PREDICTION OF LINK RELIABILITY IN A WIRELESS MOBILE AD HOC NETWORK (MANET) DUE TO PATH LOSS EFFECTS USING WEIBULL DISTRIBUTION

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AUGUST, 2016

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By

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NIGERIA

AUGUST, 2016

DECLARATION

I, IMAM Maryam Lami, hereby declare that this dissertation titled **"Prediction of Link Reliability in a Wireless Mobile Ad Hoc Network (MANET) Due to Path Loss Effects Using Weibull Distribution"** was carried out by me as part of the requirements for the award of degree of Master of Science in Communication Engineering, A.B.U-Zaria. To the best of my knowledge, this research work has never been submitted anywhere for the award of any certificate. All literatures used and cited in this report, are duly acknowledged by means of references.

Maryam Lami IMAM ____________________ ________________

Signature Date

CERTIFICATION

This dissertation titled “Prediction of Link Reliability in a Wireless Mobile Ad Hoc Network(MANET) due to Path Loss Effects Using Weibull Distribution’’ meets the requirements for the award of Master of Science (MSc) degree in Communication Engineering by Ahmadu Bello University, Zaria and it is approved for its contribution to knowledge and literature.

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Member, Supervisory Committee

Dr. S. Garba____________________ ____________________

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Dr. Y. Jibril ____________________ ____________________

Signature Date

Dean Postgraduate School

Professor K. Bala ____________________ ____________________

Signature Date

DEDICATION

This research work is dedicated to God Almighty.

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ABSTRACT

Mobile ad-hoc networks are multi hop wireless networks comprising of a collection of wireless mobile nodes configured to communicate among each other without the aid of an existing infrastructure. They are free to move randomly and organize themselves arbitrarily. The network's wireless topology may change rapidly or unpredictably. As a result, the link becomes unreliable leading to poor communication.This research work presents the prediction of link reliability in a wireless Mobile Ad-hoc Network (MANET) with path loss effect. The link reliability was investigated using the Weibull distribution function due to its flexibility, simplicity and reliability and was simulated using the developed MATLAB 2007Rb Graphic User Interface (GUI). The free space and two ray ground path loss models were used to study the path loss effects on the link reliability. The results obtained were validated by comparing the performance of the model with existing results. It was noticed that the developed model performed better by 7% for coverage area, 2% for range, 0.3% for number of mobile nodes at the point where attenuation factors were at maximum point. This proves the authenticity of the developed model. The network reliability was 98.70% when the bandwidth was 3000 MHz and propagation parameters were δ = 1.0 and γ = 1.0 respectively. In the case of link reliability and signal to interference plus noise ratio (SINR), 99.99% of link reliability was attained which occurred when the SINR was 0.9 and propagation parameters were δ = 1.0 and γ = 1.0 respectively. The effect of SINR and bandwidth on the link reliability and the development of a user dependent Matlab GUI for the link reliability prediction are significant contributions of this research.

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LIST OF ABBREVIATIONS

Acronyms	Definition
MANET	Mobile Ad-hoc Networks
MN	Mobile Nodes
TTR	Two Terminals Reliability
ATR	All Terminal Reliability
KTR	K-Terminal Reliability
AOTR	All Operational Terminal Reliability
WLAN	Wireless Local Area Networks
WPAN	Wireless Personal Area Networks
GUI	Graphic User Interface
MatLab	Matrix Laboratory
QOS	Quality of Service
CCDF	Complementary Cumulative density function
SINR	Signal to Interference plus Noise Ratio
FS	Free Space
TRG	Two Rays Ground
RWPM	Random Way Point Model

TTF	Time to Failure
TTR	Time to Repair
MTTF	Mean Time to Failure
CDF	Cumulative Distribution Function
PDF	Probability Density Function
CC	Channel Capacity
RF	Radio Frequency
BS	Base Station
LOS	Line of Sight
NLOS	Non Line of Sight
PSO	Particle Swarm Optimizat
RBD	Reliability Block Diagrams

CHAPTER ONE

INTRODUCTION

1.1 Background

In recent past, networks have been developing at a faster pace by connecting a large number of devices from servers to micro- devices embedded in objects (Wazwaz, 2005). These devices provide services that can support a variety of applications like: environment monitoring, medical services, military applications, disaster recovery (fire, flood, earth quake etc.,), law enforcement, etc. There are many instances where the network supporting such applications are mobile wireless networks, whose necessary infrastructure support is installed either in a permanent or ad hoc manner (Wazwaz, 2005). For instance, MANET serves in situations where setup of the infra-structure based network may not be feasible or desirable because of the coverage limitations, network failures, congestion, etc. Telecommunications system reliability is of great interest and major importance to developers and customers. The ultimate goal is in improved service quality, throughput, reduced cost, delay,etc (Erickson et al.1990). The special feature of MANET such as self-organizing ability and high mobility of Mobile Nodes (MN) gives a dynamic topology. But strong linking of each MN within the coverage area distinguished it from other types of networks. New scenarios are observed where users can benefit from anywhere and at any time as a result of growth experienced in the area of MANET (Haboub & Ouzzif, 2012). The node failure in a MANET may be due to variety of reasons, for example, low transmission range, out of coverage area, atmospheric effects, physical obstacles, and limited battery life time. In other words, MN time-to-failure follows some statistical distribution. Similarly, the links between the nodes areas summed to have failed when either the distance between the nodes are beyond the specified transmission range of each node, or it may be due to mobility, interference, highly dynamic topology and/or congestion of wireless links. These characteristics make modeling and reliability analysis of such networks a challenging and formidable task. In general, any system can be modeled using random graphs or probabilistic graphs with each user/terminal termed as a node and the links between them as edges.

Based on the number of communicating nodes, the network reliability for infrastructure based networks are defined as Two Terminal(TTR), All-Terminal (ATR), K-Terminal (KTR) and All operational Terminal (AoTR) Reliabilities (Padmavathy & Chaturvedi, 2013). The probability that a specified pair of nodes (the source, s and the sink, r) with known success/failure probabilities of its elements, remain connected by a path created by the operating nodes and links is defined as TTR. The probability that every node be able to communicate with every other node in the network is ATR. Similarly, the probability that at least k designated nodes can communicate with each other is KTR. The probability that all the operational nodes can communicate with each other is termed as AoTR.

1.2 Statement of Problem

Transmitting high data rates is a big problem due to the link quality which diminishes rapidly as the number of hops increase (Paz, 2010). Since real time applications are delay sensitive, they require a good reliability and quality of service analysis. Despite the extensive work done in the prediction and analysis of the reliability of ad-hoc networks, the networks are still unreliable. This necessitates the need to explore more efficient means of predicting the link reliability in a wireless mobile ad hoc network due to path loss effects by using Weibull distribution. The bandwidth, Signal to Interference plus Noise Ratio (SINR), coverage area, transmission range, number of nodes and communication duration will be used as parameters of evaluation.

1.3 Aim and Objectives

This work is aimed at predicting the link reliability in a multi hop wireless mobile ad-hoc network due to path loss effect using Weibull distribution.

The objectives are as follows:

1. Development of a Matlab Graphic User Interface (GUI) based algorithm for prediction and simulation.
2. Carrying out a wide variety of simulations using the Matlab GUI based program in order to demonstrate the effect of changes in network characteristics on link reliability.
3. Evaluation and comparison of the link reliability of the network with an existing research work.

1.4Motivation and Justification

The unpredictable dynamic nature of MANETS leads to poor link reliability of the network. Also, the environmental conditions which cause link path loss do not only affect the effective and efficient operation of the network but the reliability of the links as well. Finding the solution to these problems is the motivating factor of this research work. Though many researchers have already worked on these problems to improve link reliability, there is still room for improvement which justifies this research work as is evident in the contribution achieved.

1.5 Methodology

The methodology adopted in carrying out this research is as follows:

1. Development of :
    i. Signal propagation model based on the combined Free Space (FS) and Two Rays to Ground (TRG) path-loss model;

ii. Network reliability model;

iii. Node mobility model based on Random Way Point Mobility (RWPM);

iv. Node reliability model using Weibull distribution;

v. Link reliability model for TTR based on the FS-TRG model

2. Implementation of the proposed algorithm using GUI in Matlab

3. Simulating various scenarios of the network using the Matlab GUI based script

4. Validationof the results of the developed model using Padmavathy &Chaturvedi, (2013).

1.6 Dissertation Organization

The general introduction has been presented in chapter one. The rest of the chapters are as follows: Detailed review of similar research works and relevant fundamental concepts about pathloss, link reliability, Weibull distribution and RWPM is carried out in chapter two. In depth approach and relevant mathematical models describing the individual link reliability matrix are presented in chapter three. The result, its analysis,and discussion are presented in chapter four. Conclusion and recommendation are discussed in chapter five. Quoted references and appendices are also provided at the end of this dissertation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This section reviews pertinent theoretical concepts and similar research works. It is divided into:

(i) Review of fundamental concepts relevant to the proposed research work

(ii) Review of similar research works.

2.2 Review of Fundamental Concepts

The growth of wireless multi hop networks, especially ad-hoc networks are on the increase. Therefore, this leads to the need for best techniques to achieve a more reliable network. This section reviews the existing theories and governing principles in finding the reliability of ad-hoc networks.

2.2.1 Wireless Networks

Wireless networks refer to any network that is connected without the need of physical links, and is commonly associated with a telecommunications network whose interconnections between nodes is implemented without the use of wires (Mehta & Kumari, 2008). Wireless networks have become an area of great interest for research due to their numerous advantages such as:

(i) Flexibility

(ii) Ease of installation

(iii) Ease of expansion

(iv) Low cost of installation

(v) Convenience

(vi) Others. Figure 2.1 shows the major categories of wireless networks (Daiqiun, 2006),

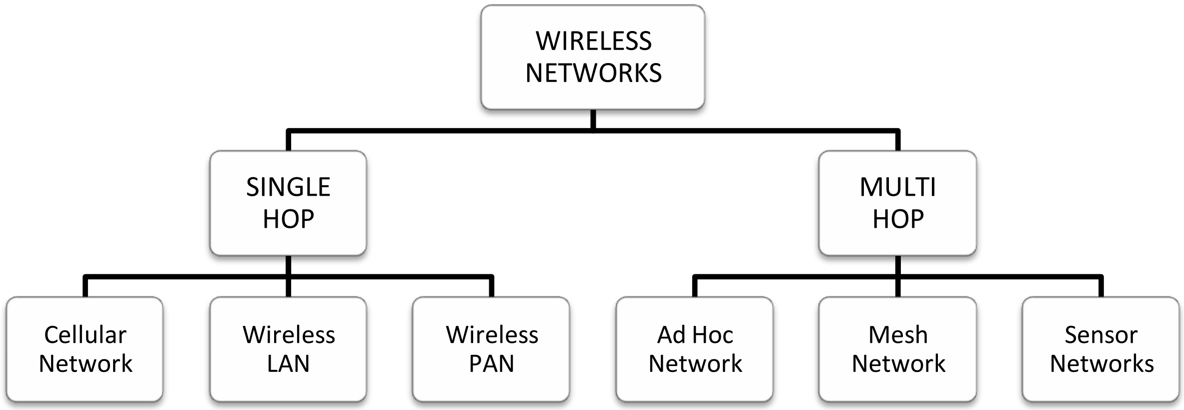


Figure 2.1: Categories of Wireless Networks (Daiqiun, 2006)

i. Single Hop Wireless Networks

Within each single hop wireless network, mobile users can be connected to the wired infrastructure or the central controller through one hop wireless transmission (Daiqiun, 2006). With different coverage area scenarios, single hop wireless network comprise cellular networks, Wireless Local Area Networks (WLANs), and Wireless Personal Area Networks (WPANs) as seen in Figure 2.2.

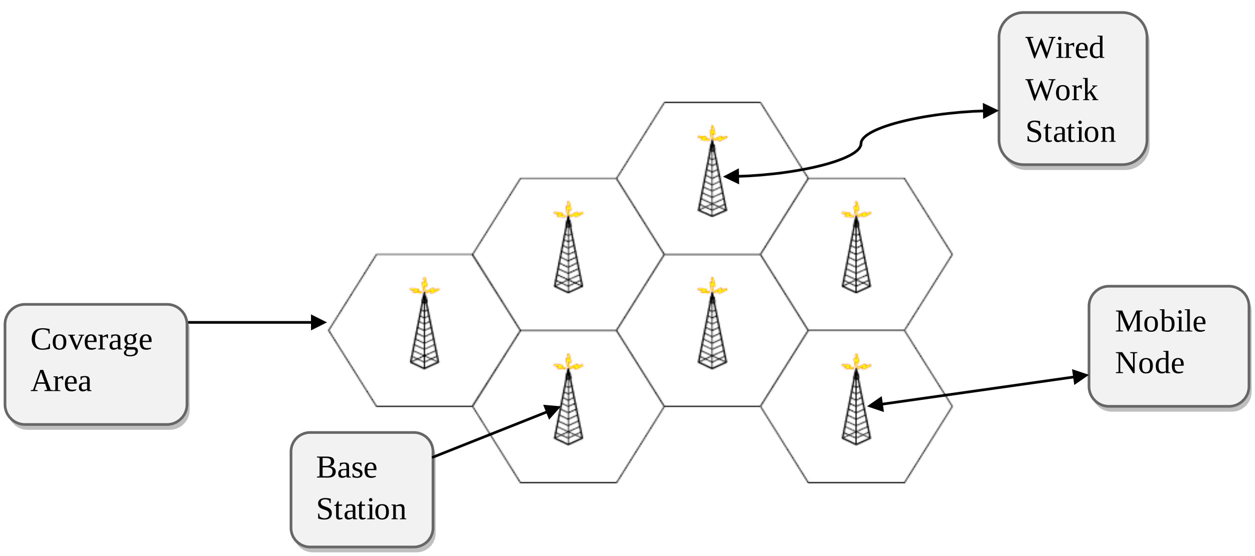


Figure 2.2:A Typical Cellular Network Configuration (Daiqiun, 2006)

Figure 2.2 shows the single hop wireless network structure of a cellular network in which the whole geographic region is divided into non overlapping sub regions called cells. In each cell, mobile users directly communicate with the base station, which is connected to the backbone wired networks. A work station communicates directly with the base station called the uplink and the base station communicates directly with the mobile station called the downlink communication.

ii. Multi- Hop Wireless Networks

Multi hop network is the communication between two end nodes through a number of intermediate nodes whose function is to relay information from one point to another. They utilize multiple wireless nodes to provide coverage to a large area by forwarding and receiving data wirelessly between the nodes. It is a set of equipment linked to each other through communication links which permit the exchange of messages among geographically scattered users. The components of multi-hop networks shown in Figure 2.1 are discussed as follows:

iii.Wireless Mesh Networks:

A wireless mesh network is a wireless network where each node is connected to many others. The network is configured to allow connections to be rerouted around broken or blocked paths, from node to node until it reaches its destination (Priyanka & Metilda, 2014). These multi hop networks composed of wireless links consists of static wireless mesh routers and potentially mobile clients (Maala et al., 2009).The main role of mesh routers is to perform a single or multi hop movement while the mesh clients are associated with users (Dipobagio, n.d). They can be mobile or immobile. Several implementations of the mesh networks exist but are not compatible with each other (Sarkar et al., 2013). Figure 2.3 shows the wireless mesh multi hop network architecture (Wazwaz, 2005).

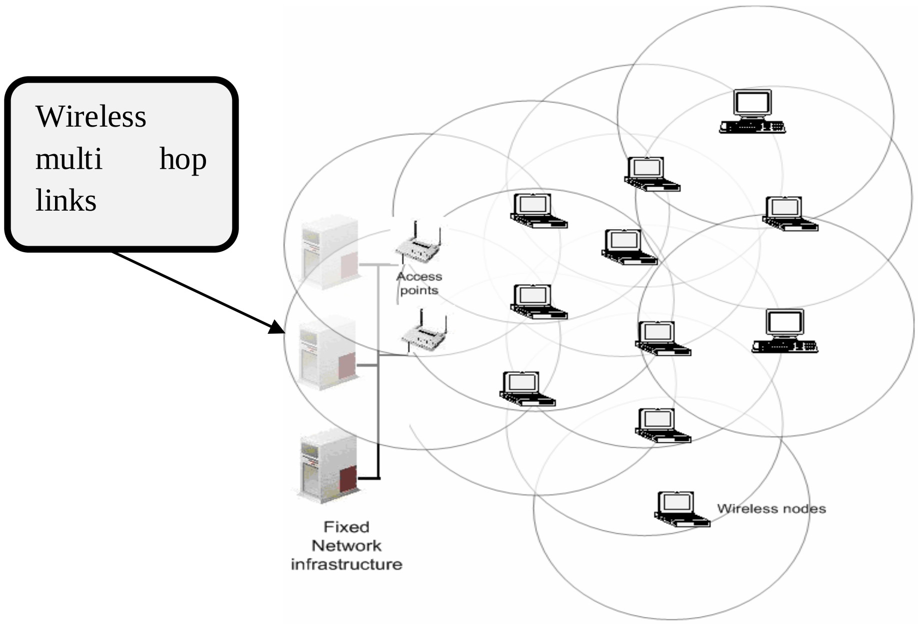


Figure 2.3: A Wireless Mesh Multi Hop Architecture (Wazwaz, 2005).

In Figure 2.3, the wireless mesh nodes use the multi hop links to forward information to other nodes.

iv.Wireless Sensor Networks:

A sensor is a device that can sense and measure a change in the physical condition of the environment, such as change of air pressure, temperature, etc. The wireless sensor networks are multi hop networks comprising of a collection of large numbers of sensor nodes deployed over the region or inside the target to be detected, monitored, or tracked (Venkatesan et al., 2013). Due to the integration of easily available, low-cost, power efficient, and reliable sensors in nodes of wireless ad-hoc networks equipped with significant computational and communication resources, a diverse range of research has opened up (Sarkar et al, 2013). These networks are finding increasing applications in many areas including disaster recovery, health care, defense, academic, and industrial environments (Sarkar et al., 2013). Figure 2.4 presents a wireless sensor network setup (Arrobo, 2012) with sensors for sensing the physical environments before hopping the information to the next node.

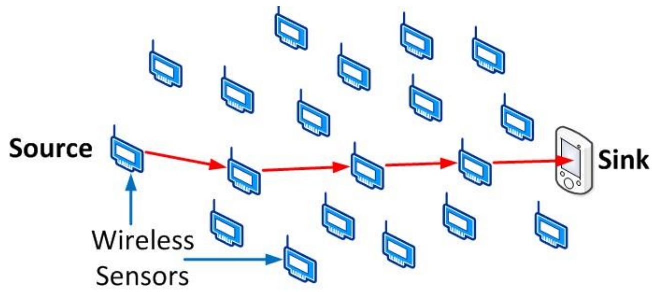


Figure 2.4: Wireless Sensor Network Architecture (Arrobo, 2012).

v.Wireless Ad-hoc Networks

With the advent of a future generation of wireless communication networking technology, an increased focus is on the multi hop ad-hoc networks. This wireless ad-hoc multi hop network is proposed for this research work. Ad-hoc networks are multi hop wireless networks comprising of a collection of wireless mobile nodes configured to communicate among each other without the aid of an existing infrastructure (Tengviel, 2012). It is of great use in situations where no fixed wired infrastructure is available. Wireless ad-hoc networks will likely be utilized more frequently in the future due to its numerous characteristics such as dynamic topologies, bandwidth constraints, etc. For example, a group of researchers en route to a conference may meet at the airport and require connecting to the wide area network. Students may also need to interact during a lecture, or firemen need to connect to an ambulance en route to an emergency scene. In such situations a collection of mobile hosts with wireless networks interfaces may form a temporary network without the aid of any established infrastructure or centralized administration (Sarkar et al, 2013). Hence, if the destination node is not within the transmission range of the source node, one or more intermediate nodes along the path would assist in forwarding the packets. In wireless Ad-hoc networks, individual nodes share the channel through a distributed mechanism (Paz, 2010). They are free to move randomly and organize themselves arbitrarily because the network's wireless topology may change rapidly or unpredictably (Sarkar et al, 2013). Figure 2.5 illustrates a wireless ad-hoc network (Daiqiun, 2006).

