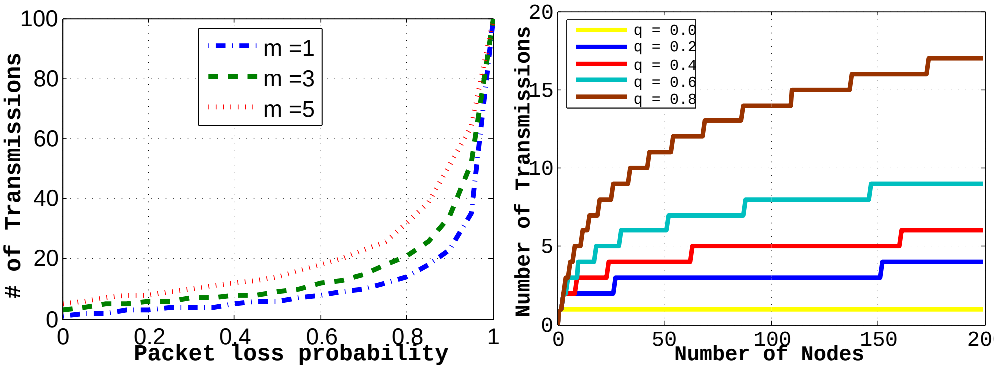
Another important term is the network lifetime which is defined in terms of the connectivity of the network. The network is said to be *non-functional* or *dead* if it partitions. We now describe the network lifetime model proposed in this thesis. In this context, we first model the lifetime of a sensor node. Subsequently, we use the node lifetime to model the lifetime of the whole network.

4.2 Incorporation of Packet Transmission Errors

The authors of MELETE assumed a network consisting of 1-hop lossless networks to derive equations (3.2), (3.3) and (3.4). So, based on 1-hop lossless network concept and using Trickle [12] as under lying data dissemination protocol, transmissions and delay expressions have been derived. In such a 1-hop network, m transmissions (packets) are broadcast during an interval. However, in practice, the number of transmissions m_{red} in one round of Trickle is greater than m as packets may get lost due to channel error and contention. Therefore, we first incorporate the effect of packet loss in the proposed models (see Fig. 4.1a and 4.1b). We will use packet loss factors m_{red}(taken from Fig. 4.1a) in equations (3.2) and (3.3) in place of m to reflect the packet loss behavior in our mathematical model.

4.3 Transmission and Reception Energy Rate

We assume that responders always have new information and are always ready to serve a requester, and requester located at the center of circular field is always ready to request the new information. So, requester generates new request immediately



(a) Effect of packet loss probability and redundancy parameter m

(b) Effect of packet loss probability and # of 1-hop neighbors

Figure 4.1: Redundant Transmissions in one round of Trickle

after fulfilling the previous request. We know that C is the total number of packets generated in response to a request generated by the requester. The number of packets transmitted by a node in a unit time, the *transmission rate*, is given by

$$T_x = \frac{C}{N \times T}, \tag{4.1}$$

where N is the total number of nodes in a network. As each transmitted packet is received, on average, by d_{avg} nodes, the number of packets received by a node in one second, the *reception rate*, is

$$R_x = \frac{d_{avg} \times C}{N \times T}. \tag{4.2}$$

It is important to note that R_x approximately equals $d_{avg} \times T_x$. Consequently, the energy consumption due to reception of packets may dominate the energy consumed due to transmission of packets. Combining (4.1) and (4.2), we get the *energy consumption rate* as:

$$e = b \times (T_x \times e_t + R_x \times e_r), \tag{4.3}$$

where e_t is transmission energy per bit, e_r is reception energy per bit and b is the size of a packet in bits.

4.4 Lifetime Distribution of a Node

The energy consumption rate e is time dependent because the forwarding probability changes with time which effects the transmissions in each request-response cycle and hence effects e. Let the nodes be deployed with an initial energy level E_0 and at time t the expected value of the energy of a node is $E(t)$, and nodes die out when energy reaches a threshold value e_{th}, then *expected lifetime* M of a node at time t is given by

$$M = \frac{E(t) - e_{th}}{e}, \tag{4.4}$$

Hence, the node lifetime depends on the rate at which energy is consumed. As the rate of data collection increases, the transmission rate and hence the energy (or battery) depletion rate increases sharply reducing the node lifetime.

