ESTIMATION OF PATH DURATION IN MOBILE AD-HOC NETWORKS:
A THEORETICAL STUDY

A Thesis by

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 The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

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DEDICATION

To my parents and my sisters

ABSTRACT

Mobile ad hoc networks (MANETs) are widely deployed for different purposes. Some of these areas are for the military, emergency rescue operations, etc. These networks are established "on the fly" and, therefore, play a decisive role in such applications. From a network point of view, MANETs are self configuring and dynamically changing networks. Since the topology changes dynamically, each node in the network must keep track of other nodes' movements and maintain connectivity. The most popular MANET routing protocols use response time or number of hops to decide the feasible routes. Estimation of path duration can enhance the efficiency of routing protocols in MANETs. One such area in reactive routing can be the assignment of route expiry time. This thesis attempts to develop a mathematical model to compute the path duration. The mathematical model is based on the concept of least remaining distance (LRD). LRD is similar to the shortest path forwarding, where the path is selected based on the least number of hops. In this technique, the path is selected by the least path duration. An analytical expression of path duration for an n-hop network is derived. The accuracy of the model is validated with the experimental results available in the literature.

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LIST OF ABBREVIATIONS

ABR	Associativity-Based Routing
AODV	Ad-Hoc On-Demand Distance Vector Routing
CDF	Cumulative Distribution Function
DSR	Dynamic Source Routing
FW	Free Way
LRD	Least Remaining Distance
MANET	Mobile Ad hoc Networks
MD	Mobile Devices
PDF	Probability Density Function
PRNET	Packet Radio Network
RPGM	Reference Point Group Mobility
RWP	Random Way Point
SURAN	Survivable Adaptive Radio Networks
WLAN	Wireless Local Area Network
WRP	Wireless Routing Protocol
ZHLS	Zone-Based Hierarchical Link State
ZRP	Zone Routing Protocol

CHAPTER 1

INTRODUCTION

1.1   Ad-Hoc Networks

Wireless networks have witnessed tremendous development in the past few years. Growth in personal computing and mobile computing has spurred this outburst of wireless networking. Wireless mobile ad hoc networks (MANETs) are a special type of wireless network, which do not have any pre-existing infrastructure-like access points. They are decentralized in nature and establish connections on the fly. Since the usage of mobile devices (MDs) and wireless networks is increasing daily, wireless ad hoc networks have attracted the attention of the research community all over the world. Even though there are many futuristic applications for MANETs, there is a still much opportunity for improvement. Among the wide open challenges are latency and security.

The evolution of ad hoc networks can be classified into first, second, and third generations. The first generation of ad hoc networks was called the packet radio network (PRNET). These networks later evolved into the survivable adaptive radio networks (SURAN) program. The second generation of ad hoc networks was an enhanced version of SURAN. These ad hoc networks were extended to mobile environments where there was no infrastructure. The third generation of ad hoc networks, which is the current generation of ad hoc networks, is again divided into two types. The first type is called infrastructured networks, an example of which is the wireless local area network (WLAN). The second type is called infrastructure less networks, generally known as MANET, which is basically a multi-hop network that is self-configuring and self-organizing. These networks are formed dynamically and are

required to deliver packets across the network. The fundamental characteristics of ad hoc networks include the following:

- Dynamically changing topology.

- Common channel needed for communication.

- Absence of centralized network management.

- Limited bandwidth and limited energy.

- Lack of infrastructure

- More resource demand on participating nodes.

MANETs are increasingly finding presence in commercial, defense, and private sectors as mobile computing becomes more widespread day by day. Users communicating over MANETs are not bounded by infrastructure constraints such as nearness to access points and reachability. All connections in MANETs are dynamic. However, not many MANETs are in use due to various technical constraints. These problems are being addressed by the scientific community.

1.2 Challenges for MANETs

Some of the major challenges for MANETs are decentralized administration, limited bandwidth, limited resources, scalability, security, and transmission quality. Bandwidth optimization in wireless networks is a major issue when compared to wired networks. This is quite obvious as wireless links cannot carry as much data as wired links. Moreover, mobile nodes depend upon battery power to use resources. Hence, efficient routing algorithms must be employed to minimize the resource constraints on nodes.

Routing in MANETs is the most important area that determines its effectiveness. Some of the key challenges in this area include managing battery power, random movement of nodes, low bandwidth, and data corruption. The existing routing protocols for MANETs can be classified as follows:

- Proactive (table-driven).

- Reactive (source-initiated on-demand-driven).

- Hybrid.