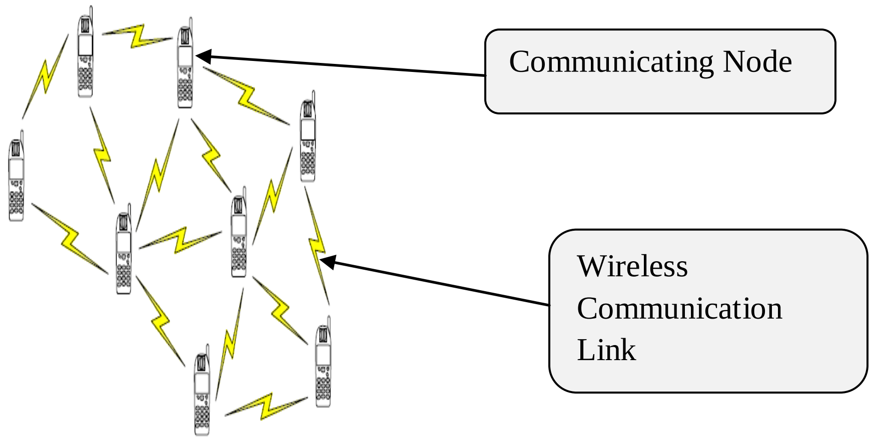


Figure 2.5: Multi Hop Wireless Structure of Ad- hoc Networks (Daiqiun, 2006)

In Figure 2.5, all the communicating nodes are not only transceivers, but also have the router function (Tengviel, 2012). Each node operates as a host and a router at the same time. Some of the challenges faced by the ad-hoc networks are as follows (Sarkar et al, 2013):

1. Limited wireless transmission range
2. Hidden terminal problems
3. Packet losses due to transmission errors
4. Mobility induced route changes
5. Battery constraints
6. Packet transmission delay and
7. Through put.

2.2.1.2Characteristics of Mobile Ad-hoc Networks (MANETs)

This is the term used for non-infrastructure networks, where a set of nodes come together to form a network for exchange of mutually beneficial information (Saxena, 2007). The mobile ad-hoc networks set up has been shown in Figure 2.5. Some of its characteristics are (Saxena, 2007):

1. **Dynamic Topologies**: Since nodes are free to move arbitrarily, the network topology may change randomly and rapidly at unpredictable times. The links may be unidirectional or bidirectional.
2. **Energy Constrained Operation**: Some or all of the nodes in a MANET may rely on batteries. This leads to another system design criteria for optimization.
3. **Limited Physical Security:** Mobile networks are generally more prone to physical security threats than the fixed cable networks. There is increased possibility of eavesdropping, spoofing and denial of service attacks in these networks.
4. **Distributed Operation**: Since there is no background network for the central control of the network operations, the control and management of the network is distributed among the terminals. The nodes involved in MANETs should collaborate among themselves and each node acts as a relay when needed to implement functions for example, security and routing(Tengviel, 2012).
5. **Multi-hop Routing:** Basic types of ad-hoc routing algorithms can be single-hop and multi-hop, based on different link layer attributes and routing protocols(Tengviel, 2012).
6. **Bandwidth Constrained, Variable Capacity Links:** Wireless links have significantly lower capacity than their wired counter parts. Also, due to multiple access, fading, noise, and interference conditions, etc, the wireless links have low throughput. Bandwidth estimation is

an important issue in MANET because the hosts do not have precise knowledge of the network status and the links change dynamically (Ali & Zafar, 2011).

For a better understanding of the ad-hoc networks, Table 2.1 shows the differences between cellular and ad-hoc wireless networks (Sarkar et al, 2013).

Table 2.1: Difference between Cellular and Ad-hoc Networks (Sarkar et al, 2013).

CELLULAR NETWORKS	**AD-HOC WIRELESS NETWORKS**
Infrastructure network	Infrastructure-less network
Fixed, pre-located cell sites and base station	No base station and rapid deployment
Static backbone network topology	Highly dynamic network topologies with multi-hop
Relatively caring environment and stable connectivity	Hostile environment (noise, losses) and irregular connectivity
Detailed planning before base station can be installed	Ad-hoc network automatically forms and adapts to changes
High setup costs	Cost effective
More setup time	Less setup time

Due to the advantages and characteristics of MANET, a need for reliability in this area is necessary.

*2.2.2*Reliability of Telecommunications Systems

Reliability refers to the likelihood that a product would be able, during a given period, of adequate condition, to carry out its intended functions and that it would not experience failure (Dhillon, 2004). It contains aspects of safety of operation, availability and performance to maintain a constant value. These attributes have a major role in carrying out the services provided by systems and telecommunications networks. Reliability of wireless networks can be evaluated based on various metrics such as transmission capacity, SINR, outage probability, throughput, transmission delay, capacity, power consumption, spectral efficiency, bandwidth usage etc (Kaynia, 2010). Reliability in telecommunications network is a measure which is both hard to define and to evaluate (Sanso et al., 1991). Transmitting messages through the wireless channels in MANET is a major challenge which affects the link reliability (Alnajjar, 2011). According to Pandey & Aneja, (2012), telecommunications networks system reliability can simply be represented mathematically as:

$$R(t) = 1 - F(t) \quad (2.1)$$

where:

R(t) = Reliability Function and

F(t) = Failure Rate (the inability of an item to function within the specified guidelines).

2.2.3 Reliability Distributions

Reliability is defined as the probability of failure free performance under stated conditions or the probability that an item can perform its intended function for a specified interval under stated conditions (Ayers, 2012). Reliability is a time dependent function and all modern system reliability analysis relies heavily on the application of probability and statistic mathematics (Ayers, 2012). The reliability function is a mathematical expression analytically relating the probability of success to time. In order to completely describe the reliability function, the concepts of the state variable, x(t) and Time To Failure(TTF) must be presented (Ayers, 2012).

$$x(t) = \begin{cases} 1, & iftheitemstateisfunctionalorsuccessful \\ 0, & iftheitemstateisfailedorunsuccessful \end{cases} \quad (2.2)$$

The state variable, x(t) is the fundamental unit of reliability analysis. All reliability analysis is based on one of two system states at any given time, which are:

(i) Successful

(ii) unsuccessful

2.2.3.1 Statistical Distributions System reliability relies heavily on the application of theories developed in the field of mathematical probability and statistics (Ayers, 2012). This section presents the mathematical details of each distribution of interest and discusses the application for which the models are most relevant.

i. Exponential Distribution

Exponential distribution is a continuous statistical distribution used extensively in reliability modeling of telecommunications systems. In reliability engineering, the exponential distribution is used because of its memory-less property and its relative accurate representation of electronic component time to failure. The Mean Time To Failure (MTTF) of an exponential random variable is given by (Ayers, 2012):

$$\text{MTTF} = \text{E}[x] = \int_0^\infty x.f(x)dx = \frac{1}{\lambda} \qquad (2.3)$$

It can be seen from equation (2.3) that the future behavior of a random variable is independent of its past behavior. Although the exponential distribution is commonly used to model component repair, it is not well suited for this task. The repair of components typically is much more accurately modeled by normal, log-normal or Weibull distributions. The reason that repair is typically modeled by an exponential random variable is due to its ease of analysis. This is best used when the repair period is insignificant with respect to the time between failures, otherwise it does not hold. The probability density function of the exponential distribution is given by (Ayers, 2012):

$$f(x) = \begin{cases} \lambda e^{-\lambda x}, & for\ x \geq 0 \\ 0, & for\ x < 0 \end{cases} \quad (2.4)$$

The cumulative density function of the exponential distribution can be calculated from the PDF (Ayers, 2012):

$$F(x) = \int_0^\infty f(x)dx = \begin{cases} 1 - e^{-\lambda x}, & x \geq 0 \\ 0, & x < 0 \end{cases} \quad (2.5)$$

ii.Normal and Log –Normal Distributions

The normal (Gaussian) and log-normal distributions are continuous statistical distributions used to model a multitude of physical and abstract statistical systems. Both distributions can be used to model a large number of varying types of system repair behavior (Pandey & Aneja, 2012). Repair is more often well modeled by normal or log-normal random variables. It is common to model the repair of a telecommunications system using a normal random variable since the normal distribution is completely defined by the mean and variance of that variable. The Probability Density Function (PDF) of the normal distribution (Ayers, 2012) is given by:

$$f(x, \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (2.6)$$

where:

μ is the mean value which represents the average value of the distribution,

σ^2 is the standard deviation which is a measure of the variability of the random variable.

The log-normal distance is the distribution of a random variable whose logarithm is normally distributed. The CDF of the normal distribution is given by a relatively complex expression involving the error function (Ayers, 2012):

$$F(x, \mu, \sigma^2) = \frac{1}{2}\left(1 + \operatorname{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right) \tag{2.7}$$

where

erf is error function

The Cummulative Density Function (CDF) provides insight into the expected behavior of the modeled repair time. The most practical method of modeling system performance using normal, log-normal or Weibull distributions is to apply Monte Carlo methods (Ayers, 2012).

iii. Weibull Distributions

This is a flexible distribution in the field of reliability engineering. The flexibility comes from the ability to model many different life time behaviors by careful selection of the shape (α) and scale (λ) parameters. Generally, all but the sophisticated telecommunications systems failure performance models use exponentially distributed TTF (Ayers, 2012). The PDFof a Weibull distributed random variable T, Weibull (α, λ) with $\alpha > 0$ and $\lambda > 0$ is given by equation (2.8)(Ayers, 2012):

$$f(t) = \begin{cases} \alpha\lambda^{\alpha} t^{\alpha-1} e^{-(\lambda t)^{\alpha}}, & for t > 0 \\ 0, & otherwise \end{cases} \tag{2.8}$$

While the CDF of the Weibull distributed random variable T is given by equation (2.9)

$$F(t) = \Pr(T \le t) = \begin{cases} 1 - e^{-(\lambda t)^{\alpha}}, & for t > 0 \\ 0, & otherwise \end{cases} \tag{2.9}$$

where:

λ is the Weibull scale parameter

α is Weibull shape parameter

t is time.

When the shape parameter $\alpha = 1$, the Weibull distribution is equal to the familiar exponential distribution.

The reliability function of a Weibull distributed random variable can be calculated by applying the definition of reliability in terms of the distribution CDF (Ayers, 2012):

This implies that:

$$R(t) = 1 - F(t) = \Pr(T \geq t) = e^{-(\lambda t)^{\alpha}} \text{ for } t > 0 \tag{2.10}$$

Recalling that the failure rate of a random variable is given by

$$Z(t) = \frac{f(t)}{R(t)} = \alpha\lambda^{\alpha} t^{\alpha-1} \qquad \text{for } t > 0 \tag{2.11}$$

where:

$f(t)$ is the probability density function

$R(t)$ is the reliability function

Z (t) is the Weibull failure rate

Empirical curve fitting or parameter experimentation is generally the best methods for selection of the shape and scale parameters for Weibull distributed random variables applied to telecommunications systems models.

2.2.4 Reliability System Modeling Techniques

The approaches for telecommunications networks include Reliability Block Diagram (RBD), Markov analysis and numerical Monte Carlo simulations (Ayers, 2012).

1. **Reliability Block Diagrams:** This is a common method for modeling the reliability of systems in which the order of component failure is not important and for which no repair of the system is required. They are success based networks of components where the mission success probability is calculated as a function of the component success probabilities. RBDs provide quick and easy results, but they sacrifice flexibility and accuracy particularly when used with complex systems topologies (Ayers, 2012).
2. **Markov Chains:** Compared to the RBDs, the Markov chains provide higher accuracy but can be challenging to apply. It also requires models to use exponentially distributed random variables for both failure and repair rates. This limits the model's flexibility. A Markov chain is a stochastic process that possesses the Markov property. The Markov property is simply the absence of memory within the process. This means that the current state of the system is the only state that has any influence on future outcomes. Markov chains are not an appropriate choice for modeling systems where previous behaviors affect the future performance (Ayers, 2012).
3. **Monte Carlo Simulation Models:** All other models presented thus far have assumed that both the TTF and TTR of a system follow an exponential distribution. The exponentially distributed random variable assumption lends mathematical simplicity to both the RBD and the Markov chain models making the mathematics of analysis sufficiently simple that quick results are possible. The results obtained are often useful for 'what if' analysis and for small system designs. The limitations imposed by assuming exponentially distributed TTF and

TTR for a system can lead to unrealistic results in many telecommunications systems. It is in such cases that Monte Carlo is beneficial. Most system models using Monte Carlo simulations involve many hours of model development and implementation (Ayers, 2012). Analysis using this approach has an advantage of allowing the analysis of a system with different failure and repair distributions thereby creating a more accurate model and better representation of the performance. It is computationally intensive and requires significant computing power to complete all but the simple simulations in a timely manner. Figure 2.6 shows a variety of reliability evaluation techniques often used (Rai & Soh, n.d). Several techniques exist for performing system analysis each with its own drawbacks and advantages.

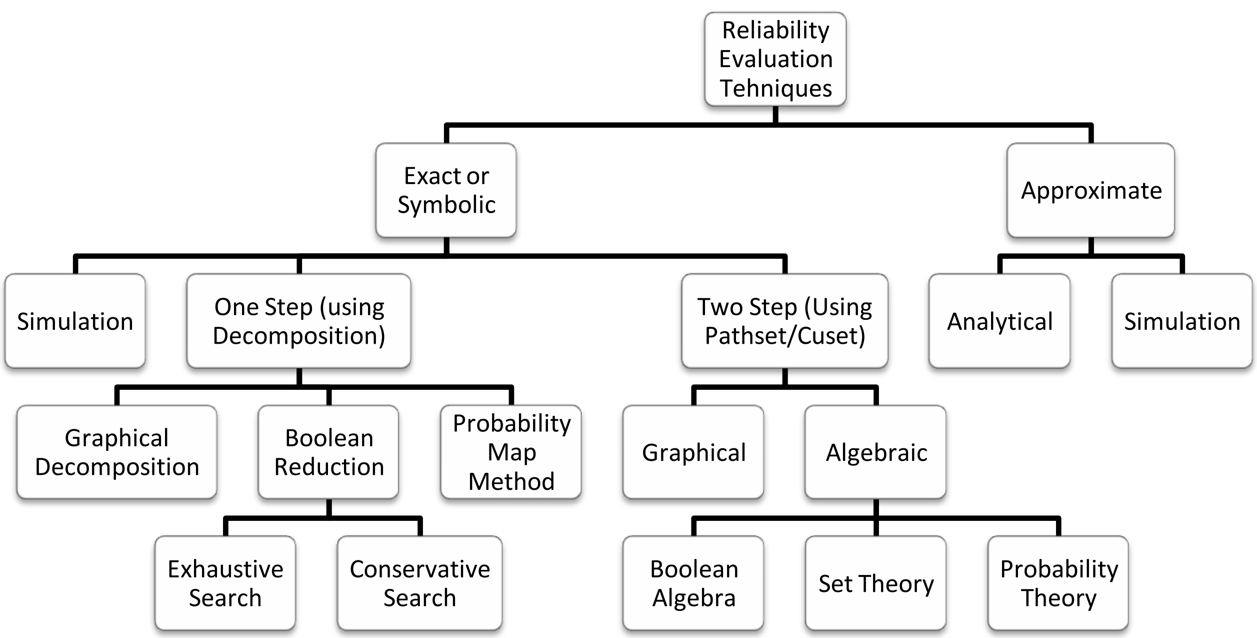


Figure 2.6: Diagram Representing the Reliability Evaluation Techniques (Rai & Soh, n.d).

Figure 2.6 shows the often used reliability evaluation techniques which may be either exact/symbolic or based on approximation (using analytic methods or simulation).

2.2.4.1Link Reliability Model

Figure 2.7 illustrates a seven nodes (A, B, C, D, E, F, and G)network. At any instant of time (t), a direct link can only exist between two nodes if their distance apart is less than the communication range (r). In MANET, link reliability is dependent on the network topology. Figure 2.7 is a geometric graph of a seven node network. The range of node i can be represented as r_i and the circular region surrounding each node represents the area where connection can be established with other nodes. Nodes that fall within the intersection of the connection region of another node can communicate directly with each other. Figure 2.8 shows the connection diagram of the nodes (A, B, C, D, E, F. and G).

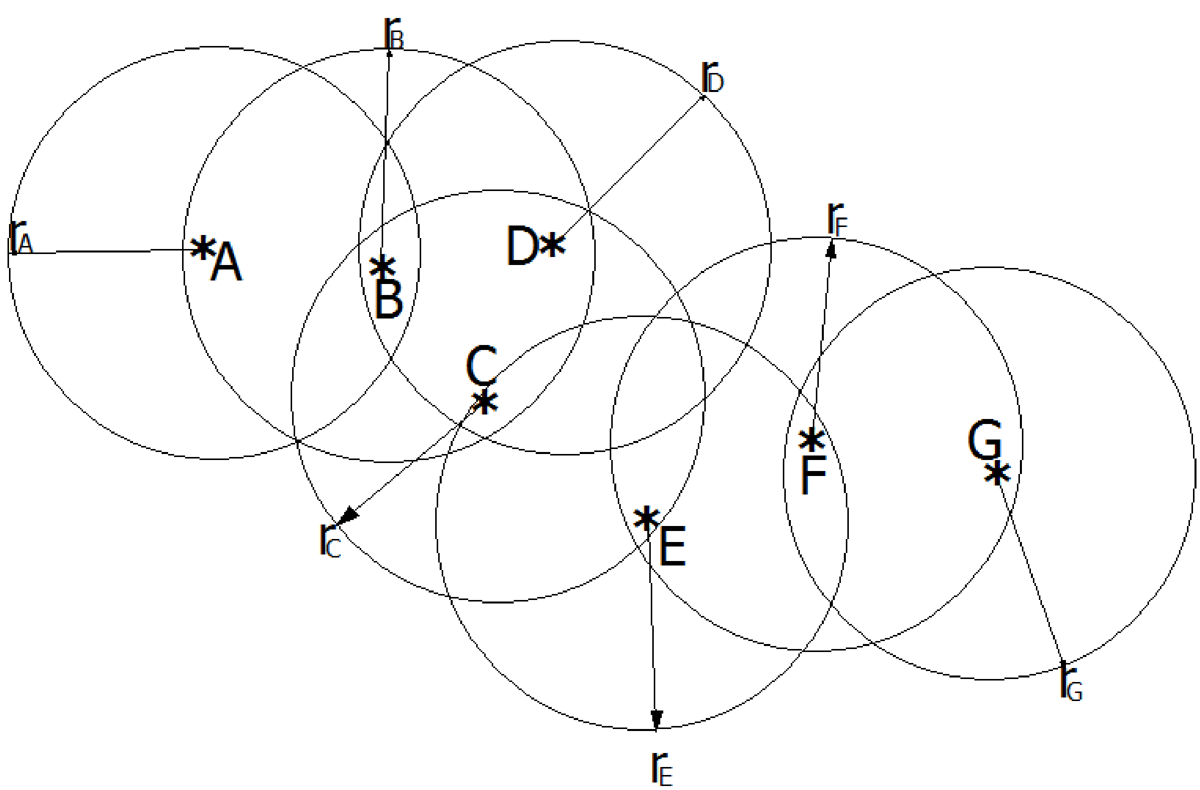


Figure2.7: A Typical Geometric Graph of Seven Nodes MANET (Padmavathy & Chaturvedi, 2013)

In Figure 2.8, direct connections are represented by thick lines while the dashed lines represent arbitrary connections. Direct connections are as a result of the intersections in Figure 2.7. Other nodes are connected through multi-hop transmissions.

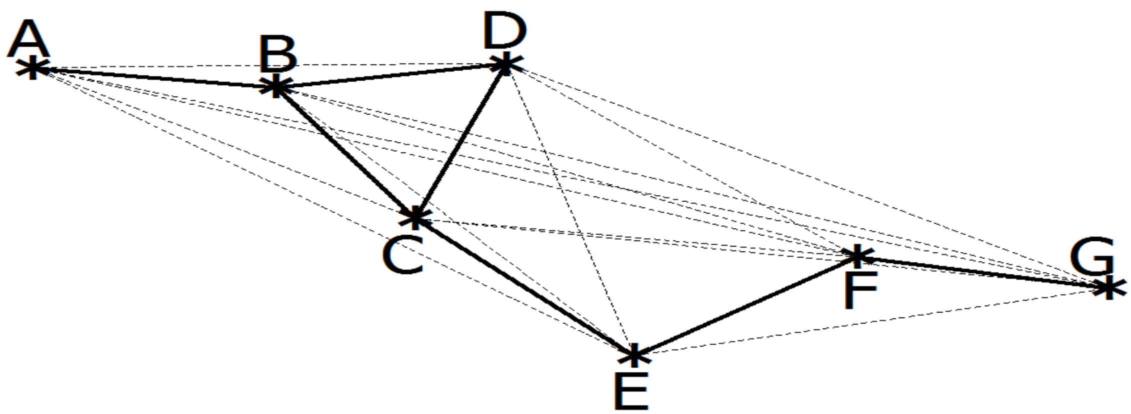


Figure 2.8:Network Graph of Figure 2.7 (Padmavathy & Chaturvedi, 2013)

From Figure 2.8, it can be seen that a direct link exists between node A and B. Nodes A and E are not within each other’s coverage range therefore transmission follows a pattern such as A to B, B to C and C to E or A to B, B to D, D to C and C to E.