We are now interested in the probability that a node will be live at time t; i.e. $P_L(t)$. If nodes lifetime is exponentially distributed with $\lambda(t) = \frac{1}{M(t)}$ as the node failure rate, the node lifetime distribution function $F(t)$ may be written as

$$F(t) = 1 - e^{-\int_0^t \lambda(t)dt}, \tag{4.5}$$

where T is random variable showing the probability of node failure at time t. Clearly, probability that a node will be live at time t is $1 - F(t)$. Therefore, using (4.5), $P_L(t)$ is given by

$$P_L(t) = e^{-\int_0^t \lambda(t)dt}. \tag{4.6}$$

$P_L(t)$ varies directly with the node expected lifetime which in turn is dependent upon the rate at which energy is consumed.

We shall now describe the network lifetime model in chapter 5.

Chapter 5

Network Lifetime Model

Recall our definition of network lifetime that the network is *alive* as long as it functions as a single entity, i.e. the network is connected. Therefore, we first derive an expression for the probability $P_U(t)$ that the network is connected at time t. Using this probability, we then calculate the expected network lifetime.

5.1 Network Connectivity

We will use the broadcast forwarding probability p_s that a packet is re-broadcast by a node and is successfully delivered to its neighboring node. Mathematically, we write it as

$$p_s = P_L(t) \times P_L(t) \times \bar{q}_c \times \bar{q}_e, \tag{5.1}$$

where $\bar{q}_c = 1 - q_c$ is the probability of no collision and $\bar{q}_e = 1 - q_e$ is the probability of no channel errors. $P_L(t)$ is the probability that node is alive to broadcast the packet successfully at time t. $P_L(t)$ is also the probability that node is alive to receive the broadcast packet successfully at time t. Assume that the network field is a circular region with a requester at the center, and responders are uniformly distributed in the field (see Fig. 5.1). The broadcast storm of request packets (or responses) ripples across the network forming concentric circular rings $\{R_0, R_1, R_2, \ldots, R_U\}$ of thickness r except R_0, which for simplicity, is assumed to be of width 0 containing only requester. Recalling expected forward degree definition which says that expected forward degree $d_f[i]$ of a node in ring i is the expected number of its neighboring nodes in $(i+1)th$ ring. The pictorial view of expected forward degree is given in Fig.5.1. Mathematically, expected forward degree may be written as

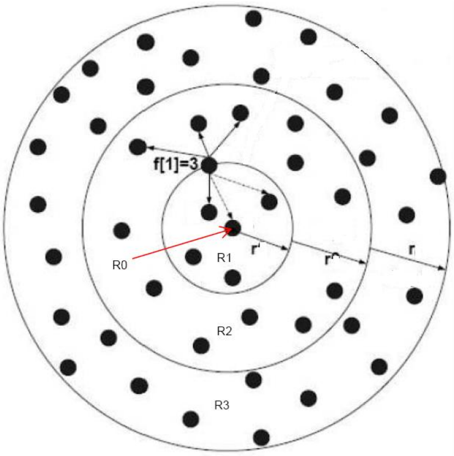


Figure 5.1: Transmission shape (Transmission rings)

$$d_f[i] = \begin{cases} \rho\pi r^2 - 1 & \text{if } i = 0 \\ \frac{3\rho\pi r^2}{\rho\pi r^2 - 1} & \text{if } i = 1 \\ \frac{(2i+1)}{(2i-1)} & \text{if } i = 2, 3, \ldots, U-1 \\ 0 & \text{if } i = U. \end{cases} \tag{5.2}$$

we model network connectivity in the form of ring connectivity. For this purpose, we partition the network into two mutually exclusive subsets of nodes: S_k and $\bar{S}_k$, where $k = 0, 1, 2, \ldots, U$, S_k contains a set of nodes belonging to rings $R_0, R_1, \ldots, R_k$ while $\bar{S}_k$ consists of nodes belonging to the remaining rings. We then define the following two events.

Event 1: All the expected number of nodes in ring R_k receiving the broadcast originated from requester fail to transmit the broadcast successfully to all of their expected forward degree nodes in R_{k+1}.

Event 2: S_k is connected component of the network.

For simplicity, we also assume that the nodes within a ring are connected. A packet broadcast by a requester is received (on-average) by $p_s \times d_f[0]$ nodes in R_1. At the second stage, the receiving nodes in R_1 re-broadcast packets which are then received by $p_s^2 \times d_f[0] \times d_f[1]$ nodes in R_2 and so on.