A typical MANET with n nodes can have up to $\frac{n(n-1)}{2}$possible links depending on the network topology (Ahmad & Mishra, 2012). Therefore, it is possible to represent these links using a connection matrix of size (n x n). The diagonal of the connection matrix will therefore contain zero elements since link can only exist between two distinct nodes (sender and receiver). The connection matrix for Figure 2.8 is shown in equation (2.12). In Figure 2.8, the paths represented by dashed lines are the arbitrary links, while those which are represented by thick lines are the actual links. In Figure 2.8, it can be observed that direct communication can occur between the following pair of nodes:

B and A

B and C

B and D

D to C

C to E

E to F

F to G

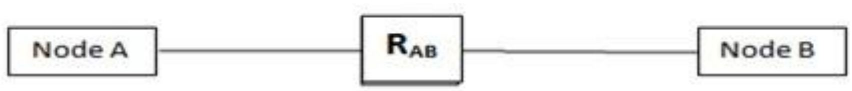
Other forms of communication can occur between distant nodes through intermediate nodes which serve as repeaters to the source signal. The number of possible paths available for information delivery from source to the intended node affects the reliability of the network. In Figure 2.8, only seven out of the 21 possible links are actually available, therefore the reliability of the configuration is low. In other for the network to have high reliability, the mobile nodes must move as closer as possible to each other. This could be achieved by decreasing the coverage area allowable for node mobility. If nodes A, B, C, D, E, F and G are represented with nodes 1, 2, 3, 4, 5, 6, and 7 respectively, then the connectivity matrix of Figure 2.8 can be given by equation (2.12) (Padmavathy & Chaturvedi, 2012). Connectivity matrix is usually used to determine the number of direct links that are available in a particular network topology and to estimate the number of possible paths available for communication between a given pair of nodes.

$$C_{ij} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ .. & 0 & 1 & 1 & 0 & 0 & 0 \\ .. & .. & 0 & 1 & 1 & 0 & 0 \\ .. & .. & .. & 0 & 0 & 1 & 0 \\ .. & .. & .. & .. & 0 & 0 & 1 \\ .. & .. & .. & .. & .. & 0 & 0 \\ .. & .. & .. & .. & .. & .. & 0 \end{pmatrix} \tag{2.12}$$

Figure 2.8 has seven direct links and two possible paths. The re-routing ability of MANETs give such nodes the ability of finding other possible links for communication. Direct links are more reliable than multi- node links. The two terminal reliability as defined earlier is always greater than the all terminal reliability since at least a link can exist between the nodes in the network, then it can exist between all nodes in the network.

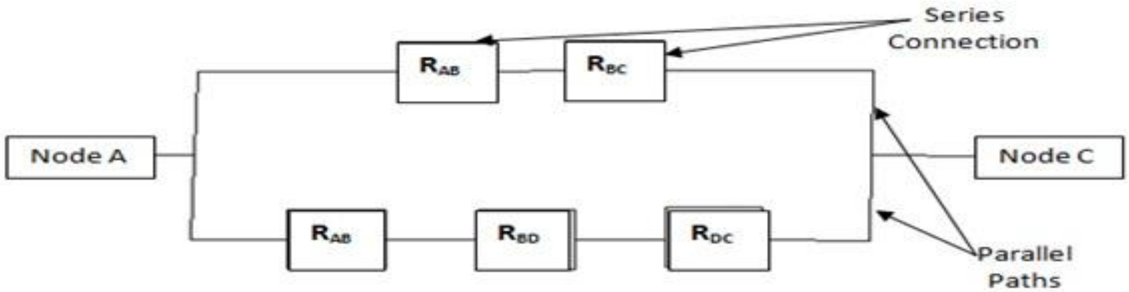
2.2.4.2 Reliability of Series and Parallel Connections

Consider nodes A, B, C and D of Figure 2.8; let R_{ij} be the reliability of the link between i and j, and let A, B and C be the communicating nodes. The link reliability of the communication between the pair of node (A, B), (B, C) and (A, C) can be described using Figure 2.9(a, b and c) (Elsayed, 2012).



(a) Series Connection between Node A and B

(b) Series Connection between Node B and C



(c) Nodes A and C Connection using Series and Parallel Paths

Figure 2.9: Reliability of Nodes Connections

For series path 1 of Figure 2.9(c) is given as:

$$R_1 = R_{AB} R_{BC} \tag{2.13}$$

Similarly for series path 2 of the same figure:

$$R_2 = R_{AB} R_{BD} R_{DC} \tag{2.14}$$

Therefore, for parallel paths 1 and 2:

$$R_{AC} = 1 - (1 - R_1)(1 - R_2) \tag{2.15}$$

Substituting values of R_1 and R_2 from equations (2.13) and (2.14) gives:

$$R_{AC} = 1 - (1 - R_{AB} R_{BC})(1 - R_{AB} R_{BD} R_{DC}) \tag{2.16}$$

2.2.4.3 Link Reliability

The link reliability is a key concept in wireless communications (Kaynia, 2010). It is defined as the probability that a received signal falls below the predefined threshold required for a receiver to successfully decode its packet (Kaynia, 2010). Another alternative way to define it is to consider the rate of the transmission (if the required transmission rate is higher than the Channel

Capacity (CC)), data lost in the channel, and packets received in outage (Kaynia, 2010), thereby degrading the link reliability.

Mathematically, outage probability is defined as (Kaynia, 2010):

$$P_{out} = P_r(SINR \leq \beta) = P_r\left[CC \leq R_{req}\right] \quad (2.17)$$

where:

P_{out} is outage probability

SINR is Signal to Interference plus Noise Ratio

β is SINR threshold required for correct packet reception.

C is channel capacity

R_{req} is requested rate of the transmissions

P_r is probability

The reliability in wireless ad-hoc networks depends on various factors (Kaynia, 2010) including the following:

(i) Node distribution

(ii) Network topology

(iii) Models used for path loss attenuation and fading effects.

Success probability is defined as the probability that a transmission is received successfully at the receiver, that is, the measured SINR is above a certain threshold β for the duration of the packet. This implies that (Kaynia, 2010):

$$\text{Success probability (link reliability)} = 1 - P_{out} \quad (2.18)$$

where:

P_{out} is outage probability

2.2.5 Path Loss

While packets are being forwarded through the network, some loses are inevitable especially in the wireless link (Yasar 2007). Wireless computer networks are apt to failures and loss of access due to:

(i) Environmental conditions

(ii) Changing locations of mobile nodes and changes in components

(iii) Structure easily change the system reliability.

Path loss is the difference between received signal power and transmitted power (Yang, 2010). Many path loss models are available which consider different terrains and other environmental conditions. The wireless channel properties need special attention, that is, path loss and multipath fading models (Chaltseva, 2011). In the indoor environment, the propagation of radio waves is mainly affected by two types of losses: the path loss and the loss due to small and large scale fading (Chaltseva, 2011). The small scale fading arises due to the multipath propagation effect and the large scale fading is due to the shadowing effect. It is well known that path loss accounts for the signal attenuation due to the physical distance between the transmitter and receiver in a wireless scenario (Maala et al., 2009). The transmitter's Radio Frequency (RF) output does not reach the receiver in its original form. The amplitude of an RF signal decreases with distance as the signal spreads out in space. Path loss represents the attenuation which a signal undergoes on the path between the transmitter and receiver and is usually expressed as a ratio of the transmitted and received powers as shown in equation (2.21)(Hassan et al., 2005). This attenuation is typically in the order of d^{-2} to d^{-4} for a distance d depending on the environment (for example, free space or in building) and the radio frequencies being used (De-Couto, 2004). Receivers will receive weaker signals on longer links. In addition, there may be obstacles blocking part of the transmitter's signal such as walls or foliage which will further attenuate the signal seen at the receiver. A signal transmitted by a given node to an intended receiving node gets weak and weaker as it travels along the channel. This loss in signal strength along the transmission path can be attributed to attenuation and fading. Finally, loss in radio hardware such as cables and connectors can also decrease the power of the received signal. For the channel model, only the path loss attenuation effects will be considered ignoring both the short term and long term fading. The total attenuation is referred to as path loss and is typically constant over time for a given radio link, assuming that neither end is moving and that the environment is static. The path loss depends on the distance between the sender and the receiver and the wavelength (λ) (Wazwaz, 2005). The lambda (λ) of the packet transmission is given by the propagation velocity of light (c) divided by the frequency (f) (Yang, 2010):

$$\lambda\ (\mathrm{m}) = \frac{C\ (ms^{-1}}{f\,(Hz)} \tag{2.19}$$

The path loss (L_p) is given by,

$$L_p = \frac{16\pi^2 d^i}{L^2} \tag{2.20}$$

where i is 2 for free space environment, i is 3 or 4 for normal environment.

The received power depends on the path loss as shown in equation (2.21) and the path loss is a function of distance squared as shown in equation (2.20). The farther the distance, the more the power is needed to transmit the signal effectively (Yang, 2010):

$$p_R = \frac{p_T}{L_p} \tag{2.21}$$

where:

p_R is the power of the receiver

p_T is the power of the transmitter.

L_p is path loss.

The received power calculation considers the gains applied on both the transmitter and the receiver antennas as shown by the following Friis equation (Yang, 2010):

$$p_R = \frac{P_T G_T G_R}{L_P} \tag{2.22}$$

where:

P_R is Receiver Power

P_T is Transmitter Power

G_R is Receiver Gain

G_T is Transmitter Gain

Path loss models can be either empirical or analytical in nature (Yang, 2010). Though the models differ in their methodologies, all of them have distance between the transmitter and the receiver as a critical parameter. The most commonly used path loss models are discussed briefly (Yang, 2010) as follows:

1. Free Space Model: This is an analytical model that describes the power loss in free space. In free space, electromagnetic waves diminish as a function of inverse distance square or $\frac{1}{d^2}$ (Yang, 2010), where d is distance between the transmitter and receiver.

In its linear form, the free space path loss model is as shown by Yang (2010):

$$L_p = \frac{(4\pi d)^2}{\lambda^2} \tag{2.23}$$

where

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

λ is wavelength of the signal in meters

equation 2.23 can be presented in decibel (dB form) as follows:

$$L_p = 147.56 - 20\log(f) - 20\log(d) \tag{2.24}$$

Path loss varies strictly as a function of distance. The free space model is mostly used in satellite and deep space communications systems where the signal truly travels through free space.

2. Plane Earth Model: In terrestrial environment, the path loss experienced is worse than that in free space. The most significant difference between terrestrial and free space is the presence of ground (ground reflections) in a terrestrial environment. In addition, there are often obstacles between the Base Station (BS) and the mobile. As a result, the received signal can be made up of signals travelling via direct and indirect paths, that is Line of Sight (LoS) and non LOS and involve refraction and reflection from objects (buildings, trees and hills) between the transmitter and the receiver. Therefore, path loss in terrestrial is higher than that in free space and the extent of the loss is even more strongly influenced by the distance between the transmitter and the receiver. In terrestrial environment, an analytical model known as the plane-earth model is (Yang, 2010):

$$L_p = \frac{{h_t}^2 {h_r}^2}{d^4} \tag{2.25}$$

where

d is distance between transmitter and receiver in meters

h_t is height of transmit antenna in meters

h_r is height of receive antenna in meters

The model analytically calculates path loss by taking into account the phase difference between two paths (the direct path and the ground reflected path). In practice, a correction factor (a) that depends on the frequency of the carrier is added to yield (Yang, 2010):

$$L_p = a \frac{{h_t}^2 {h_r}^2}{d^4} \qquad (2.26)$$

In decibels,

$$L_p = \log(a) + 20log(h_t) + 20log(h_r) - 40log(d) \qquad (2.27)$$

where

Path loss slope is -40dB/decade.

a is correction factor

3. Simple Empirical Model: Although two analytical models presented so far have strong theoretical underpinnings, one based on expanding wave-front in free space and one based on two paths on plain earth. In terrestrial environments, the power loss rarely varies by exactly $\frac{1}{d^2}$ or $\frac{1}{d^4}$. Path loss models often have to be augmented by actual measurements of the propagation environment. A simple empirical model of path loss that can be tuned by measurements is (Yang, 2010):

$$L_p = \left(\frac{\lambda}{4\pi d_{ref}}\right)^2 \left(\frac{d_{ref}}{d}\right)^\alpha \qquad (2.28)$$

where:

d is distance between transmitter and receiver in meters

d_{ref} *is* reference distance, commonly taken to be some fixed distance from the transmitter.

α is path loss exponent (it depends on the actual propagation environment often ranging from 3 in low loss rural areas to 5 in high loss dense urban areas (high loss)).

In decibels form, the path loss, L_p is (Yang, 2010):

$$L_p = 147.56 - 20log(f) - 20log(d_{ref}) + 10\alpha log(d_{ref}) - 10\alpha log(d) \qquad (2.29)$$

For d_{ref} is 1,

$$L_p = 147.56 - 20log(f) - 10\alpha log(d) \qquad (2.30)$$

From equation (2.29), the slope of the equation is $-10\alpha \; dB/decade$

4. Erceg Model: Is an empirical model that is more complex. The Erceg model illustrates a more complicated path loss model that depends on parameters such as frequency, height of the base station, height of the mobile and terrestrial conditions. The model is quite powerful and uses different parameters to model the path loss. It is based on propagation measurements taken at 1.9GHz, but has since been modified for higher frequencies. The median path loss is given by Yang, (2010):

$$L_p = 147.56 - 20log(f) - 20log(d_{ref}) + 10\alpha log(d_{ref}) - 10\alpha log(d) + (C_f)(C_h)$$

(2.31)

where:

f is frequency in Hz

d is distance between base station and the mobile station in meters

α is the path loss exponent

d_{ref} is reference distance (=100m)

C_f is frequency correction factor

C_h is correction factor for the height of the mobile

The path loss exponent (Yang, 2010) is given as:

$$\alpha = a - bh_b + \frac{C}{h_b} \qquad (2.32)$$

where:

h_b = antenna height of the base station in meters (it needs to be between 10m and 80m).

A, B and C are different terrains

The parameters in the path loss exponent expression depend on the three types of terrain ranging from high loss to low loss: terrain A (hilly/moderate to heavy density of trees); terrain B (hilly/light density of trees or flat/moderate to heavy density of trees), and terrain C (flat/light density of trees).

5. Okumura-Hata Model: The Okumura-Hata model is another empirically based path loss model. It was based on extensive empirical measurements taken in urban environments by Okumura and others in 1968. In 1980, Hata simplified the work of Okumura and provided an expression for path loss that later became known as the Okumura-Hata model. The path loss expression is (Yang, 2010):

$$L_p = \text{-}65.55\text{-}26.16log(f) + 13.82log(h_b) + a(h_m) - [44.9 - 6.55log(h_b)]log(d)$$

(2.33)

where:

f is carrier frequency in MHz

h_b is antenna height (in meters) of the base station

h_m *is* antenna height (in meters) of the mobile

d is distance (in Km) between the base station and the mobile user

$a(h_m)$ *is* corrector factor that depends on the height of the mobile antenna.

For many years, it has been a widely used model for predicting path loss in wireless systems, especially at the cellular frequencies.

6. COST 231 Hata Model: Although the Okumura-Hata model has been used in wireless communication for a long time, the model is only valid up to 1.5GHz. The European cooperation in the field of scientific and research (COST) extended the Okumura-Hata model to the COST-231 Hata model, which is an empirical model that is valid up to 2GHz. The path loss predicted by the COST-231-Hata model is (Yang, 2010):

$$L_p = -46.3 - 33.9log(f) + 13.82log(h_b) + a(h_m) - [44.9 - 6.55log(h_b)]log(d)K_o$$

(2.34)

where:

f is carrier frequency in MHz

h_b is antenna height (in meters) of the base station

h_m is mobile antenna height (in meters)

d is distance (in Km) between the base station and the mobile user.

$a(h_m)$ and K_o are used to account for whether the propagation takes place in an urban or a dense urban environment.

2.3 Review of Similar Works

Considerable works have been done by many researchers to predict the link reliability of MANETS. This sub-section presents the review of some key works carried out and published by researchers which are similar to this research work.

Sanso *et al.*, (1991) proposed a reliability measure that takes into account routing and rerouting policies after failures. The performance measure was based on the routing model outcome where lost call traffic was considered. In this work, it was assumed that only the arcs (links) failed, that is, nodes did not fail while in reality, both nodes (physical elements) and arcs could fail. Independence of arc failure was assumed when failures were dependent. Many calls would be lost from failure time to the rerouting time and this effect was not taken into consideration. The work was based on the assumption that the actual flows carried by the link at any given point in time were independent random variables. In reality, they may not be so. The stochastic routing resolution method was used to evaluate the network performance. In the work, the number of states to be taken into account could be tremendously high, therefore, a special enumeration algorithm had to be implemented. The procedure in the work was conceived for circuit switched networks only which is gradually being faced out.

Hayashi & Takeo, (2008) proposed a reliability model to analyze telecommunications networks that did not focus on topological information but focused only on the traffic path information. It was achieved using the top-down approach model which focused only on traffic path level computation with an assumption that only optical fibers fail and that nodes were perfectly reliable which was not accurate because nodes were also subject to failures and their failures could cause total system failure. The mapping from complete-sets to tie-sets enumeration was used after finishing the main algorithm at the traffic path level.

Altiparmak et al., (2009)put forth a new encoding method for using neural network models to estimate the reliability of telecommunication networks with identical link reliabilities. The approach was used for widely varying reliabilities but only highly reliable communications systems were considered which might not be suitable for lower level communication systems reliability solutions. The method was designed to estimate the reliability of networks with identical link reliability which might be a challenge when viewing non identical links reliability. The method did not rely on a vector of all possible links between nodes. It was mentioned that the work had an advantage of being used for multiple network sizes and topologies but equal numbers of network topologies were generated for each design point and they all had same characteristics. However, the general approach cannot discriminate among networks with the same topological inputs.

Kamulina, (2011) proposed an approach of managing the reliability of the network based on their performance with economic losses and cost of the system, profit from the operation of the network and penalties for delay were the parameters used. This was achieved using the analytic approach, though simulation is more flexible than the analytic method and it is more suitable for large networks. The economic losses of users and network owners due to the unreliability of the networks were not looked into. No part of the work was able to show validation in terms of efficiency, reduced calculation time and less complexity as aimed.

Kamulina, (2012) developed mathematical models for reliability with dependent failures. The dependence between the states of the subsystem was considered and formulas for the non stationary and stationary availability co-efficient were derived. Exponential distributed times between failures and arbitrary distributions of recovery times were assumed. This was achieved using probability theory, stochastic processes, and mathematical reliability theory methods with data transmission, data processing and storage, with network control and recovery as main parameters. In the paper, it was assumed that with Network Control Center (NCC) failure, the Access and Transport Network (ATN) and the Computer Processing Center (CPC) would continue to function which is not the case. In the real network situation, when the network control center fails, access and transport network also fail.

The literatures reviewed earlier are based on research in the wired environment. The following works have also been reviewed in the wireless environment research.

Khandani et al., (2005) studied the problem of communication reliability and diversity in multihop wireless networks. A new network model was developed which took the fading nature of the wireless physical layer into account using the outage probability model for a fading channel to develop a probabilistic model for a wireless link. It established a relationship between the link reliability, the distance between communicating nodes and the transmission power. Route diversity was introduced as a way to improve the end to end route reliability by taking advantage of the wireless broadcast property, independence of fade state between different pairs of nodes, and the space diversity created by multiple relay nodes along the route. The outage link was defined in the model as the situation when the instantaneous capacity supported by the link is less than the transmission rate. It was assumed that the fade state was not known to the transmitter which in reality was not so. The probability of the decoder error was assumed approximately zero when channel was not in outage. Instantaneous capacity and fading were modeled as a Rayleigh random variable with assumption that the network operated on a time division protocol which had a weakness because of its need for fixed length messages to fit into time slices. The received signal noise was assumed to be only the zero mean AWGN. The multi hop route approach was treated as a single end to end pipe which does not portray the multi hop environment and therefore cannot give an accurate result.

Dominiak et al.,(2007) compared the currently available reliability algorithm for wired networks with wireless network propagation models in order to present an efficient way to calculate the terminal pair reliability in IEEE802.16 mesh networks. The channel model was based on the path loss, shadowing and fast fading. The path loss model adopted by the IEEE802.16 WG was based on measurements obtained by AT&T wireless services across the united states which considered the hilly terrain and flat terrain, while the multi path fading model was achieved using the Rice distribution with strongest impact being caused by wind and foliage. The link outage probability due to multi path fading of the signal and the link outage probability due to the multi path fading of L statistically independent Rice interferers were assumed to be independent. The uplink and down link were also assumed to be independent. All vertices and edges were considered to fail independently which may not be so because in a failure in the vertices will certainly affect the reliability of the edges and vice versa.

Pal et al., (2008) considered the problem of analytically evaluating the reliability of a general multi-hop, multi-channel, multi-radio, multi-rate cognitive radio network serving a given multi-application demand vector. In the work, spectrum was utilized opportunistically to service demands of various secondary users in a multi hop cognitive radio network, in the presence of primary users. The presence of multiple simultaneous applications in the network was assumed. It was also assumed that each secondary node was equipped with multiple SSCRs and a device either transmits at maximum bandwidth or did not transmit at all which might not be so in most cases. Setting a threshold value for the bandwidth would have reduced this risk. A fixed multi hop wireless network was assumed with n perfectly reliable and homogeneous nodes and that channel properties of communicating nodes were different. Also it was assumed that each radio was capable of fast switching between all the channels, with a switching overhead which seemed unrealistic considering today's expensive switching technologies. Al-Ghanim's heuristic and state space decomposition method were used in the algorithm. Though there was an improvement in the reliability by the increasein the number of radios, the percentage increase was not an increasing trend and may lead to congestion. It was noticed that substantial gains could be achieved by only a small increase in the number of radio resources per node. However, the computation of the mathematical reliability bounds for a multichannel, multi-radio, multi-rate cognitive radio network servicing a multi-application demand is still unsolved.

Onwuka et al., (2011) presented MANET as a reliable network in disaster areas due to the critical needs for telecommunications in disaster reduction. The ease of deployment and infrastructure less nature of the network were some of the reasons why MANET was recommended in disaster areas. However, this paper provided only theoretical results without any technique being used to prove their reasons.

Chen et al.,(2012)proposed the two terminal reliability of a MANET under the asymptotic spatial distribution of the random way point mobility model. The study was performed to assess the effect of nodal density and network topology on network reliability. The probability of link existence under the spatial distribution was not constant. Therefore, the reliability measure would not be the same for all nodes in the network but, a function of the location of the source node. The transmission process was considered probabilistic in nature. Analytical expressions for one and two hop connectivity were developed. However, it was assumed that the system had reached steady state so that asymptotic spatial node distribution could be applied on every node in the system which might not always be so in reality. Based on the method used, for routes of possibly three or more hops, exact analytical expressions for connectivity are difficult to achieve. Thereby the need to bring the model closer to reality.

Singh et al., (2012)addressed theapplication of ant colony optimization algorithm to solve the routing problem in MANETs. Various categories of ant colony algorithm like proactive(table driven), reactive(on-demand), and hybrid(combination of the two) approaches were discussed. The ant colony algorithms allowed for direct agent to agent communication which made them more suitable for MANETs. However, in practical application of ant colony algorithm, the operation factor was the ant residual pheromone update accumulation and gradually to the convergence of the optimal path. But in the early algorithm, the pheromone was very scarce and makes the convergence speed slow down which may limit the accuracy of the results. If a hybrid of the genetic algorithm and the ant colony are used, it might produce a more flexible better result.

Dinakar et al., (2013) presented a comparison between MANETS and opportunistic networks. Frequent occurrence of link failure and challenges in their implementation were also discussed. It was noted that to overcome the frequent link failures, opportunistic networks could be utilized in MANETS. Though the problems, challenges, advantages and limitations were discussed, no solution was given to the issues in this area.

Zhao et al., (2013) presented a novel two terminal reliability for MANET by proposing a node reliability model for MANET with an algorithm to compute the reliability of MANET. The main purpose of the paper focused on the node reliability in the dynamic MANET environment. The random way point model was used. Monte Carlo method was also used for the reliability analysis. Results showed that node failure affected the network reliability. However,it was assumed that every node was of the same type and with the same situation. Also, every node pair within the wireless transmission range was considered to be connected however, this may not be so in reality thereby affecting the efficacy of their model.

Venkatesan *et al.*, (2013) discussed different modeling approaches to evaluate the reliability for which the wireless sensor network was deployed. Quality of service measures were not considered and other link reliability measures such as signal to noise ratio, throughput, delay, power, and bandwidth. However, in this paper, techniques were only suggested without any proof of validation due to real situation application.

Padmavathy & Chaturvedi, (2013) evaluated the MANET reliability using propagation based link reliability model. A hybrid model considering the free space and two ray ground propagation models were used. Imperfect nodes and links were considered and Monte Carlo simulation approach was used. The nodes were modeled using the random waypoint model. It was assumed that there was no signal interference between nodes where as in reality it exists,which was a serious setback in this work.

Sinha & Kanchan, (2014) presented a numerical model of the propagation for predicting narrow band path loss for mobile communication in urban areas. Uniform theory of diffraction (UTD) where shadow and Line of Sight (LoS) zones were considered when the motion mobile antenna was used. Some assumptions were made in the model such as the earth is plain where as it has been proven that the earth is spherical. It had also assumed that the buildings were of uniform height which may not be so in all cases. The buildings were assumed to be replaced by opaque absorbing screens which imply that it cannot be used for real situations. The line of sight (LOS) propagation was achieved using the 2 ray model which was not generally accurate for cities or indoors. However, the UTD could complicate and slow down many realistic propagation calculation procedures thereby affecting the efficacy of the results.

Manickavelu & Vaidyanathan, (2014) proposed a particle swarm optimization (PSO) based node and link life time prediction algorithm for route recovery in MANET. Though the minimization of data loss and communication overhead using PSO prediction was achieved, the PSO technique easily suffers from the partial optimism, which causes less exactness at the regulation of its speed and the direction. Therefore, this limits the results obtained from this work.

Umapathi et al., (2015) presented a hybrid ant routing algorithm for reliable through-put using MANET. The algorithm made use of ant like mobile agents which sample the nodes between source and destination. It was noted that the increase in throughput resulted in higher efficiency. Though the ant colony optimization reduced the time needed for connection set up and ensured the delivery of data, but analysis was difficult. Its probability distribution also changed by iteration and time to convergence was uncertain. These are some of the limitations to this work which could affect the precision of the work.

In view of the shortcomings identified in the reviewed literatures, this research proposal is to predict the link reliability in a wireless mobile ad-hoc network due to path loss effects using Weibull distribution. It is aimed at developing a more robust model considering Padmavathy & Chaturvedi's work in which bandwidth and signal to interference plus noise ratio will be introduced as additional metrics. this is because a gap is still not filled due to the fact that MANETs are bandwidth constrained and SINR is a critical issue in wireless networks which must be filled.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This section describes the detailed procedure carried out to estimate the link reliability of a mobile ad hoc network. This was achieved using the Weibull distribution and simulated using the developed MATLAB based GUI.

3.2 Development of Signal Propagation Model

In this work, a hybrid signal propagation model based on the traditional Free-Space (FS) and the Two Rays to Ground (TRG) is used. This model is termed as the FS-TRG model. The link reliability based on the proposed propagation model can be explained with the aid of Figure 3.1 (Padmavathy & Chaturvedi, 2013). In this model, signal propagation is assumed to depend on two parameters (δ and γ), δ is a fraction of the transmission range (r) and its value lies between zero (0) and one (1). Therefore the product δr_j is less than or equal to one and thus it represents the maximum distance d_{ij} for which the link reliability is equal to one. For any distance d_{ij} less than δr_j, the reliability of link ij is equal to one. γ is also a fraction of the transmission range (r) and its value also lies between zero (0) and one (1). Therefore, the product γr_j is less than or equal to one and thus it represents the maximum distance d_{ij} for which the link reliability obeys the FS model. For any distance d_{ij} less than γr_j, the reliability of link ij obeys the FS model. The value of γ is always greater than or equal to δ. Therefore, the link reliability only obeys the TRG model if and only if the distance d_{ij} is greater than γr_j, but less than r_j (Padmavathy & Chaturvedi, 2013).

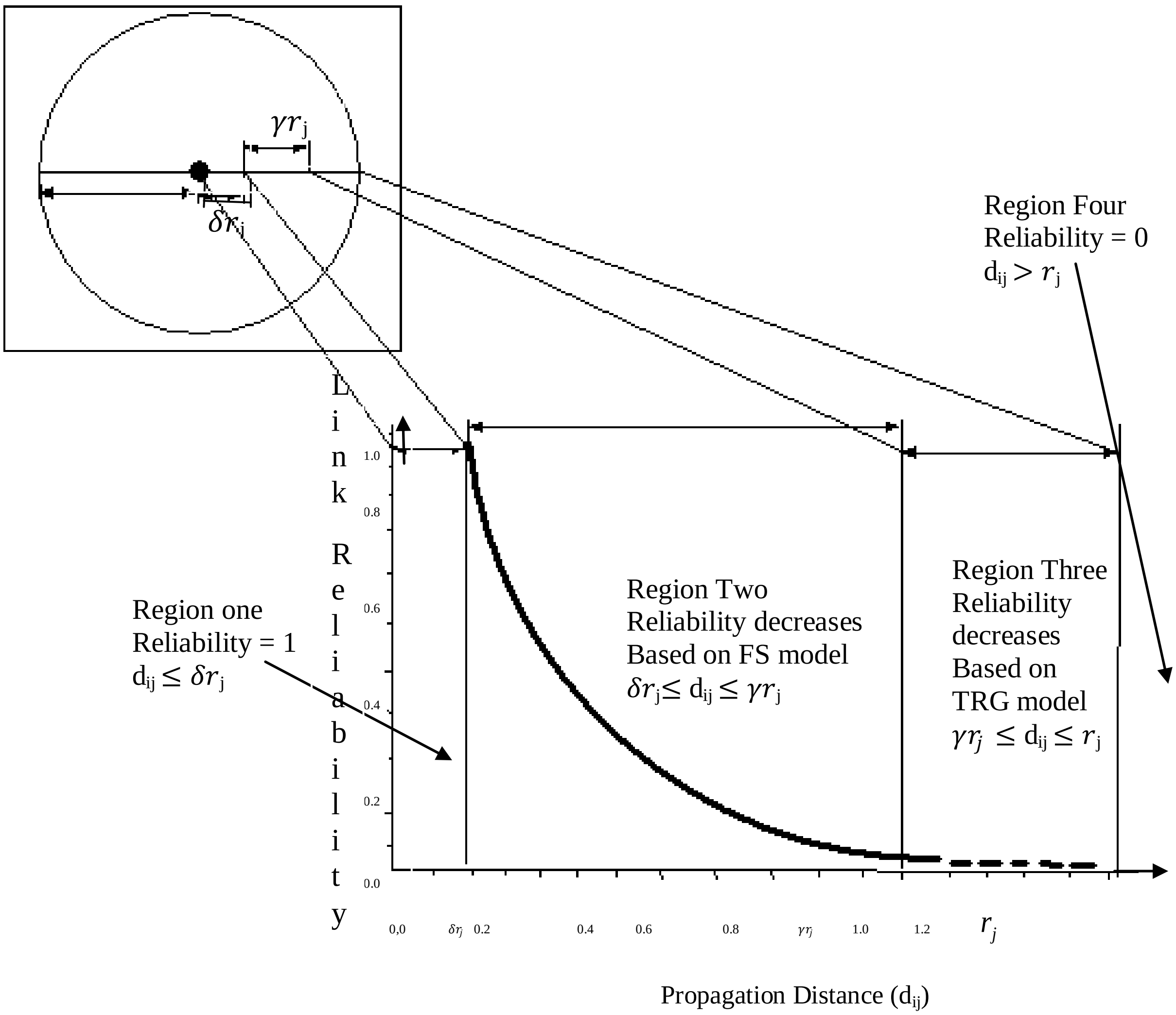


Figure 3.1: Link Reliability Based on Propagation Model (Padmavathy & Chaturvedi, 2013**)**

3.3 Development of Network Reliability Model

At any instant, within the time specified for a complete transmission, that is, sender to receiver, MANET can be represented as a fixed geometric random graph G (U, L, t) consisting of a set of n number of mobile nodes moving according to RWPM, with a set of L communicating links (Baskaran & Padanicamy, 2013). The time-to-failure of nodes follow a known failure distribution and links are established in a single or multi-hop fashion based on the nodes' proximity, transmission range and propagation-based link reliability model. The successful communication between a set of nodes is a random event with a probability R_G (t) given that all the nodes are in U, where k nodes must be operational. For instance, for communication to exist between the designated node-pair (s, r), it is necessary that the (s, r) pair must be operational. Mathematically, let G (U, L, t) be a representative network with a set of U designated nodes. Then, reliability of the network can be expressed as shown in equation (3.1) (Padmavathy & Chaturvedi, 2013).

$$R_G(\tau) = \left(\prod_{\mathrm{u_i} \in k} R_{u_i}(\tau)\right) R_{(G/k)}(\tau) \tag{3.1}$$

where

$R_G(\tau)$ is the network reliability

R_{u_i} is the reliability of the ith node

$R_{(G/k)}(\tau)$ is the reliability of the operational nodes in the network

Therefore, equation (3.1) is utilized to compute the reliability of MANET at a particular instant within the communication duration. It should be noted that the failure of designated nodes will certainly lead to network failure.

3.4 Development of Node Mobility Model

In this work, the mobile nodes are assumed to move within the simulation boundary according to Random Way Point Mobility (RWPM) model. Here, the nodes move to new location by selecting a velocity between (Vmin, Vmax) and direction (0, 2π). If any node reaches the boundary, it reflects and comes inside the simulation region. The new positions of the nodes overtime were determined at regular time intervals dt and at every incremental time interval the new node positions can be calculated as a function of velocity and direction using equations (3.2) and (3.3) (Neogy et al., 2011).

$$x_i(\tau + \Delta\tau) = x_i(\tau) + \Delta\tau . v_i(\tau). \cos\emptyset_i(\tau) \tag{3.2}$$

$$y_i(\tau + \Delta\tau) = y_i(\tau) + \Delta\tau . v_i(\tau). \sin\emptyset_i(\tau)\} \tag{3.3}$$

where:

$x_i(\tau + \Delta\tau)$ and $y_i(\tau + \Delta\tau)$ are the new Cartesian coordinates of node i at the new time instant $\tau + \Delta\tau$;

$x_i(\tau)\ and\ y_i(\tau)$ are the initial Cartesian coordinates of node i at initial time instant τ;

$\Delta\tau$ is the incremental time instant;

$v_i(\tau)$ is the velocity of node i at time instant τ; and

$\emptyset_i(\tau)\ is$ the motional direction of node i at time instant τ.

These can be explained using Figure 3.2. It depicts the direction of change at different locations of simulation boundary of the Mobile Nodes (MN). In case a MN violates the boundary due to its movements, then the MN is forced to move within the boundary based on its location. This can be achieved by modifying the direction of the MN with which it moves. For example, when an MN lies in the region ($x_i(t)$, X_{max}, $y_i(t)$, Y_{max}), then the direction is changed to about 225^o and the MN is made to reach the position (X_{max}, Y_{max}). Then the MN continues along this new path. In a similar fashion, validity checks in the implementation of RWPM for nodes to move within the simulation area for all eight different positions can be simulated.

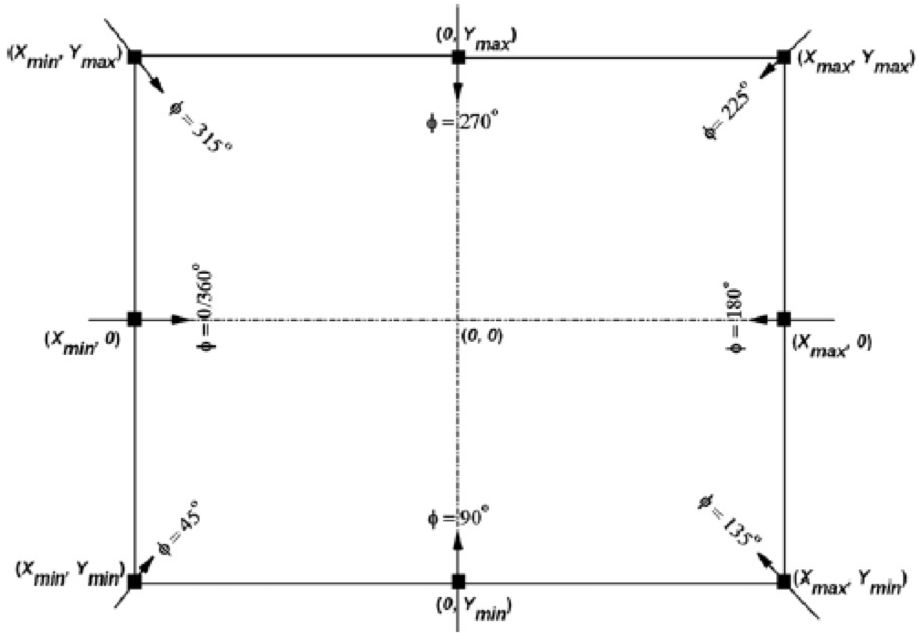


Figure 3.2: Direction of Change for Different Locations of the MN (Padmavathy & Chaturvedi, 2013).

3.5 Development ofNode Reliability Model

The MNs in the network are defined by a vector $\vec{\boldsymbol{u}}$ with its individual status defined as $u_i$where i is 1, 2, .,n, and u_i, are the elements in the network. The nodes in the network are not perfectly reliable. Instead, their failure times follow a Weibull distribution with a certain scale (θ) and shape (β) parameter. Therefore, the reliability of a node is defined using equation (3.4) (Padmavathy & Chaturvedi, 2013).

$$R_{ui}(\tau) = Pr(u_i(\tau) = 1) = e^{(-\tau/\theta)^{\beta}} \quad (3.4)$$

where:

$$u_i(\tau) = \begin{cases} 1 & if i^{th} node is operational at time \tau \\ 0 & if i^{th} node fails at time \tau \end{cases} \quad (3.5)$$

$R_{ui}(\tau)$ is the reliability of ith node in the universal set U of mobile nodes at time instant τ;

Pr(·) is the probability that a given event will occur;

$\theta, and\ \beta$ are the weibull scale and shape parameters respectively;

3.6 Development of Link Reliability Model

The link parameters of MANET such as Channel Capacity (CC), Bandwidth (B), Noise (N), Path Loss (PL), etc. can be used in order to determine the reliability of a given path required for communication between a set of nodes. In this work, the signal propagation model is represented by Figure 3.1. In the model, reliability of any signal path is dependent on the path length and the number of possible paths. Equation (3.11) shows a relationship between the CC, B, N, and received power P_r.

$$\mathrm{CC} = \mathrm{B}\log_2\left(1 + \frac{\mathrm{P_r}}{\mathrm{NB}}\right) \text{(Ali et al., 2014)} \tag{3.6}$$

and

$$\mathrm{N} = \mathrm{KT} \tag{3.7}$$

Where:

CC is the channel capacity (bps)

B is the bandwidth (Hz)

P_r is the receiver power (W)

N is the noise

K is the Boltzmann constant (1.3806503e-23$m^2 kg s^{-2} k^{-1}$)

T is the temperature in Kelvin (K)

Based on the FS model it can be shown that

$$P_r = \frac{C_l^2 P_t}{(4\pi df)^2} \qquad (3.8)$$

By substituting equation (3.7) and (3.8) into (3.6), equation (3.9) results:

$$\text{CC}= Blog_2\left(1 + \frac{C_l^2 P_t}{(4\pi df)^2 KTB}\right) \qquad (3.9)$$

Equation (3.9) can be further simplified as follows:

$$2^{\left(\frac{CC}{B}\right)} = 1 + \frac{C_l^2 P_t}{(4\pi df)^2 KTB} \qquad (3.10)$$

$$(4\pi df)^2 KTB = \frac{C_l^2 P_t}{2^{\left(\frac{CC}{B}\right)} - 1} \qquad (3.11)$$

$$(4\pi df)^2 = \frac{1}{KTB}\left[\frac{C_l^2 P_t}{2^{\left(\frac{CC}{B}\right)} - 1}\right] \qquad (3.12)$$

Equations (3.13) and (3.14) give the maximum allowable length of communicating link (d) for the path loss not to exceed the maximum allowable value in terms of CC and SINR, respectively.

$$d = \frac{1}{4\pi f}\sqrt{\frac{1}{KTB}\cdot\left[\frac{C_l^2 P_t}{2^{\left(\frac{CC}{B}\right)} - 1}\right]} \qquad (3.13)$$

$$d = \frac{1}{4\pi f}\sqrt{\frac{1}{KTB}\cdot\left[\frac{C_l^2 P_t}{SINR}\right]} \qquad (3.14)$$

d can be replaced by r which stands for the range. Therefore, r is the maximum distance between the transmitter and the receiver for which there can be direct communication.

$$r = \frac{1}{4\pi f}\sqrt{\frac{1}{KTB}\left[\frac{C_l^2 P_t}{2^{\left(\frac{CC}{B}\right)}-1}\right]} = \frac{1}{4\pi f}\sqrt{\frac{1}{KTB}.\left[\frac{C_l^2 P_t}{SINR}\right]} \tag{3.15}$$

Finally, by varying the parameters of the network, a required transmission range can be determined. Various conversions can be applied to equation (3.15) to allow parameter definition in the required unit (Padmavathy & chaturvedi, 2013):

In general, link reliability based on FS-TRG model can be given as follows (Padmavathy & Chaturvedi, 2013):

For node i and j:

$$R(d_{ij}) = \begin{cases} 1 & for d_{ij} \leq \delta r \\ \frac{\delta^2}{(1-\delta^2)}\left[\frac{r^2}{d_{ij}^2}-1\right] & \text{for } \delta r < d_{ij} < \gamma r \\ \frac{\delta^2\gamma^2}{(1-\delta^2)(1+\gamma^2)}\left[\frac{r^4}{d^4}-1\right] & for \gamma r < d_{ij} < r \\ 0 & r \leq d_{ij} \end{cases} \tag{3.16}$$

The Two Terminal Reliability R_{TTR} can also be given as follows (Ali et al., 2014):

$$R_{TTR} = R_i R_j \left[\sum_{x=1}^{L} R_{path(x)}\right] \tag{3.17}$$

where:

R_i *and* R_j are the reliabilities of nodes i and j respectively.