In general, $p_s^k \times (\prod_{i=0}^{k-1} d_f[i])$ nodes belonging to R_k will receive the broadcast originated from the requester at the center, where $k > 0$. Let

$$n_e(k) = p_s^k(\prod_{i=0}^{k-1} d_f[i]), k > 0 \tag{5.3}$$

The probability that all these nodes $n_e(k)$ are not connected to all of their expected degree nodes in R_{k+1} is ${q_s}^{n_e(k)\times d_f[k]}$ which satisfies Event 1. Now assuming that P_k is the probability that S_k is connected, then

$$P_r\{\text{Event}\ \ 1 \text{ and }\ \text{Event}\ \ 2\} = {q_s}^{n_e(k)\times d_f[k]} \times P_k \tag{5.4}$$

where $q_s = 1 - p_s$. Since the sum of these probabilities for all values of k must be equal to unity i.e.

$$\sum_{k=0}^{U-1} {q_s}^{n_e(k)\times d_f[k]} \times P_k + {q_s}^{n_e(U)\times d_f[U]} \times P_U = 1 \tag{5.5}$$

The above expression yields the probability $P_U(t)$ that the network is functional at time t as:

$$P_U(t) = 1 - \sum_{k=0}^{U-1} {q_s}^{n_e(k)\times d_f[k]} \times P_k \tag{5.6}$$

Equation (5.6) shows that the network connectivity decays exponentially as the number of rings increases. For instance, when $k \to \infty$, $P_U(t) \to 0$.

5.2 Expected Network Lifetime

We use $P_U(t)$ to compute the expected lifetime of the network. Since $P_U(t)$ is the probability that network will be functional at time t, integrating (5.6) with respect to t will yield the expected network lifetime as:

$$L[P_U(t)] = \int_0^\infty \left(1 - \sum_{k=0}^{U-1} {q_s}^{n_e(k)\times d_f[k]} \times P_k\right) \mathrm{d}t. \tag{5.7}$$

This concludes our network lifetime model. In the next chapter 6, we investigate the effects of different parameters on the lifetime and discuss the insights provided by the proposed model.

5.3 Rings Based Consumed Energy Standard Deviation

To have a view of energy consumption distribution among nodes, rings based energy consumption standard deviation can be quit helpful. To calculate standard deviation mathematically, energy consumed during the network lifetime is assumed to be distributed among the rings nodes according to the probability given in equation 5.8. Let E_i be the energy consumed during the lifetime by ring i and $\bar{E}$ be the mean energy consumed by a ring i.e.$\bar{E} = \frac{E}{L}$ (where E is the total energy consumed by all the nodes and L is total number of rings of circular network field), then standard deviation is calculated as in equation 5.9.

$$P_r\{X > (i-1)rH\} = (1 - \frac{(i-1)^2}{L^2})^z \tag{5.8}$$

where, $L = \frac{U}{H}$

$$\sigma = (\sum_{i=1}^{L} (E_i - \bar{E})^2 . P_r\{X > (i-1)rH\})^{1/2} \tag{5.9}$$

Chapter 6

Results and Conclusion

6.1 Radio Energy Model

To analyze the impact of different parameters on the network lifetime, we assume that radio dissipates $E_{elec} = 50\frac{nJ}{bit}$ energy to run the transmitter/receiver circuitry while $p_{amp} = 100\frac{pJ}{bit.m^2}$ are expended by the transmitter amplifier. Therefore, $e_r = E_{elec}$ and $e_t = E_{elec} + p_{amp}.r^2$.

6.2 Simulation

We wrote the code in *nesC* for simulation using *Tinyos-2.1.0 TOSSIM*. We deployed a network of $41X41$ grid with a 15-distance unit spacing. Using TOSSIM's empirical model shipped with the software, we generated the network. We calculated average packet loss by the formula which is also followed by *TOSSIM*. A single requester was located at the center of the network, while z responders were uniformly distributed in the network.

We performed simulation using minimum time interval of $100\mu s$ for maximum transmission rate and $6000\mu s$ for minimum transmission rate. Our transmissions cost as shown in Fig. 6.2, 6.3

and 6.4 is based on the average value of 400 rounds for each value of H and z. In each round we randomly distribute z responders instead of keeping them at same places.

To reduce the transmission cost due to non-synchronized behavior of nodes, we used half of the time interval as listening period for all nodes, restricting nodes to select a random time in other half to transmit or suppress transmission accordingly. Doing this we reduce transmissions following the listening trend of Fig. 6.1.

In our mathematical model we have incorporated both listening and packet loss factors in place of trickle redundancy constants of one-hope lossless network i.e. we have plugged in *"2 × packet loss factor"* in place of $m1$ and $m2$ in equations 3.2 and 3.3. So, mathematical model sets upper bound on transmissions which is very close to real transmissions. So, we have also taken under consideration the non-synchronized behavior of the network which reflects the real life behavior. Although it sets a bound on transmission cost but this is the most tightened bound as compared to the loose bound showing non-synchronized trend in Fig. 6.1

To calculate lifetime of the network, the requester keep on sending requests after each request-response round and the responders are always have the new information to send.