$R_{path(x)}$ is the reliability of connection path x

L is number of possible paths between the intending communicating nodes.

In this work, equation (3.15), (3.16), and (3.17) were used to model the MANET link reliability problem in MATLAB. The MATLAB functions (script) are shown in appendix C.

3.7 Implementation of the Link Reliability Algorithm

The flow chart of the developed link reliability algorithm is shown in Figure 3.3 and the algorithm is described by the following steps:

1 Define the required parameters needed for simulation

2 Determine the reliability of the nodes at time t using Weibull distribution

3 Define the node position (initial network topology)

4 Estimate the Two Terminal Reliability (TTR) of the network based on equations (3.16) and (3.17) and the range (r) estimated using equation (3.15).

5 Simulate mobility using Random Way Point Mobility (RWPM)

6 Re-estimate the reliability of the network active nodes, and compute the link reliability again based on the new topology.

7 Increment the time and perform instructions 5 and 6 until the simulation time is exhausted.

8 Print the final result.

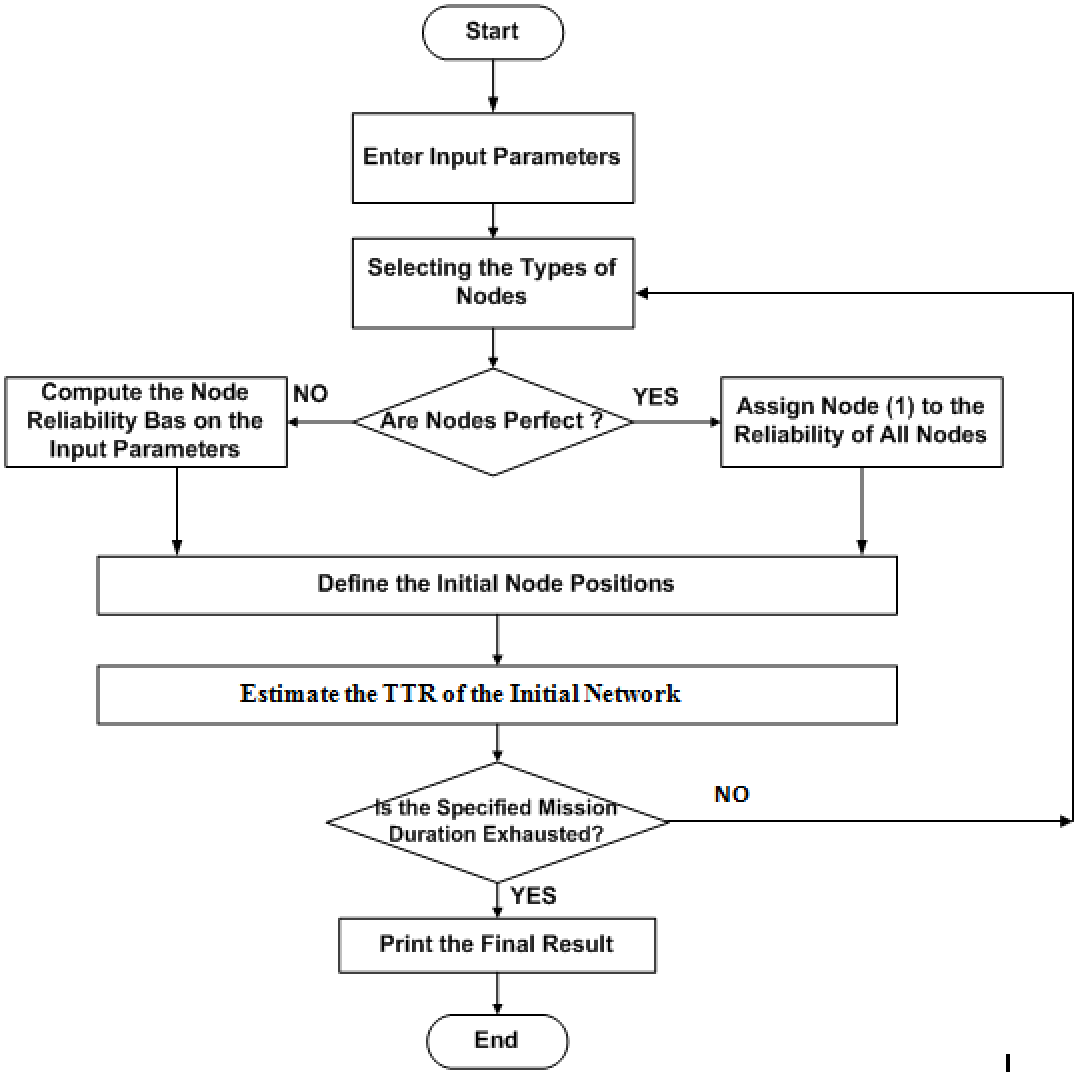


Figure 3.3: Flow Chart of the Link Reliability Algorithm of the Network.

3.8Input Parameters

The list of parameters required as input to the developed simulator in other to simulate the link reliability of MANET is as follows:

1. Sigma ($0<\delta<1$)
2. Gamma ($0<\gamma<1$)
3. Source Node Number (Sender)

4. Sink Node Number (Receiver)
5. Operating Frequency (f. MHz)
6. Number of Simulation Runs
7. Number of Mobile Nodes (n)
8. Bandwidth (B. Hz)
9. Pause Time (dt. Sec)
10. Coverage Area (A. Sq. m)
11. Operating Temperature (T. K)
12. Weibull Scale Parameter (ϴ)
13. Transmitted Signal Power (mW)
14. Minimum Velocity Node (m/s)
15. Maximum Velocity Node (m/s)
16. Weibull Shape Parameter (β)
17. Communication Duration (Mission Time sec.)
18. Threshold Value (dB or Mbps)
19. Choice of Threshold Value (SINR or Channel Capacity (CC))
20. Choice of Node Type (Perfect or Non-Perfect)

The developed simulator and the parameters used are shown in Figure 3.4. This simulator is based on a hybrid of Free Space (FS) and Two Rays to Ground (TRG) models.

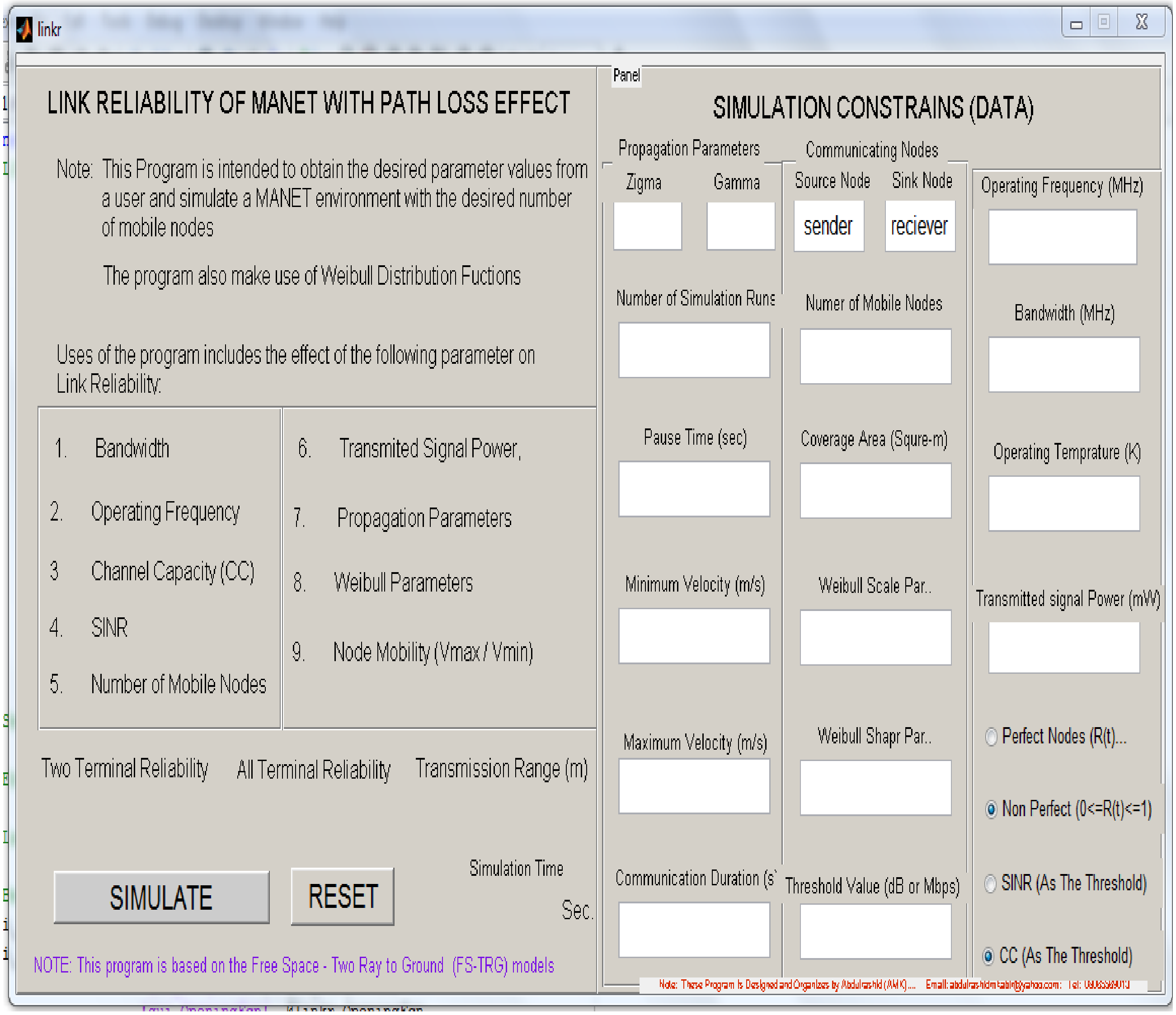


Figure 3.4:Developed Link and Node Reliability Simulator.

The MATLAB Functions (Script) that run the developed simulator (GUI) are shown in Appendices B and C.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

In this section, different scenarios of MANET link reliability are simulated using the developed simulation tool (MATLAB GUI). The GUI was used for all simulations and the results obtained were plotted in the MATLAB environment. The MATLAB function scripts for the simulation are given in the Appendices B and C. The validation is also discussed in section 4.3.

4.2 Results

The simulation results obtained were plotted against the individual metrics considered. Here, the effect of: (i) coverage area, (ii) range, (iii) communication duration, (iv) number of mobile nodes, (v) bandwidth, and (vi) signal to interference plus noise ratio on the link reliability were then presented graphically.

4.2.1Effect of Coverage Area on the Link Reliability

The effect of coverage area on link reliability can be studied using the developed simulator by keeping the allowable communication range constant at 3m and varying the coverage area. In this work, the coverage area is varied at an interval of 50square-meter. In Figure 4.1, each of the curves has a unique propagation parameter (δ and γ) setting as indicated in the legend. In Figure 4.1, it could be observed that as the coverage area increased, the MANET link reliabilitydecreased, and the higher the product of δ and γ, the higher the link reliability.

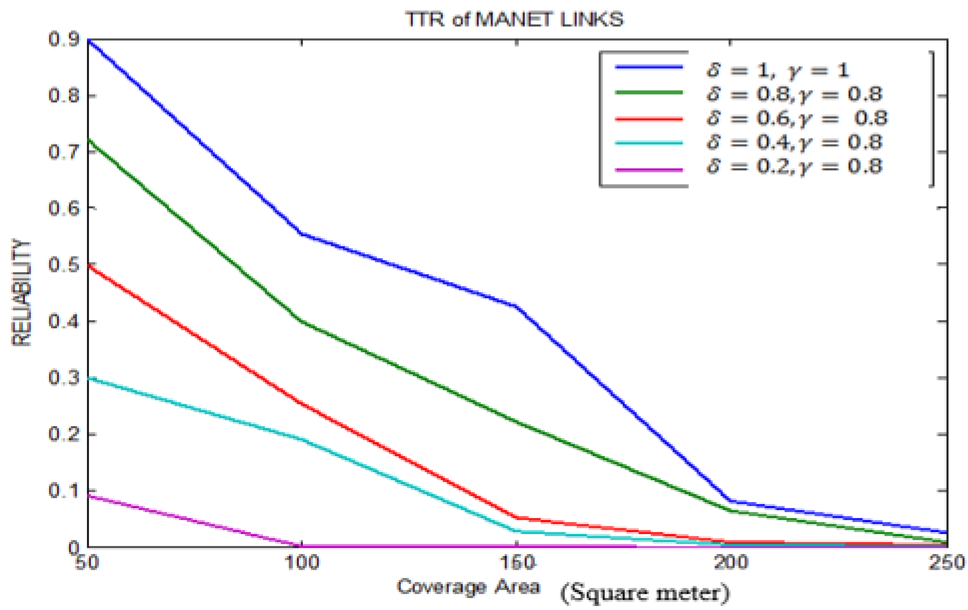


Figure 4.1: Graph showing the Effect of Coverage Area on Link Reliability

4.2.2 Effect of Range on the MANET Link Reliability

The effect of range on link reliability can be studied using the developed simulator by keeping the allowable coverage area (region within which the mobile nodes are allowed to move) constant at 64m-sqr and varying the range. In this work, the motion of the mobile nodes is assumed to follow a RWPM and the coverage area is assumed to be square in shape. Therefore, for a coverage area of 64m-square, the length of the square sides is 8m. As the communication range is varied from 3 to 8m, the probability that the nodes are closer to one another increases and therefore the link reliability increases. In Figure 4.2, each of the curves has a unique propagation parameter (δ and γ) setting as indicated in the legend. In Figure 4.2, it could be observed that: as the range increase, the MANET link reliability increases, and the higher the product of δ and γ, the higher the link reliability.

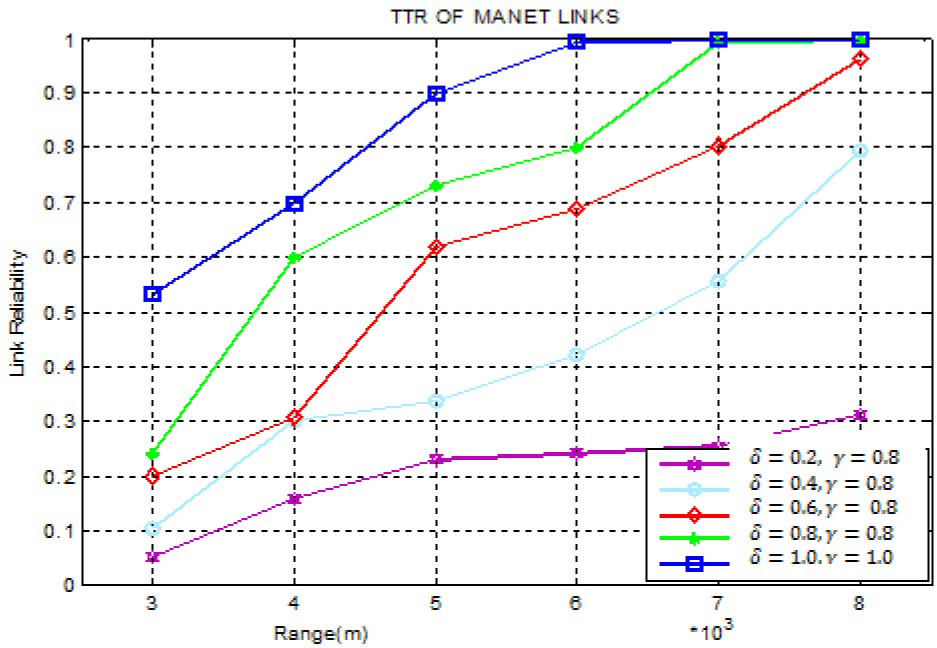


Figure 4.2: Graph showing the Effect of Range on Link Reliability

4.2.3 Effect of Communication Duration on the MANET Link Reliability

The effect of communication duration on link reliability can be studied using the developed simulator by keeping the allowable communication range and coverage area constant at 3m and 64m-square respectively while the communication duration is varied. In this work, the communication duration is varied between 500 and 3000 sec. at an interval of 500 sec. In Figure 4.3, each of the curves has a unique propagation parameter (δ and γ) setting as indicated in the legend. In Figure 4.3, it could be observed that as the communication duration increases, the MANET link reliability slightly decreases. This is due to the fact that some nodes might become imperfect over time. The higher the product of δ and γ, the higher the link reliability.

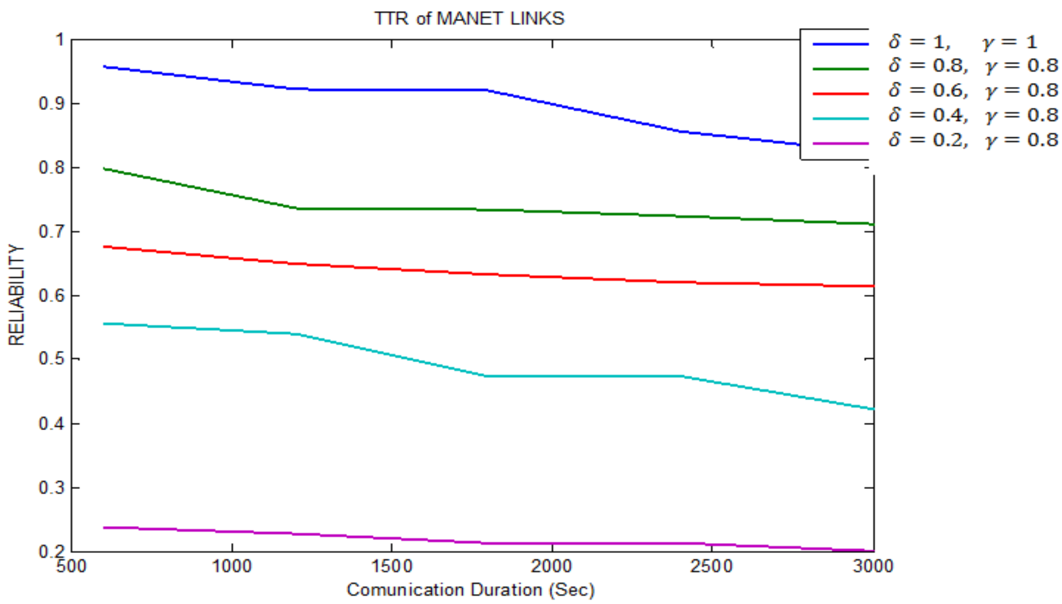


Figure 4.3: Graph showing the Effect of Communication Duration on the Link Reliability.

4.2.4 Effect of Number of Nodes on the Link Reliability

The effect of number of nodes on link reliability can be studied using the developed simulator by keeping the allowable communication range and coverage area constant at 3m and 64m-square, respectively while the number of nodes is varied. In this work, the number of nodes is varied between 20 and 100 at an interval of 20. In Figure 4.4, each of the curves has a unique propagation parameter (δ and γ) setting as indicated in the legend. In Figure 4.4, it could be observed that as the number of nodes increases, the MANET link reliability increase. This is due to the increase in node density over fixed coverage which increases the possibility of connection. The higher the product of δ and γ, the higher the link reliability.