6.3 Impact of Search Space and Responders on Transmission Cost

Throughout our results we have observed that transmissions during simulation remain below as compared to transmissions from mathematical model which confirm our mathematical model

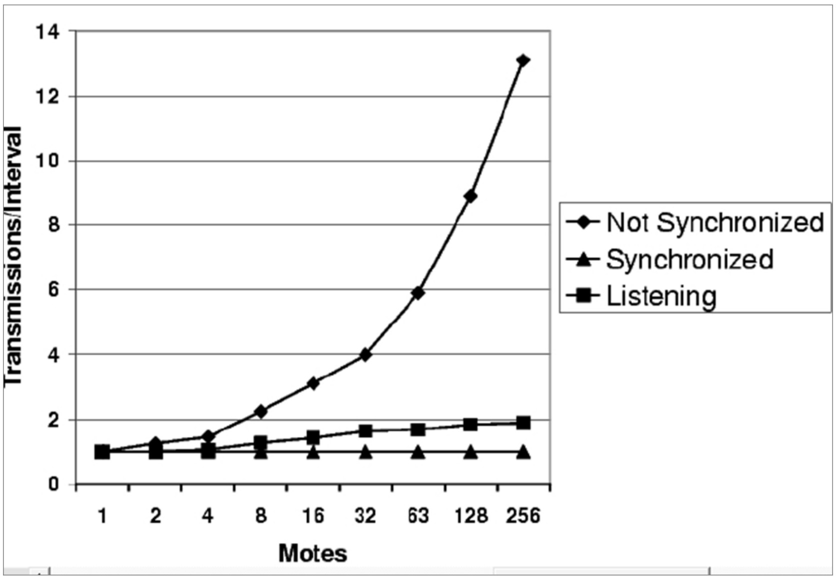
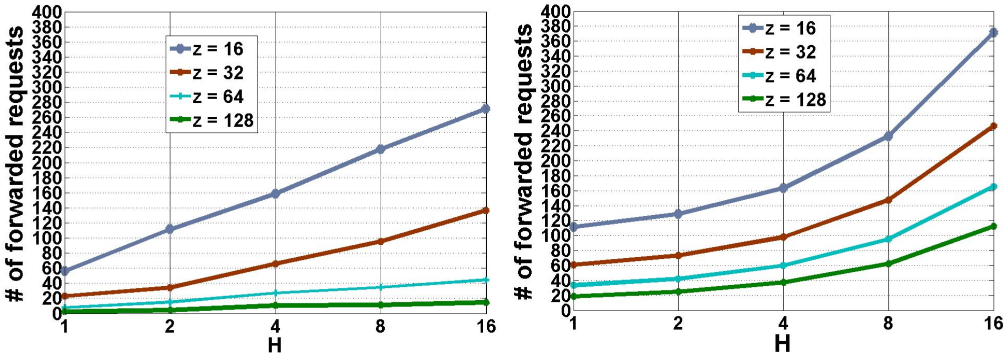


Figure 6.1: One-hope lossless network transmissions under Trickle[11].

results. See figures 6.2, 6.3 and 6.4.

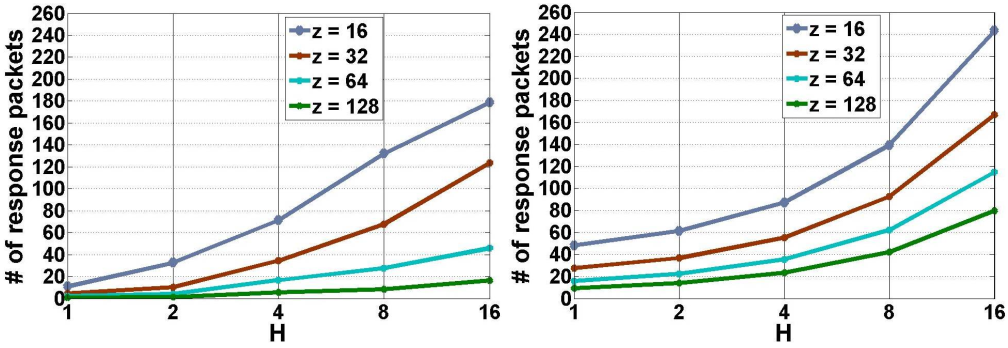
The number of transmissions increases with increasing value of H. It is as expected because higher values of H expand the search area to larger number of rings causing high transmissions while lower values of H restrict search area to lower number of rings causing lower transmissions. See figures 6.2, 6.3 and 6.4.

With higher values of z (responders), transmissions decrease while with lower values of z, transmissions increase. See figures 6.2, 6.3 and 6.4. It is because higher value of z increase the probability of finding the responder in the area near to the requester. In other words, higher values of z restrict the search area to lower number of inner rings while lower value of z causes search area to be expanded to larger number of rings.



(a) Simulation results (b) Model results

Figure 6.2: Impact of different values of H on transmission cost of forwarded request packets ($U = 10, q = 8, m1 = 1, m2 = 2, p = 1$, packet loss rate = 0.08, $r = 30.0$, node density=0.005).

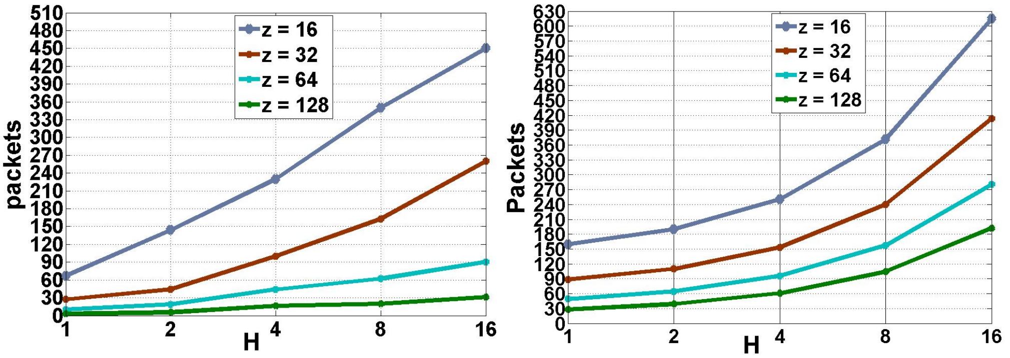


(a) Simulation results (b) Model results

Figure 6.3: Impact of different values of H on transmission cost of response packets ($U = 10, q = 8, m1 = 1, m2 = 2, p = 1$, packet loss rate = 0.08, $r = 30.0$, node density=0.005).

6.4 Transmission Time

Transmission time increases with decrease in the values of H. It is maximum at $H = 1$. Lower values of H restrict expanding the search area which causes more time to be taken to search



(a) Transmissions in simulation

(b) Transmissions in Model

Figure 6.4: Impact of different values of H on transmission cost of forwarded request and response packets ($U = 10, q = 8, m1 = 1, m2 = 2, p = 1$, packet loss rate = 0.08, $r = 30.0$, node density=0.005).

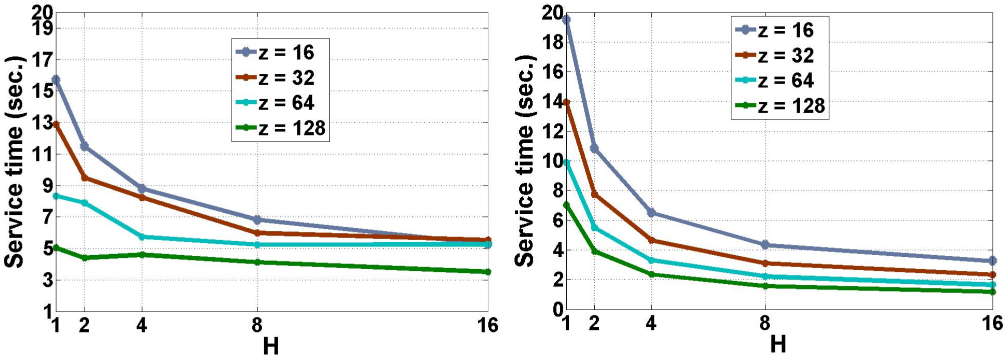
responder(s) due to lazy forwarding characteristic of MELETE protocol. See Fig. 6.5 and 6.6. Transmission time decreases with increase of transmission radius. Increasing transmission radius increases the search area which facilitates the search of responder(s) and hence decreases the transmission time.