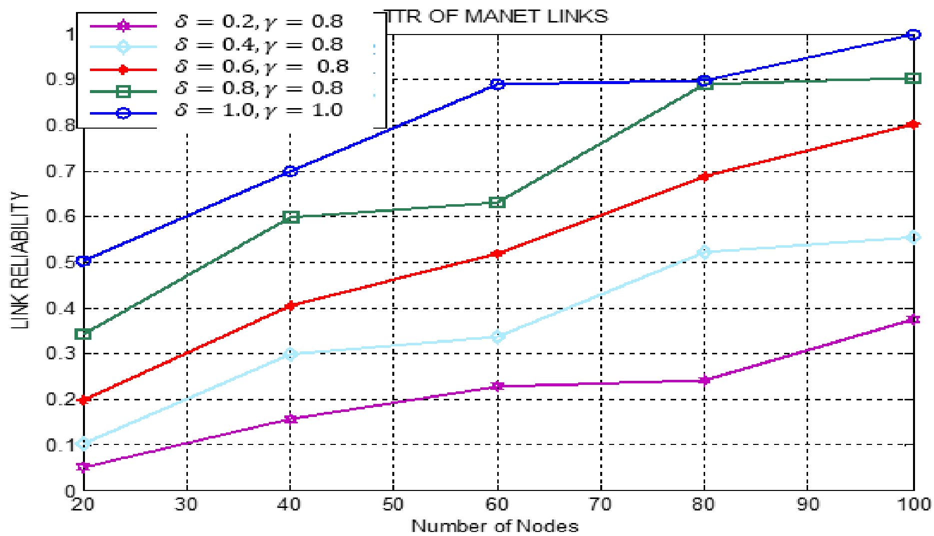


Figure 4.4: Graph showing the Effect of Number of Nodes on Link Reliability

4.3Validation

The model was developed to be user dependent, but for the purpose of validation, similar parameters used by Padmavathy & Chaturvedi, (2013) were also used in this work. The parameters are presented in Table 4.1

Table 4.1: Table showing Parameters used for Validation.

S/N	Parameters	Definition	Values	Values in S.I Units
1	N	Number of nodes	18	18
2	T	Time of operation	72hrs	259200s
3	R	Transmission range	3miles	4.827m
4	θ	Weibull	1000	1000
5	β	Weibull	1.5	1.5
6	A	Coverage Area	65 sq. miles	168,350,000m^2
7	V_{max}	Maximum Velocity	6miles/hr	2.70m/s
8	V_{min}	Minimum Velocity	3miles/hr	1.34m/s
9	n_{sim}	No. of simulation runs	10,000	10000
10	δ	Free Space Parameter	0< $\delta \leq 1$	0< $\delta \leq 1$
11	γ	Two ray ground parameter	$\delta < \gamma \leq 1$	$\delta < \gamma \leq 1$

Based on the parameters presented in Table 4.1, the performance of the developed model was evaluated using the relationship between link reliability and each of the following:

(i) Network coverage area

(ii) Network range

(iii) Communication duration

(iv) Number of mobile nodes

(v) Bandwidth

(vi) SINR.

Each of these elements has an effect on the link reliability. The relationships of each of these elements on link reliability are discussed in subsections 4.3.1 through 4.3.5.

4.3.1 Performance evaluation using link reliability and coverage area (m^2)

In order to evaluate and validate the performance of the developed model, the model parameters presented in Table 4.1 were employed. Various propagation parameters were used and the corresponding simulation results obtained for each parameter are shown in Table 4.2.

Table 4.2: Table of Coverage Area and Link Reliability.

s/n	**LinkReliability**					**Coverage Area (m^2) $\times 10^6$**
	$\delta = 0.1,$ $\gamma = 0.8$	$\delta = 0.2,$ $\gamma = 0.8$	$\delta = 0.4,$ $\gamma = 0.8$	$\delta = 0.6,$ $\gamma = 0.8$	$\delta = 1.0,$ $\gamma = 1.0$	
1	0.025	0.075	0.300	0.750	0.825	129.50
2	0.020	0.060	0.200	0.400	0.700	168.35
3	0.018	0.017	0.125	0.250	0.430	259.00
4	0.016	0.016	0.075	0.135	0.275	378.14
5	0.005	0.005	0.005	0.075	0.150	582.75

The results presented in Table 4.2 were plotted for every propagation parameter and the responses of the graphsgenerated are shown in Figure 4.5.

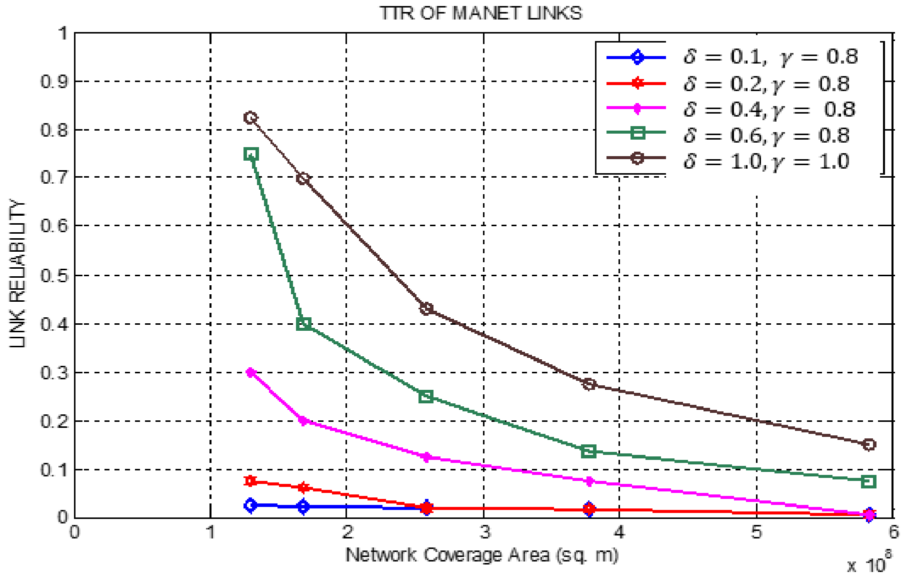


Figure 4.5: Effect of Coverage Area onLink Reliability Graph of Improved Model

The results on Table 4.2 and the graphs on Figure 4.5 for the model of this work correspond to those presented by Padmavathy & Chaturvedi, (2013), though the two models are not thesame. The two models showed that link reliability decreases with increase in network coverage area. Also, it could be observed that the higher δ and γ values, the higher is the link reliability for both models. Since the designed model agreed with an already established model of Padmavathy & Chaturvedi, (2013), it proved the authenticity and validity of the new model. However, in order to show the difference in performance between this new approach and that of Padmavathy & Chaturvedi, (2013), the variation of link reliability with network coverage area of both models were plotted together as shown in Figure 4.5 to give an indication which model performs better.

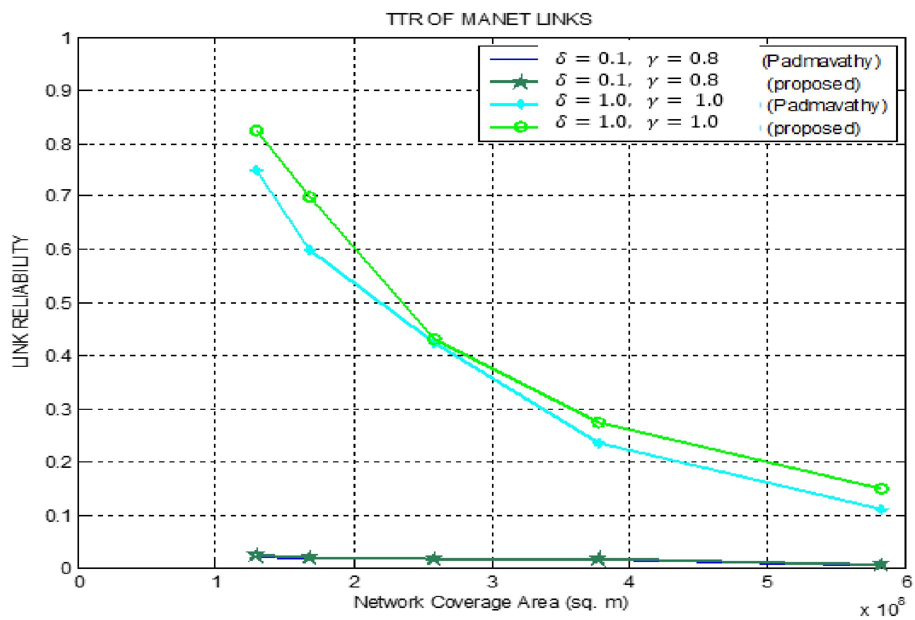


Figure 4.6: Link Reliability of Padmavathy & Chaturvedi, (2013) and Developed Model with respect to Coverage Area

From Figure 4.6,it can be observed that the developed approach attained a maximum link reliability of 82.5% as compared with Padmavathy& Chaturvedi's approach which has a maximum link reliability of 75.5%. Both approaches attained the maximum when the network coverage area was $129.5\times 10^6 m^2$ for $\delta = 1$ *and* $\gamma = 1$. Simialrly, for $\delta = 0.1$ *and* $\gamma = 0.8$ which represent the worst case scenariothe developed model slightly performed better with a maximum of 2.50% as compared with Padmavathy & Chaturvedi,(2013) whose maximum link reliability was 2.3%. This shows the robustness of the approach used in this research and how better it is with respect to link reliability when compared to an existing model.

4.3.2 Performance Evaluation using Link Reliability and Range(m)

Another metric used for measuring the performance was the link reliability and transmission range. Values of other network parameters such as coverage area, time, etc were kept constant,while the transmission range was changed to observe its effect on the link reliability. The simulation of this set up was run and its results recorded as shown in Table 4.3.

Table 4.3: Table of Transmission Range and Link Reliability

s/n	Link Reliability					Range (m)
	$\boldsymbol{\delta = 0.1, \gamma = 0.8}$	$\boldsymbol{\delta = 0.2, \gamma = 0.8}$	$\boldsymbol{\delta = 0.4, \gamma = 0.8}$	$\boldsymbol{\delta = 0.6, \gamma = 0.8}$	$\boldsymbol{\delta = 1.0, \gamma = 1.0}$	
1	0.010	0.050	0.200	0.380	0.670	4827
2	0.030	0.120	0.450	0.700	0.920	6436
3	0.065	0.270	0.760	0.950	0.970	8045
4	0.090	0.400	0.800	0.945	0.960	9654
5	0.150	0.550	0.880	0.940	0.940	11263
6	0.200	0.650	0.900	0.940	0.936	12872

The results presented in Table 4.3 were plotted for the individual propagation parameters and the responses of the graphs generated are shown in Figure 4.7.

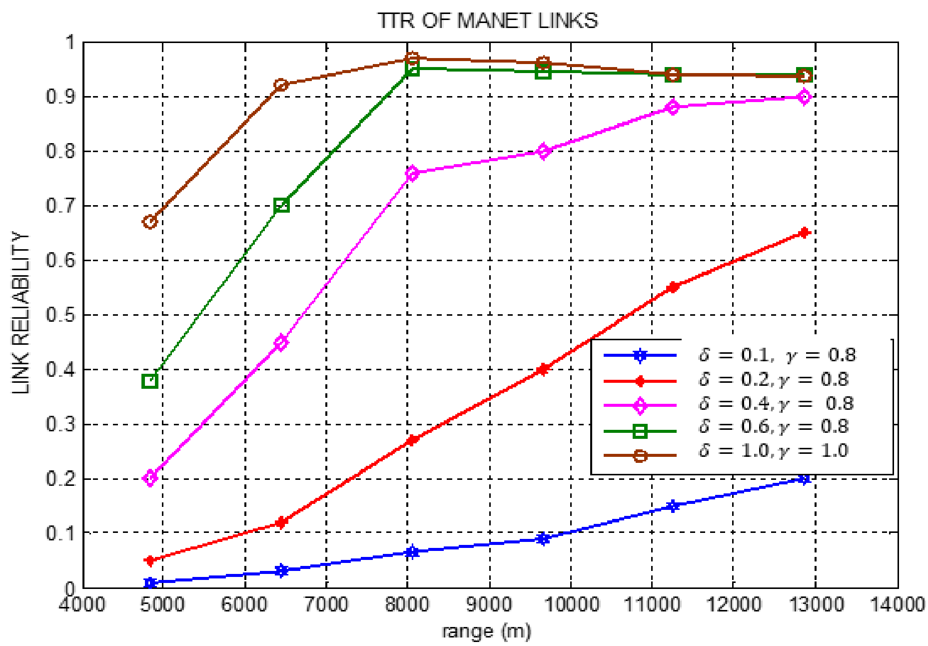


Figure 4.7: Link Reliability Graph of Improved Model showing the Effect of Range with Known Parameters

From Figure 4.7, it can be observed that an increase in range increases the link reliability of the network. However, the mobile network approaches stable state with a further increase in the transmission range beyond 11263m. This figure corresponds to the result presented by Padmavathy & Chaturvedi,(2013), thus confirms the validity of the developed model. The difference of the two models can also be examined with respect to the effect of transmission range on the network reliability as presented in Figure 4.8

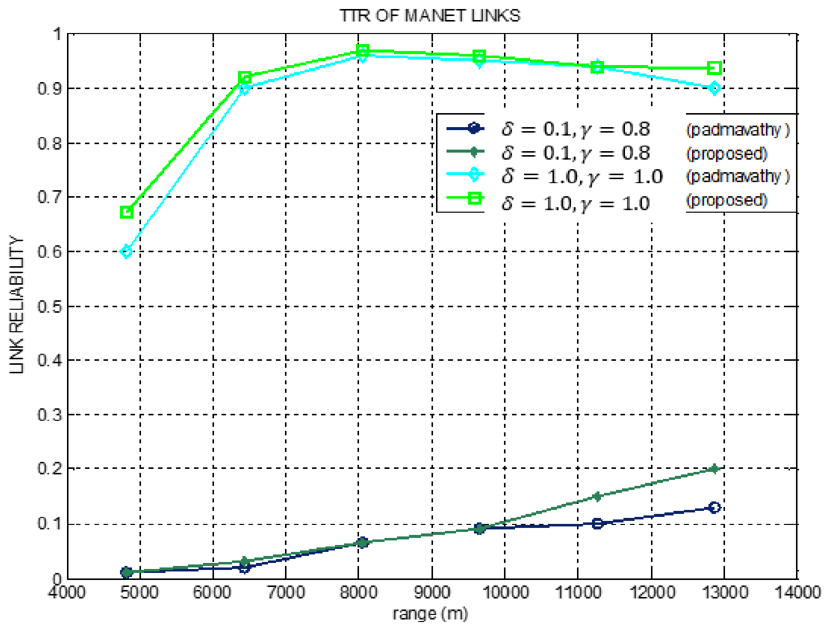


Figure 4.8: Link Reliability Graphs of Padmavathy & Chaturvedi, (2013) and developed Model with respect to Range

Similar to Figure 4.7, the proposed method of Figure 4.8 has an improved performance as compared with Padmavathy& Chaturvedi's approach. It has a maximum link reliability of 97.0% when $\delta = 1$ *and* $\gamma = 1$as compared with padmavathy& Chaturvedi's approach which has a maximum link reliability of 95% when $\delta = 1$ *and* $\gamma = 1$. Both approaches attained maximum when the communication range was 8045m. Similarly, when $\delta = 0.1$ *and* $\gamma = 0.8$ which represent the worst case scenario, the developed model slightly performed better with a maximum of 2.00% as compared with Padmavathy & Chaturvedi,(2013) whose maximum link reliability was 1.30%. This again points to the superiority of the developedmodel over the existing model in terms of the effect of transmission range on link reliability.

4.3.3 Performance Evaluation using Link Reliability and Time(s)

The effect of time in seconds on the link reliability has been widely reported as a metric for measuring performance in mobile networks. Table 4.4 shows the simulation result of link reliability and time when other factors such as network coverage area, transmission range etc are kept constant.

Table 4.4: Table of Link Reliability and Time

s/n	Link Reliability					Time (s)
	$\boldsymbol{\delta = 0.1}$, $\boldsymbol{\gamma = 0.8}$	$\boldsymbol{\delta = 0.2,}$ $\boldsymbol{\gamma = 0.8}$	$\boldsymbol{\delta = 0.4,}$ $\boldsymbol{\gamma = 0.8}$	$\boldsymbol{\delta = 0.6,}$ $\boldsymbol{\gamma = 0.8}$	$\boldsymbol{\delta = 1.0,}$ $\boldsymbol{\gamma = 1.0}$	
1	0.02	0.09	0.35	0.65	0.93	0
2	0.02	0.08	0.34	0.63	0.93	36000
3	0.02	0.08	0.33	0.61	0.92	72000
4	0.02	0.10	0.32	0.60	0.90	108000
5	0.02	0.09	0.30	0.58	0.88	144000
6	0.02	0.07	0.29	0.53	0.85	180000
7	0.02	0.07	0.25	0.47	0.84	216000
8	0.02	0.06	0.23	0.40	0.75	252000

The results presented in Table 4.4 were plotted for every propagation parameter and the responses of the graphs generated are shown in Figure 4.9.

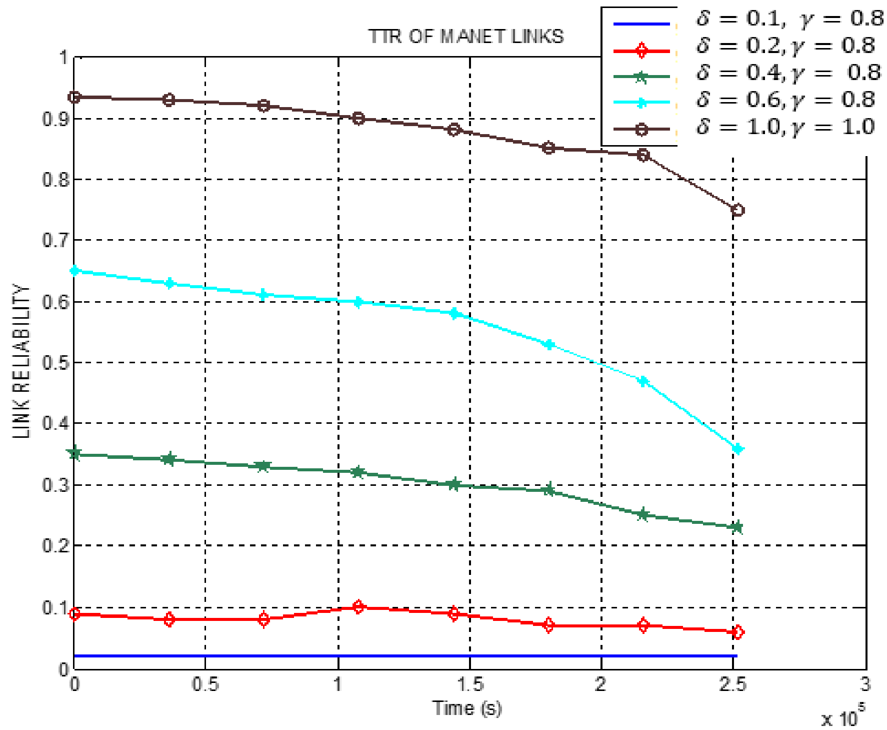


Figure 4.9:Effect of Time on Link Reliability Graph of Improved Model

From Figure 4.9, it can be observed that the link reliability of the network has similar behaviours for the various propagation parameters when communication duration was varied. Figure 4.9 corresponds to the result presented by Padmavathy & Chaturvedi,(2013) which is a confirmation of the validity of the developed model. The effect of transmission time on link reliability is only evident with higher values of δ and γ. When δ and γ are very small, there is hardly an effect of time on link reliability as shown by the orange line and the blue plain line at the bottom of Figure 4.9. The situation changes as the values of δ and γ increase to higher values, link reliability decreases as time increases. There is gradual decrease of reliability between 0 and 144000s, while above 180000s the link reliability drop becomes prominenet, particularly where δ and γvalues are very high.