6.5 Network Lifetime Evaluation

6.5.1 Impact of search space

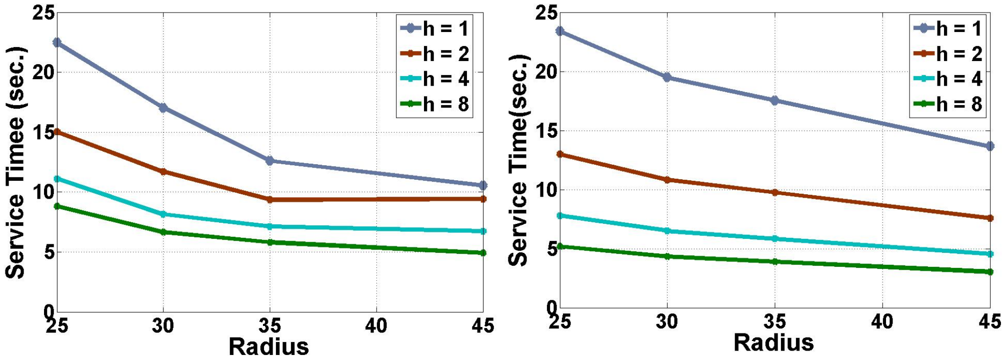
We observe that lifetime trend of the network as shown in simulation is generally on higher side as compared to mathematical results. See Fig. 6.7 and 6.8. It is in accordance with our expectations as transmissions calculated from mathematical model give us maximum bound.

As a whole lifetime increases as value of H decreases in both



(a) Simulation results (b) Model results

Figure 6.5: Impact of different values of H on Transmission time ($U = 10, q = 8, m1 = 1, m2 = 2, p = 1$, packet loss rate = 0.08, $r = 30.0$, node density=0.05).



(a) Simulation results (b) Model results

Figure 6.6: Impact of different values of r on Transmission time ($U = 10, q = 8, m1 = 1, m2 = 2, p = 1$, packet loss rate = 0.08, $r = 30.0$, node density=0.05).

model results and simulation results as expected, but in particular the difference in lifetime of simulation and model decreases with the decreasing of H. But at $H = 1$, this difference is reversed i.e. lifetime from simulation becomes less than that of mathematical model. See Fig. 6.7 and 6.8.

This is because in mathematical model, total transmissions load has uniformly been divided among all the nodes of the network for all values of H. While in case of simulation, higher values of H cover larger search area giving the results as expected but for $H = 1$, search area is restricted only to a few inner rings putting whole load on lesser number of nodes which decreases the lifetime of the nodes of inner rings. So, node(s) nearer to requester become down earlier in contrast as expected from mathematical model causing partitioning of the network.

The lifetime at larger radius i.e. at $r = 45$ again supports the above reasoning because even for $H = 1$ the lifetime in simulation remains larger than model lifetime as with larger radius search area increases.

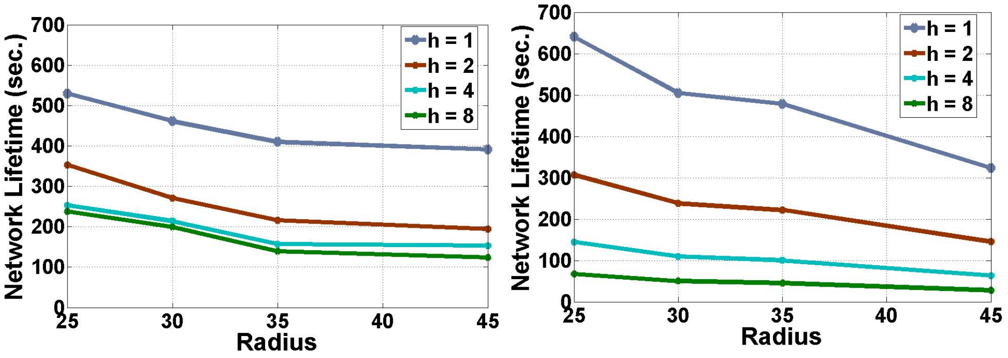
It is observed that at $H = 2$, the simulation results exactly follows mathematical results. It means that $H = 2$ provides neither larger nor narrow search area, partitioning the network as early as expected by mathematical model due to failure of individual nodes .

6.5.2 Impact of Transmission Radius

In general the lifetime decreases with increase in transmission radius. It is as expected because at higher transmission radius more energy is consumed in transmission of a bit as compared with at lower transmission radius. See Fig. 6.7 and 6.8.

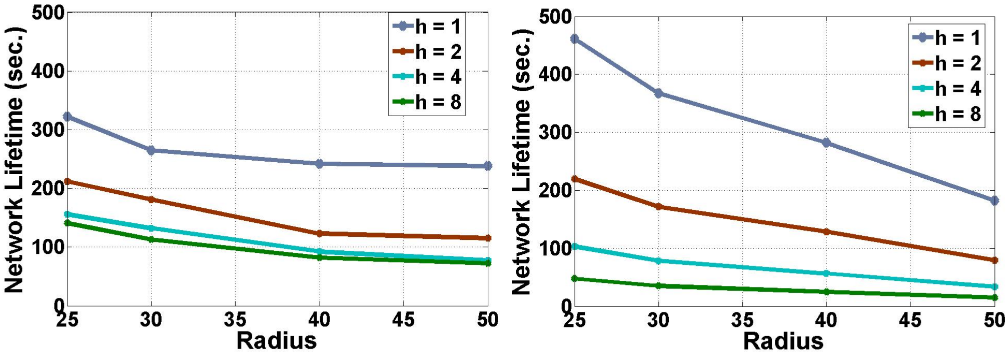
6.5.3 Impact of Responders

It has also been observed that for lower value of H, the number of responding nodes directly affect the lifetime. However, when