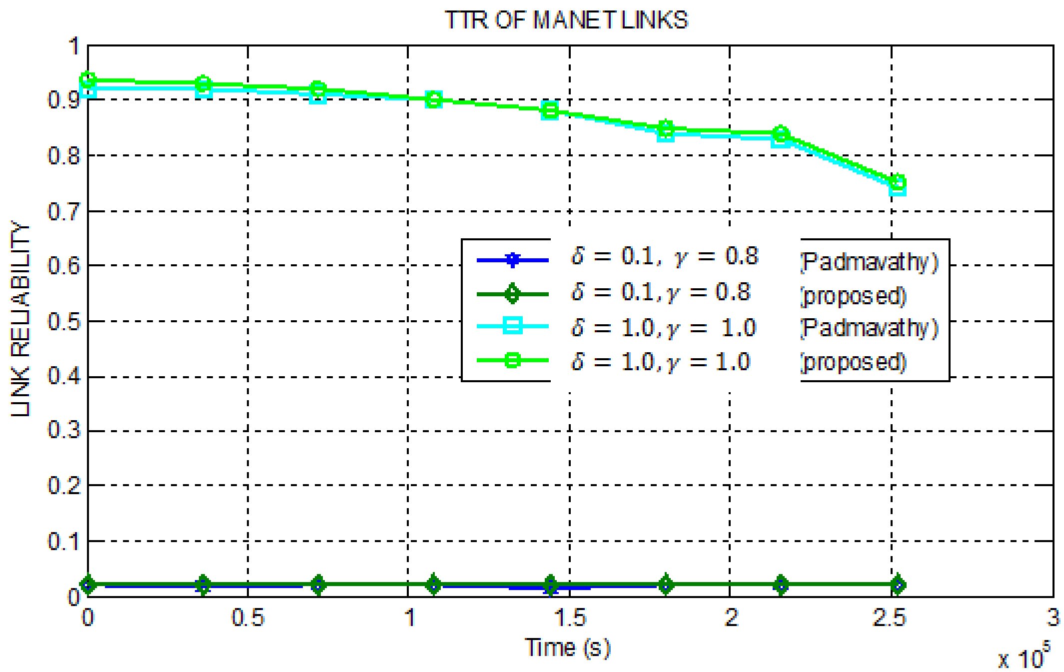


Figure 4.10: Link Reliability Graphs of Padmavathy & Chaturvedi,(2013) and Developed Model with respect to Time

A comparison was also drawn between the Padmavathy & Chaturvedi,(2013) model and the proposed one as shown in Figure 4.10 with respect to the effect of time on link reliability. This is another way of showing the advantage of the proposed model over the existing model. Though the difference becomes less apparent when δ and γ are very small, there is still some degree of evidence to show that the proposed model was better from the simulation results. In general, the two model results tend to converge at a time greater than 100000s which implies that a maximum limit is reached where by no effect of time is noticed again. From Figure 4.10,it can be observed that the proposed approach attained a maximum link reliability of 93.5% as compared with Padmavathy& Chaturvedi's approach which has a maximum link reliability of 92.0%. Both approaches attained the maximum when the communication duration was between 0-144000s for $\delta = 1$ *and* $\gamma = 1$. Simialrly, for $\delta = 0.1$ *and* $\gamma = 0.8$ which represent the worst case scenario, the proposed model slightly performed better with a maximum of 2.0% as compared with the existing model.

4.3.4 Performance Evaluation using Link Reliability and Number of Nodes

The link reliability and number of nodes is another appropriate metric used for measuring the performance of the model. Various propagation parameters were used and the corresponding simulation result obtained for each parameter is shown in Table 4.5.

Table 4.5: Table of Number of Nodes and Link Reliability

s/n	Link Reliability					No. of nodes
	$\boldsymbol{\delta = 0.1, \gamma = 0.8}$	$\boldsymbol{\delta = 0.2, \gamma = 0.8}$	$\boldsymbol{\delta = 0.4, \gamma = 0.8}$	$\boldsymbol{\delta = 0.6, \gamma = 0.8}$	$\boldsymbol{\delta = 1.0, \gamma = 1.0}$	
1	0.020	0.050	0.220	0.400	0.700	18
2	0.020	0.060	0.250	0.470	0.750	22
3	0.020	0.050	0.300	0.580	0.850	27
4	0.045	0.200	0.700	0.930	0.950	50
5	0.060	0.520	0.950	0.960	0.960	100

The result presented in Table 4.5 was plotted for every propagation parameter and the responses of the graphs generated are shown in Figure 4.11.

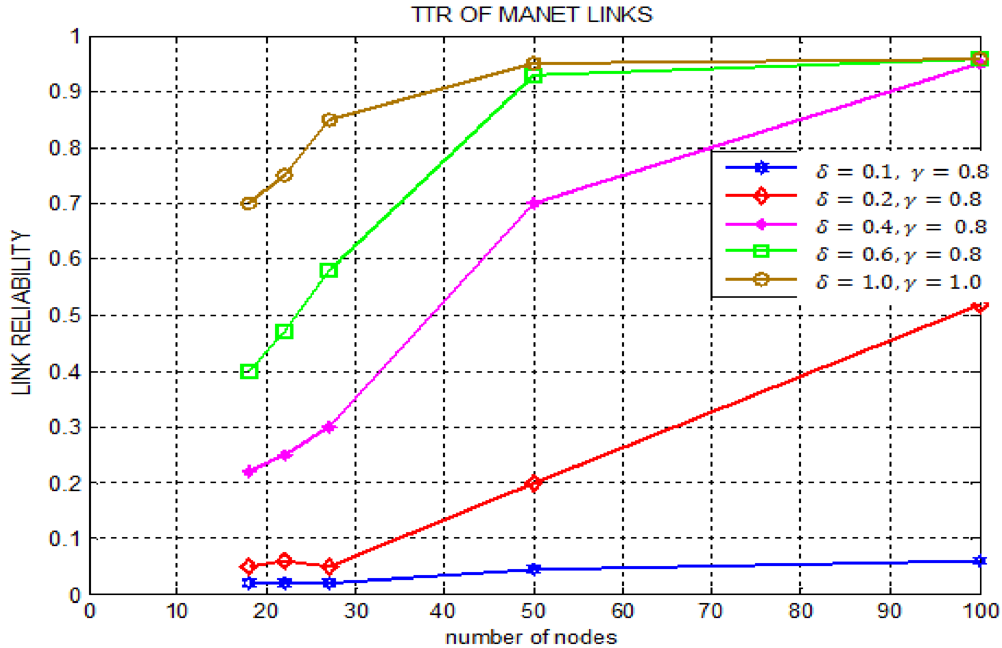


Figure 4.11:Effect of Number of Nodes on Link Reliability Graph of Improved Model

From Figure 4.11, it can be observed that the link reliability of the network is also affected by the number of nodes in the network and corresponds to the results presented by Padmavathy & Chaturvedi,(2013) which again confirms the authenticity of the developed model. The proposed model was also compared with that of Padmavathy & Chaturvedi,(2013) in terms of the effect of number of nodes on the link reliability in order to determine a better model. The comparison is illustrated as shown in Figure 4.12.

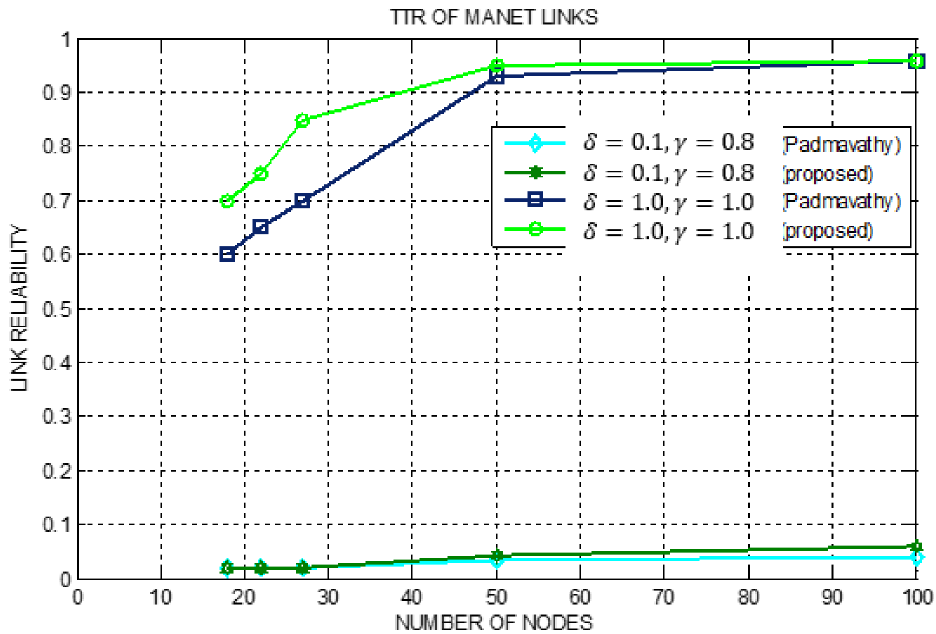


Figure 4.12: Link Reliability Graphs of Padmavathy & Chaturvedi, (2013) and the Developed Model with Respect to Number of Nodes

FromFigure 4.12, it can be observed that the proposed approach attained a maximum link reliability of 96.0% as compared with Padmavathy& Chaturvedi's approach which has a maximum link reliability of 95.7%. Both approaches attained the maximum when the number of nodes was maximum (100) for $\delta = 1$ *and* $\gamma = 1$. Similarly, for $\delta = 0.1$ *and* $\gamma = 0.8$ which represent the worst case scenario, the proposed model slightly performed better with a maximum of 6.0% as compared with Padmavathy & Chaturvedi,(2013) whose maximum link reliability was 4.8% at this point. This also indicates the robustness of the approach used in this research. It is also worth noting that the two models behave similarly at lower δ and γ values with respect to the number of nodes effect on reliability. But as δ and γ values increase, the two models become different in behavior, though converging at higher number of nodes and propagation parameters (δ and γ) which implies that a saturation point has been reached where by the number of nodes can no more affect the link reliability.

4.3.5 Effect of Bandwidth on Link Reliability

To further verify the robustness of the devoloped model, the effect of bandwidth on link reliability of the MANET was evaluated. Various propagation parameters were considered and the simulation results are presented in Table 4.6.

Table 4.6: Table of Bandwidth and Link Reliability

s/n	**Link Reliability** $\boldsymbol{\delta = 0.1, \gamma = 0.8}$	$\boldsymbol{\delta = 0.2, \gamma = 0.8}$	$\boldsymbol{\delta = 0.4, \gamma = 0.8}$	$\boldsymbol{\delta = 0.6, \gamma = 0.8}$	$\boldsymbol{\delta = 1.0, \gamma = 1.0}$	**Bandwidth (MHz)**
1	0.0934	0.0301	0.0562	0.0277	0.0350	500
2	0.2067	0.3730	0.5204	0.2281	0.2209	1000
3	0.3474	0.5803	0.5716	0.7661	0.9064	1500
4	0.3537	0.6557	0.7522	0.8877	0.9235	2000
5	0.4470	0.7179	0.7706	0.9206	0.9778	2500
6	0.5086	0.7411	0.8419	0.9419	0.9870	3000

The result presented in Table 4.6 was plotted for every propagation parameter and the responses of the graphs generated are shown in Figure 4.13.

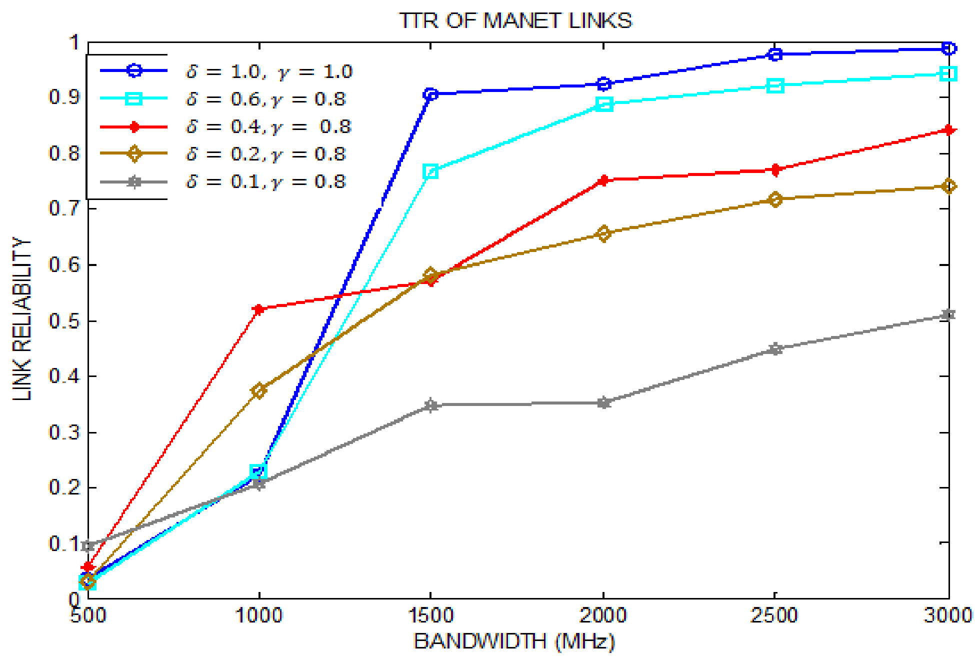


Figure 4.13: Effect of Bandwidth on Link Reliability Graphs of Improved Model

It can be observed from Figure 4.13 that, an increase in bandwidth increases the reliability of the network. The variations inδ and γshow the corresponding superimposed response, differentiated based on different colours in Figure 4.13. The MANET has the highest link reliability (98.7%) when$\gamma$is 1.0 andδ is 1.0. At this point, variation in network propagation parameters has little or no effect on the performance of the network. Figure 4.13shows the relationship between link reliability and bandwidth. The response of the network has similar pattern based on the variations in propagation parameters considered. “The link reliability of the network attained 98.70%, 94.19% and 84.19% when the propagation parameters (δ and γ) were at1.0 and 1.0, 0.6and 0.8, 0.4 and 0.8, respectively. Similarly, the link reliability of the network was observed to be 74.11% and 50.86% when the propagation parameters (δ and γ) were 0.2 and 0.8, and 0.1 and 0.8. A sharp rise was observed though some imperfections exist which is as a result of the random and dynamic nature of MANET.

4.3.6 Effect of SINR on Link Reliability

The effect of signal to interference plus noise ratio on link reliability is also considered as a metric for measuring performance in this research work. The simulation result obtained for various propagation parameters is given in Table 4.7.

Table 4.7: Table of SINR and Link Reliability

	Link Reliability					
s/n	$\boldsymbol{\delta = 0.1, \gamma = 0.8}$	$\boldsymbol{\delta = 0.2, \gamma = 0.8}$	$\boldsymbol{\delta = 0.4, \gamma = 0.8}$	$\boldsymbol{\delta = 0.6, \gamma = 0.8}$	$\boldsymbol{\delta = 1.0, \gamma = 1.0}$	**SINR(dB)**
1	0.1113	0.2232	0.3237	0.4024	0.4965	0.1
2	0.1224	0.2869	0.3997	0.4997	0.5997	0.3
3	0.2970	0.3946	0.5393	0.7479	0.7979	0.5
4	0.5769	0.8672	0.9936	0.9997	0.9987	0.7
5	0.5758	0.8424	0.9901	0.9997	0.9999	0.9

The result presented in Table 4.7 was plotted for every propagation parameter and the responses of the graphsgenerated are shown in Figure 4.14.

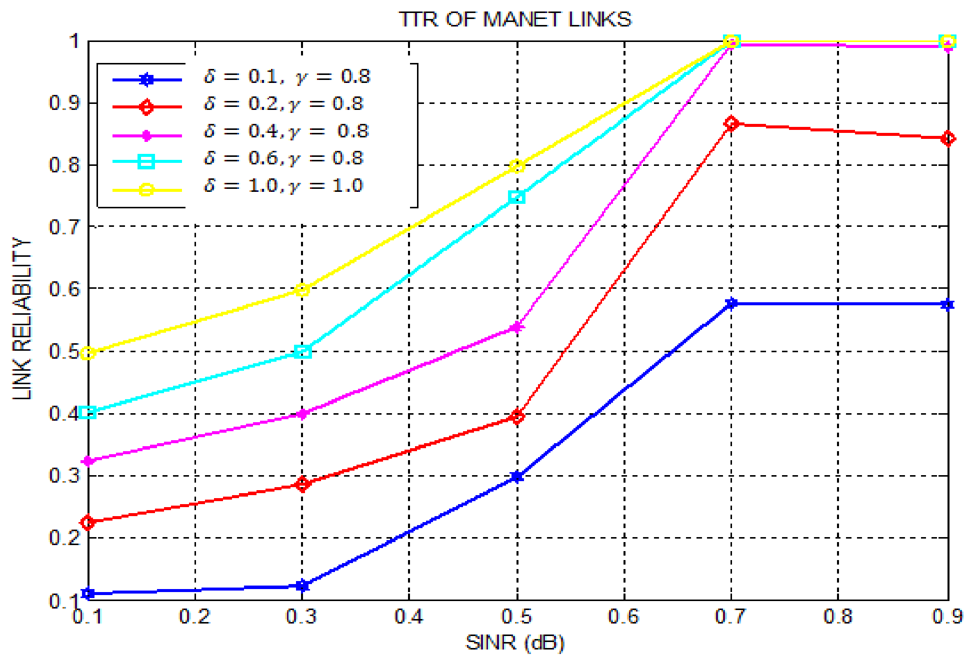


Figure 4.14: Effect of SINR on Link Reliability Graphs of Improved Model

Figure 4.14 shows the relationship between link reliability and signal to interference plus noise ratio. The response of the network has similar pattern based on the variations in propagation parameters considered. It can be observed that all the superimposed responses for each propagation parameter appear to be stable when the signal to interference plus noise ratio is 70% and all through the simulation process. At this point, the link reliability of the network attained 99.99%, 99.97% and 99.01% when the propagation parameters (δ and γ) were at 1.0 and 1.0, 0.6and 0.8, 0.8 and 0.8, respectively. Similarly, the link reliability of the network was observed to be 57.58% and 84.24% when the propagation parameters (δ and γ) were 0.1 and 0.8, and 0.2 and 0.8. The stability observed at 0.7 indicates that, at this point, variations in network parameters do not influence the reliability of the network.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter presents the conclusion and limitations encountered during the course of this research. Areas of future research have also been recommended.

5.2 Conclusion

The link reliability model of a mobile ad hoc network has been developed. This was achieved using the Weibull distribution due to its flexibility, simplicity and reliability. The model was simulated using the developed MATLAB based GUI. The path loss effect was obtained using the free space and two ray ground propagation models. Simulation results show that as coverage area was increased between 50 to 250 km-sqr, the link reliability decreased. When the product of δ and γ was low (0.16), the saturation area was at 100 but increased for higher product of δ and γ (1) towards 250. When all parameters were kept constant and range alone was varied between 3-8km, the link reliability increased (from 0.05 to 0.55) and (0.3 to 1). With lower product of δ and γ (0.16), the reliability was from 0.05 to 0.3 but for higher product (1), it was 0.55 to 1. Communication duration was noticed to have less effect on the link reliability though moving in a decreasing manner. The higher the product of δ and γ, the higher the network reliability (0.96 to 0.82) observed. The number of mobile nodes was also varied between 20 to 100. It was noticed that the link reliability was between 0.05 to 0.38 for lower product of δ and γ (0.16) and 0.5 to 0.97 for higher product of δ and γ (1). When bandwidth was varied between 500-3000MHz, the link reliability increased and the lower product of δ and γ (0.16) had a reliability of 0.1 to 0.5 while the higher product (1) had a link reliability of 0.03 to 0.98. When SINR was varied between 0.1 and 0.9dB, the link reliability increased and the lower product of δ and γ (0.16) had link reliability between 0.1 to 0.48, and the higher product of δ and γ (1) had link reliability between 0.5 to 1. It can therefore be concluded that higher product of the propagation parameters gave higher link reliability based on the parameters considered.

5.3 Significant Contributions

Many researchers have worked on predicting the link reliability of MANET. Many researches have also been conducted on different areas of its application. The significant contributions of this research work are as follows:

i. Development of a user dependent Matlab GUI application for prediction of link reliability in MANET with path loss effects in which SINR and bandwidth were considered as added metrics.

ii. The improved model performed better by 7% for coverage area, 2% for range and 0.3% for number of mobile nodes at maximum points when the products of $\delta and\, \gamma$ were at a maximum.

iii. The developed link reliability model showed a performance of 98.70% link reliability when bandwidth was 3000MHz and 99.99% when SINR was 0.9

5.4 Limitations

The limitations of this research work are itemized as follows:

i. The data used for this research work (coverage area, range, time, bandwidth, SINR and number of mobile nodes) is estimated and not measured.

ii. It was assumed that the mobile network moves within the simulation boundary which may not be so for all cases

iii. In this work, the motion of the mobile nodes is assumed to follow a RWPM and the coverage area is assumed to be square in shape. This may not also be the same for all cases

5.5 Recommendations for Further Work

The following possible areas are recommended for future work:

i. Field datashould be considered for validation in further research work.

ii. Security such as eavesdropping, black hole, etc in MANET can be also be considered.

iii. ATR and AoTR for MANET can also be considered in future work.

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Appendix A

Reliability Parameters

Based on the combined model represented by Figure 4.1, the link reliability can be derived as follows in terms of the calculated range.

Let

Region 1:

$$\frac{A}{\delta^2 r^2} + B = 1$$

Region 2:

$$\frac{A}{\delta^2 r^2} + B = \frac{C}{\gamma^4 r^4} + E$$

Region 3 :

$$\frac{A}{r^4} + B = 0$$

And

$$\frac{C}{r^4} + E = 0$$

Solving the equations,

$$A = \frac{r^2 \delta^2}{(1 - \delta^2)}$$

$$B = \frac{\delta^2}{(1-\delta^2)}$$

$$C = \frac{\gamma^2\delta^2 r^4}{(1-\delta^2)(1+\gamma^2)}$$

$$E = \frac{-\gamma^2\delta^2}{(1-\delta^2)(1+\gamma^2)}$$

Appendix B

The MATLAB GUI Main Function

```
function varargout = linkr(varargin)

gui_Singleton = 1;

gui_State = struct('gui_Name',       mfilename, ...

'gui_Singleton',  gui_Singleton, ...

'gui_OpeningFcn', @linkr_OpeningFcn, ...

'gui_OutputFcn',  @linkr_OutputFcn, ...

'gui_LayoutFcn',  [] , ...

'gui_Callback',   []);

if nargin && ischar(varargin{1})

    gui_State.gui_Callback = str2func(varargin{1});

end

if nargout

    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});

else

    gui_mainfcn(gui_State, varargin{:});
```

```
en

function linkr_OpeningFcn(hObject, eventdata, handles, varargin)

handles.output = hObject;

guidata(hObject, handles);

set(handles.Q1,'value',0);

set(handles.Q0,'value',1);

set(handles.S1,'value',0);

set(handles.S2,'value',1);

function varargout = linkr_OutputFcn(hObject, eventdata, handles)

varargout{1} = handles.output;

function TTR_CreateFcn(hObject, eventdata, handles)

function ATR_CreateFcn(hObject, eventdata, handles)

function R_CreateFcn(hObject, eventdata, handles)

function Timer_CreateFcn(hObject, eventdata, handles)

function OF_Callback(hObject, eventdata, handles)

function OF_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
end
function B_Callback(hObject, eventdata, handles)
function B_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function OT_Callback(hObject, eventdata, handles)
function OT_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function PTX_Callback(hObject, eventdata, handles)
function PTX_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
function Q1_Callback(hObject, eventdata, handles)

set(handles.Q1,'value',1);

set(handles.Q0,'value',0);

function Q0_Callback(hObject, eventdata, handles)

set(handles.Q1,'value',0);

set(handles.Q0,'value',1);

function S1_Callback(hObject, ~, handles)

set(handles.S1,'value',1);

set(handles.S2,'value',0);

function S2_Callback(hObject, eventdata, handles)

set(handles.S1,'value',0);

set(handles.S2,'value',1);

function s_Callback(hObject, eventdata, handles)

function s_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end
```

```
function N_Callback(hObject, eventdata, handles)

function N_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function CA_Callback(hObject, eventdata, handles)

function CA_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function WSCP_Callback(hObject, eventdata, handles)

function WSCP_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function WSHP_Callback(hObject, eventdata, handles)

function WSHP_CreateFcn(hObject, eventdata, handles)
```

```
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function THRESH_Callback(hObject, eventdata, handles)

function THRESH_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function r_Callback(hObject, eventdata, handles)

function r_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function zigma_Callback(hObject, eventdata, handles)

function zigma_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');
```

```
end

function NS_Callback(hObject, eventdata, handles)

function NS_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function dt_Callback(hObject, eventdata, handles)

function dt_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function Vmin_Callback(hObject, eventdata, handles)

function Vmin_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function Vmax_Callback(hObject, eventdata, handles)
```

```
function Vmax_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end



function CD_Callback(hObject, eventdata, handles)

function CD_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

function gamma_Callback(hObject, eventdata, handles)

function gamma_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))

    set(hObject,'BackgroundColor','white');

end

% --- Executes on button press in RUN_TTR.

function RUN_TTR_Callback(hObject, eventdata, handles)
```

```
gamma=str2double(get(handles.gamma,'String'));

CD=str2double(get(handles.CD,'String'));

Vmax=str2double(get(handles.Vmax,'String'));

Vmin=str2double(get(handles.Vmin,'String'));

dt=str2double(get(handles.dt,'String'));

NS=str2double(get(handles.NS,'String'));

zigma=str2double(get(handles.zigma,'String'));

r=str2double(get(handles.r,'String'));

THRESH=str2double(get(handles.THRESH,'String'));

WSHP=str2double(get(handles.WSHP,'String'));

WSCP=str2double(get(handles.WSCP,'String'));

CA=str2double(get(handles.CA,'String'));

N=str2double(get(handles.N,'String'));

s=str2double(get(handles.s,'String'));

PTX=str2double(get(handles.PTX,'String'));

OT=str2double(get(handles.OT,'String'));

B=str2double(get(handles.B,'String'));
```

```
OF=str2double(get(handles.OF,'String'));

q1=get(handles.Q1,'value');

q2=get(handles.Q0,'value');

Si=get(handles.S1,'value');

Sj=get(handles.S2,'value');

if q1==1

   q=1;

else

if q2==1

       q=0;

end

end

if Si==1

   s1=1;

else

if Sj==1

       s1=2;
```

```
end

end

[Timer TTR
ATR,R]=linkrlbwbl(CD,N,CA,WSCP,WSHP,NS,THRESH,OF,B,OT,PTX,s1,Vmax,Vmin,dt,zi
gma,gamma,q,s,r);

set(handles.TTR,'string',TTR);

set(handles.R,'string',R);

set(handles.ATR,'string',ATR);

set(handles.Timer,'string',Timer);

function RESET_Callback(hObject, eventdata, handles)

set(handles.TTR,'string',' ');

set(handles.R,'string',' ');

set(handles.ATR,'string',' ');

set(handles.Timer,'string',' ');
```

Appendix C

The Link Reliability Main Function

```
Function[TimerTTRATR
R]=linkrlbwbl(CD,N,CA,WSCP,WSHP,NS,THRESH,OF,B,OT,PTX,s1,Vmax,Vmin,dt,zigma,g
amma,q,s,r)
day=clock;

day=day(:,4:end);

day(1,1)=day(1,1)*60;

day(1,2)=day(1,2)*60;

day=sum(day);

Time1=day;

result=[];

M=N;

if log10(M)<1

   dec=0.5;

else

   dec=1;

end
```

```
for begin=1:10

s=s/s;

r=r*N/r;

if s1==1

    rng=(2.0322e5/OF)*sqrt(PTX/(OT*B*10^(THRESH/10)));

end

if s1==2

    rng=(2.0322e5/OF)*sqrt(PTX/(OT*B*(2^((THRESH)/(B))-1)));

end

X=(sqrt(CA)/2)*rand(N,1);

Y=(sqrt(CA)/2)*rand(N,1);

for aa=1:N

        X(aa,1)=X(aa,1)*(-1)^(randi(N,1));

        Y(aa,1)=Y(aa,1)*(-1)^(randi(N,1));

end

dij=[];

Rl=[];
```

```
for i=1:N

for j=1:N

if i~=j

    dij(i,j)=(((X(i)-X(j))^2)+(Y(i)-Y(j))^2)^0.5;

end

end

end

for ii=1:N



for jj=1:N

if ii~=jj

if dij(ii,jj)<zigma*rng

      Rl(ii,jj)=1;

else

if zigma*rng<=dij(ii,jj)

if dij(ii,jj)<=gamma*rng

      Rl(ii,jj)=((zigma^2)/(1-zigma^2))*(((rng^2)/(dij(ii,jj))^2)/2-1);
```

```
else

if gamma*rng<dij(ii,jj)

if dij(ii,jj)<rng

        Rl(ii,jj)=((zigma^2)/(1-zigma^2))*((gamma^2)/(1+gamma^2))*(((rng^4)/(dij(ii,jj))^4)-
1);

else

if dij(ii,jj)>=zigma*rng

        Rl(ii,jj)=0;

end

end

end

end

end

end

end

end

end

if q==0
```

```
Rn=exp(-(((dt)/WSCP)^WSHP));
end
if q==1
    Rn=1;
end
N_array=1:N;
N_array(:,[s,r])=[];
N_array2=[];
if N~=2
for l=1:N-2
    LL=combntns(N_array,l);
    [lntt,brtt]=size(LL);
    L=[];
for lll=1:lntt
        LLL=perms(LL(lll,:));
        L=[L;LLL];
end
```

```
    [lnt,brt]=size(L);
for ll=1:lnt
    N_array1=zeros(1,(2*(N-1)));
    N_array1(1,(2:2:(2*(1+brt)-1)))=L(ll,:);
    N_array1(1,(3:2:2*(1+brt)))=L(ll,:);
    N_array1(1,1)=s;
    N_array1(1,(2*(1+brt)))=r;
    N_array2=[N_array2;N_array1]
end
end
Rel=[]
[nl,nb]=size(N_array2);
for NL=1:nl
for NB=1:2:nb
if N_array2(NL,NB)~=0
if N_array2(NL,(NB+1))~=0
            Rel(NL,(NB+1)/2)=Rl(N_array2(NL,NB),N_array2(NL,(NB+1)));
```

```
end
end
end
end
Rel=Rel*Rn^2;
for rl=1:nl
for rb=1:(N-1)
if Rel(rl,rb)==0
        Rel(rl,rb)=1;
end
end
end
Relprod=Rel(:,1);
for start=2:(N-1)
   Relprod=Relprod.*Rel(:,start);
end
Rel=(sum(sum(Relprod))/nl);
```

```
else
    Rel=Rn*Rl(1,2)*Rn;
end
ttr=Rel;
ttrel=ttr;
for ns=1:(NS-1)
    Ttotal=CD-dt;
    count=1;
    t=dt;
while Ttotal>dt
    count=count+1;
    Ttotal=Ttotal-dt;
    t=t+dt;
if q==0
    Rn=exp(-(((t)/WSCP)^WSHP))/exp(-(((t-dt)/WSCP)^WSHP));
else
if q==1
```

```
        Rn=1;
end
end
  th=rand(N,1)*2*pi;
  V=round(Vmin)*ones(N,1)+randi((round(Vmax-Vmin)),N,1);
  X=X+dt*V.*cos(th);
  Y=Y+dt*V.*sin(th);


for lxy=1:N
if abs(X(lxy))>sqrt(CA)/2
        X(lxy)=((X(lxy))/abs(X(lxy)))*sqrt(CA)/2;
end
if abs(Y(lxy))>sqrt(CA)/2
        Y(lxy)=((Y(lxy))/abs(Y(lxy)))*sqrt(CA)/2;
end
end
dij=[];
```

```
Rl=[];
for i=1:N
for j=1:N
if i~=j
     dij(i,j)=(((X(i)-X(j))^2)+(Y(i)-Y(j))^2)^0.5;
end
end
end
for ii=1:N
for jj=1:N
if ii~=jj
if dij(ii,jj)<zigma*rng
       Rl(ii,jj)=1;
else
if zigma*rng<=dij(ii,jj)
if dij(ii,jj)<=gamma*rng
       Rl(ii,jj)=((zigma^2)/(1-zigma^2))*(((rng^2)/(dij(ii,jj))^2)/2-1);
```

```
else
if gamma*rng<dij(ii,jj)
if dij(ii,jj)<rng
    Rl(ii,jj)=((zigma^2)/(1-zigma^2))*((gamma^2)/(1+gamma^2))*(((rng^4)/(dij(ii,jj))^4)-
1);
else
if dij(ii,jj)>=zigma*rng
    Rl(ii,jj)=0;
end
end
end
end
end
end
end
end
end
```

```
N_array=1:N;

N_array(:,[s,r])=[];

N_array2=[];

if N~=2

for l=1:N-2

   LL=combntns(N_array,l);

   [lntt,brtt]=size(LL);

   L=[];

for lll=1:lntt

      LLL=perms(LL(lll,:));

      L=[L;LLL];

end

   [lnt,brt]=size(L);

for ll=1:lnt

   N_array1=zeros(1,(2*(N-1)));

   N_array1(1,(2:2:(2*(1+brt)-1)))=L(ll,:);

   N_array1(1,(3:2:2*(1+brt)))=L(ll,:);
```

```
   N_array1(1,1)=s;

   N_array1(1,(2*(1+brt)))=r;

   N_array2=[N_array2;N_array1];

end

end

Rel=[];

[nl,nb]=size(N_array2);

for NL=1:nl

for NB=1:2:nb

if N_array2(NL,NB)~=0

if N_array2(NL,(NB+1))~=0

            Rel(NL,(NB+1)/2)=Rl(N_array2(NL,NB),N_array2(NL,(NB+1)));

end

end

end

end

Rel=Rel*Rn^2;
```

```
for rl=1:nl

for rb=1:(N-1)

if Rel(rl,rb)==0

            Rel(rl,rb)=1;

end

end

end

Relprod=Rel(:,1);

for start=2:(N-1)

    Relprod=Relprod.*Rel(:,start);

end

Rel=(sum(sum(Relprod))/nl);

else

    Rel=Rn*Rl(1,2)*Rn;

end

ttr=ttr+Rel;

end
```

```
ttr=ttr/count;

ttrel=ttrel+ttr;

end

if Rl==zeros(N)

    TTR=0;

else

TTR=ttrel/NS;

end

R=rng;

TTTT=TTR;

comb=combntns((1:N),2);

[lc,bc]=size(comb);

ttrall=[];

for combs=1:lc

    s=comb(combs,1);

     r=comb(combs,bc);

if s1==1
```

```
    rng=(2.0322e5/OF)*sqrt(PTX/(OT*B*10^(THRESH/10)));
end
if s1==2
    rng=(2.0322e5/OF)*sqrt(PTX/(OT*B*(2^((THRESH)/(B))-1)));
end
X=(sqrt(CA)/2)*rand(N,1);
Y=(sqrt(CA)/2)*rand(N,1);
for aa=1:N
        X(aa,1)=X(aa,1)*(-1)^(randi(N,1));
        Y(aa,1)=Y(aa,1)*(-1)^(randi(N,1));
end
dij=[];
Rl=[];
for i=1:N
for j=1:N
if i~=j
        dij(i,j)=(((X(i)-X(j))^2)+(Y(i)-Y(j))^2)^0.5;
```

```
end
end
end
for ii=1:N
for jj=1:N
if ii~=jj
if dij(ii,jj)<zigma*rng
        Rl(ii,jj)=1;
else
if zigma*rng<=dij(ii,jj)
if dij(ii,jj)<=gamma*rng
        Rl(ii,jj)=((zigma^2)/(1-zigma^2))*(((rng^2)/(dij(ii,jj))^2)/2-1);
else
if gamma*rng<dij(ii,jj)
if dij(ii,jj)<rng
        Rl(ii,jj)=((zigma^2)/(1-zigma^2))*((gamma^2)/(1+gamma^2))*(((rng^4)/(dij(ii,jj))^4)-
1);
else
```

```
if dij(ii,jj)>=zigma*rng
            Rl(ii,jj)=0;
end
end
end
end
end
end
end
end
end
if q==0
Rn=exp(-(((dt)/WSCP)^WSHP));
end
if q==1
    Rn=1;
end
```

```
N_array=1:N;

N_array(:,[s,r])=[];

N_array2=[];

if N~=2

for l=1:N-2



   LL=combntns(N_array,l);

   [lntt,brtt]=size(LL);

   L=[];

for lll=1:lntt

      LLL=perms(LL(lll,:));

      L=[L;LLL];

end

   [lnt,brt]=size(L);

for ll=1:lnt

   N_array1=zeros(1,(2*(N-1)));

   N_array1(1,(2:2:(2*(1+brt)-1)))=L(ll,:);
```

```
    N_array1(1,(3:2:2*(1+brt)))=L(ll,:);

    N_array1(1,1)=s;

    N_array1(1,(2*(1+brt)))=r;

    N_array2=[N_array2;N_array1];

end

end

Rel=[];

[nl,nb]=size(N_array2);

for NL=1:nl

for NB=1:2:nb

if N_array2(NL,NB)~=0

if N_array2(NL,(NB+1))~=0

            Rel(NL,(NB+1)/2)=Rl(N_array2(NL,NB),N_array2(NL,(NB+1)));

end

end

end

end
```

```
Rel=Rel*Rn^N;

for rl=1:nl

for rb=1:(N-1)

if Rel(rl,rb)==0

            Rel(rl,rb)=1;

end

end

end

Relprod=Rel(:,1);

for start=2:(N-1)

    Relprod=Relprod.*Rel(:,start);

end

Rel=(sum(sum(Relprod))/nl);

else

    Rel=Rl(1,2)*Rn^N;

end

ttr=Rel;
```

```
ttrel=ttr;

for ns=1:(NS-1)

    Ttotal=CD-dt;

    count=1;

    t=dt;

while Ttotal>dt

    count=count+1;

    Ttotal=Ttotal-dt;

    t=t+dt;

if q==0

    Rn=exp(-(((t)/WSCP)^WSHP))/exp(-(((t-dt)/WSCP)^WSHP));

else

if q==1

        Rn=1;

end

end

   th=rand(N,1)*2*pi;
```

```
  V=round(Vmin)*ones(N,1)+randi((round(Vmax-Vmin)),N,1);

  X=X+dt*V.*cos(th);

  Y=Y+dt*V.*sin(th);

for lxy=1:N

if abs(X(lxy))>sqrt(CA)/2

        X(lxy)=((X(lxy))/abs(X(lxy)))*sqrt(CA)/2;

end

if abs(Y(lxy))>sqrt(CA)/2

        Y(lxy)=((Y(lxy))/abs(Y(lxy)))*sqrt(CA)/2;

end

end

dij=[];

Rl=[];

for i=1:N

for j=1:N

if i~=j

      dij(i,j)=(((X(i)-X(j))^2)+(Y(i)-Y(j))^2)^0.5;
```

```
end
end
end
for ii=1:N
for jj=1:N
if ii~=jj
if dij(ii,jj)<zigma*rng
        Rl(ii,jj)=1;
else
if zigma*rng<=dij(ii,jj)
if dij(ii,jj)<=gamma*rng
        Rl(ii,jj)=((zigma^2)/(1-zigma^2))*(((rng^2)/(dij(ii,jj))^2)/2-1)+dec/(1+log10(M));
else
if gamma*rng<dij(ii,jj)
if dij(ii,jj)<rng
        Rl(ii,jj)=((zigma^2)/(1-zigma^2))*((gamma^2)/(1+gamma^2))*(((rng^4)/(dij(ii,jj))^4)-
1);
else
```

```
if dij(ii,jj)>=zigma*rng

            Rl(ii,jj)=0;

end

end

end

end

end

end

end

end

end

N_array=1:N;

N_array(:,[s,r])=[];

N_array2=[];

if N~=2

for l=1:N-2

    LL=combntns(N_array,l);
```

```
    [lntt,brtt]=size(LL);

    L=[];

for lll=1:lntt

        LLL=perms(LL(lll,:));

        L=[L;LLL];

end

    [lnt,brt]=size(L);

for ll=1:lnt

    N_array1=zeros(1,(2*(N-1)));

    N_array1(1,(2:2:(2*(1+brt)-1)))=L(ll,:);

    N_array1(1,(3:2:2*(1+brt)))=L(ll,:);

    N_array1(1,1)=s;

    N_array1(1,(2*(1+brt)))=r;

    N_array2=[N_array2;N_array1];

end

end

Rel=[];
```

```
[nl,nb]=size(N_array2);

for NL=1:nl

for NB=1:2:nb

if N_array2(NL,NB)~=0

if N_array2(NL,(NB+1))~=0

        Rel(NL,(NB+1)/2)=Rl(N_array2(NL,NB),N_array2(NL,(NB+1)));

end

end

end

end

Rel=Rel*Rn^N;

for rl=1:nl

for rb=1:(N-1)

if Rel(rl,rb)==0

      Rel(rl,rb)=1;

end

end
```

```
end
Relprod=Rel(:,1);
for start=2:(N-1)
   Relprod=Relprod.*Rel(:,start);
end
Rel=(sum(sum(Relprod))/nl);
else
   Rel=Rl(1,2)*Rn^N;
end
ttr=ttr+Rel;
end
ttr=ttr/count;
ttrel=ttrel+ttr;
end
end
if Rl==zeros(N)
```

```
    TTR=0;
else
TTR=ttrel/NS;
ttrall=[ttrall,TTR];
end
ttrall=sum(ttrall)/lc;
ATRR=ttrall;
TTRRR=TTTT;
TTR=max(ATRR,TTRRR);
ATR=min(ATRR,TTRRR)/3;
result=[result;[TTR,ATR]];
end
result=sum(result)/10;
ATR=min(result);
TTR=max(result);
day=clock;
day=day(:,4:end);
```

```
day(1,1)=day(1,1)*60;

day(1,2)=day(1,2)*60;

day=sum(day);

Time2=day;

Timer=Time2-Time1;
```