(a) Simulation results (b) Model results

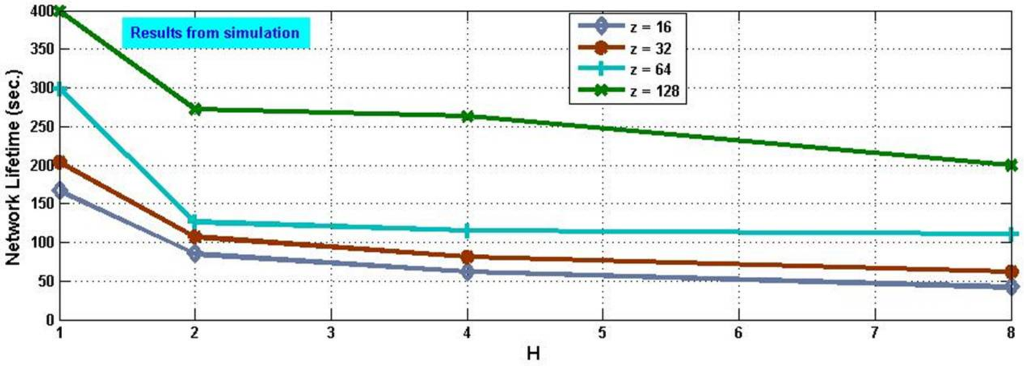
Figure 6.7: Impact of transmission radius on Network Lifetime ($m1 = 1, m2 = 2, p = 1, q = 8$, node density=0.005, Node Energy = 5.0E+10 pj.



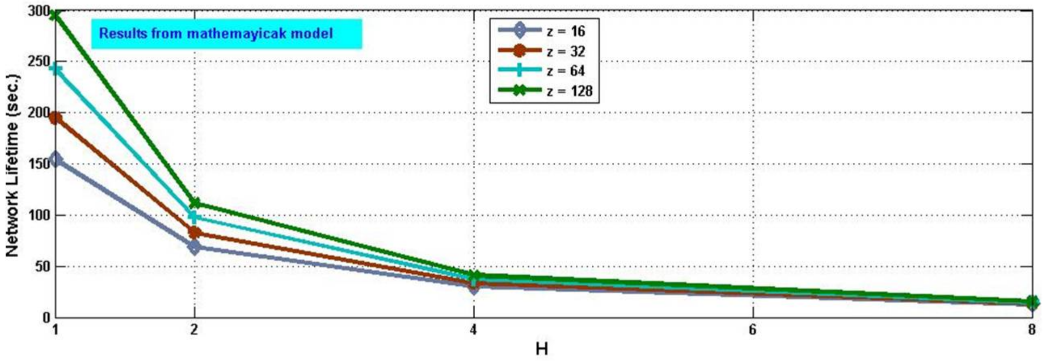
(a) Simulation results (b) Model results

Figure 6.8: Impact of transmission radius on Network Lifetime ($m1 = 1, m2 = 2, p = 1, q = 8$, node density=0.005, Node Energy = 3.0E+10 pj)

the search space H is increased, the number of responding nodes becomes irrelevant. See Fig. 6.9.



(a) Simulation results

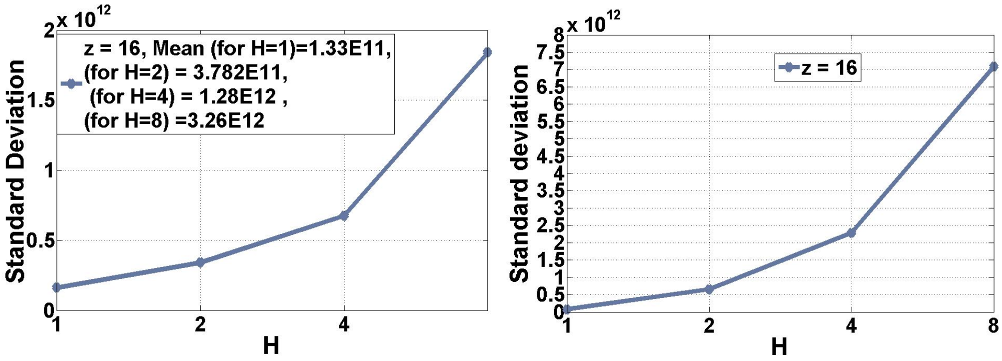


(b) Model results

Figure 6.9: Impact of search space on network lifetime.($m_1 = 1, m_2 = 2, p = 1$, radius=45, node density=0.005, Node Energy=2.0E+10pj)

6.6 A View of Network Energy Load

We provide a view of the distribution of consumed energy among nodes after network expires. We calculate standard deviation at each value of H for ring based energy consumption among nodes. Both mathematical and simulation results support each other and provide a practical insight as shown in Fig. 6.10. Lower values of σ at lower values of H clearly show that, "the



(a) Simulation results (b) Model results

Figure 6.10: Standard deviation of energy consumption of rings.(Mean rings consumed energy $= 2.5E + 12, m_1 = 1, m_2 = 2, u = 12, p = 1$, packet loss rate = 0.05, node density = 0.005, Transmission radius = 25, Node Energy = 2.0E+10pj)

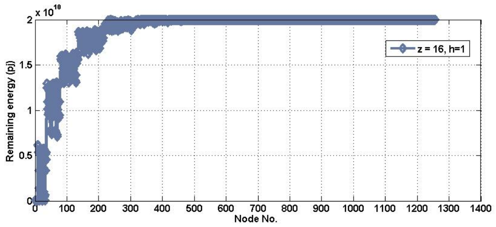
more we restrict searching to inner rings, the more energy load will be on inner nodes", and higher values of σ at higher values of H show that energy is distributed to larger proportion of the network.

Fig. 6.11 shows another view of energy load distribution detail among nodes for $H = 1, 2, 4, 8$. In the Fig. 6.11, the nodes have been numbered such that node with smaller number belongs to some inner ring and a node with larger number belongs to some outer ring. It also shows that for lower values of H, the inner nodes deplete more energy. But for higher values of H, the nodes energy depletion distribution seems uniform.

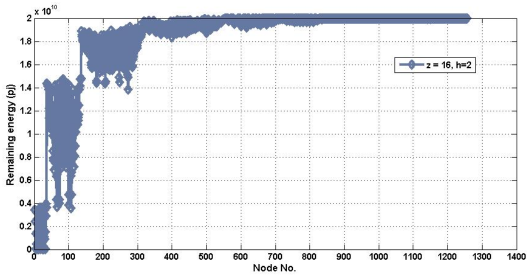
6.7 Conclusion and Future Directions

standard deviations as shown in Fig. 6.10a and 6.10b, and node wise energy distribution as shown in Fig. 6.11a, 6.11b,6.11c and

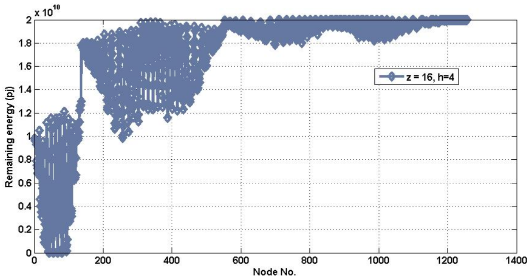
6.11d show that for lower values of H, particularity for $H = 1$, consumed energy is restricted to the space near the requester in the inner rings in contrast to the assumption in our model that it has been divided among all network nodes uniformly. But for higher values of H, the energy consumption seems to be uniform among nodes and rings. So, we conclude that our model gives better results for higher values of H which covers larger rings or number of nodes. We also suggest as future direction that if probability based consumed energy distribution is followed for calculating lifetime, the mathematical model can become more realistic.



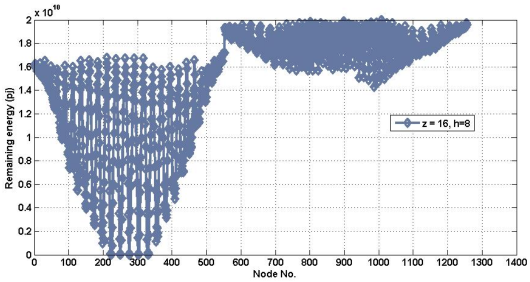
(a) H=1



(b) H=2



(c) H=4



(d) H=8

Figure 6.11: Remaining energy distribution among nodes ($m_1 = 1, m_2 = 2, u = 12, p = 1$, packet loss rate = 0.05, node density=0.005, transmission radius=25.0, Node Energy = $2.0E{+}10$ pj)

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