Proactive routing protocols maintain routes to different networks, even when there is no traffic in the network. Examples of prominent proactive routing protocols are the destination-sequenced distance vector (DSDV) and the wireless routing protocol (WRP). These protocols watch for routes to all destinations in the network. When a node wants to initiate a connection to any other node in the network, proactive routing protocols connect very quickly. The delay for establishing a connection is very small since the route will be readily available in the routing table. These protocols are called table-driven as they store route information similarly to conventional routing protocols in wired networks.

On the other hand, reactive routing protocols discard the conventional routing tables and therefore need not update the routing tables on a regular basis as they do in proactive routing protocols. Routes are established "on demand" in reactive routing protocols. When a source requires a route to a destination, reactive routing protocols initiate the following actions: Establish a route by the route-discovery procedure.

a. Maintain the route by some form of route-maintenance procedure.

b. Sustain the route until either the route is no longer desired or it becomes inaccessible.

c. Finally tear down the route by the route-deletion procedure.

Examples of well-known reactive routing protocols are the ad hoc on-demand distance vector (AODV) and dynamic source routing (DSR).

Hybrid routing protocols combine the nodes into zones. Then, after the network is divided into zones, the proactive approach is used to maintain connectivity within the zones. Routing information between zones is maintained using the reactive approach. This implies that the communication within the zone is much faster than the communication between zones. A better end-to-end delay is provided by the zone routing protocol (ZRP) and zone-based hierarchical link state (ZHLS) routing protocol for large wireless domains. Furthermore, these protocols can provide a better trade-off between communication overhead and delay. However, the effectiveness of this balance depends on the size of the network. On the whole, hybrid routing protocols are more suitable for larger domains.

Convergence is another issue in wireless networks that run different protocols. Nodes must wait until the network is completely connected. However, problems such as signaling and power consumptions are minimized. Mobility is another aspect which is common to both protocols. Whenever the location of the node shifts due to mobility, the previous links that were passing data may not be active later. Because of this situation, the routing protocol must keep watch over the link availability in order to initiate the route request as soon as the link becomes unavailable. To effectively achieve this objective, a proper route notification and keep-alive system needs to be in place.   In

addition, a route-prediction mechanism should be available so that the node can know the lifetime of the link beforehand. If these features are not available, the nodes must stop transmitting until a new path is established. All these aspects increase the complexity of the routing protocol.

1.3   Link Duration and Path Duration

As pointed out earlier, the mobility of nodes has a considerable effect on the topology, which in turn affects the network's performance. The parameters that signify the performance of a MANET are as follows:

- Link duration

- Path duration

Link duration is the amount of time it takes to reach the nearest node within the transmission range. When a node wants to send data to a neighbor, the link should be available until the entire content is sent across. If the link between the nodes breaks, then there would be an interruption in the information sent. In a multi-hop environment, the route to the destination is traced by the routing protocol that is active. This protocol may be either reactive or proactive. Irrespective of the approach chosen, the route to the destination is found depending on the available links at that moment. The amount of time the route is valid is called path duration or route duration. Links may become invalid after a period of time due to mobility, signal strength, etc. Path duration may be defined as the sum of all the link durations along the path. Among all the paths that are available for a specific destination, the minimum path duration route is chosen by a node. Therefore, link duration and path duration affect the throughput and efficiency of a routing protocol.

Route expiry is a field in a routing table that decides the validity of a route. This value gives the maximum number of hops that the data can travel before reaching the destination or declaring the route as invalid. A node having knowledge of path duration and link duration can set this value accordingly. Moreover, these values help in minimizing the packet loss in the network by estimating how long a route will be active in the network. Selecting the routes based on these parameters is not a simple task, requiring knowledge of other parameters like orientation of the nodes in space, their direction of movement, velocity etc. Such a prediction would be easy if the nodes could move with an installed GPS. But MANETs often have an infrastructure due to their dynamic nature. The routing protocols that are widely used do not select a path based on these parameters. For instance, AODV selects a path based on the first available route, and DSR selects a path on the basis of minimum hop count.

The analysis of these routing protocols is made on the basis of various mobility models. A mobility model is a framework that represents the movement of mobile users, their locations, and parameters like velocity, acceleration, etc. A variety of mobility models are random way point (RWP), reference point group mobility (RPGM) and free way (FW), to name a few. The ubiquitous model among all the models is the random way point (RWP) model.

1.4 Thesis Outline

The remainder of this thesis is organized as follows: Chapter 2 presents an overview of the existing literature related to mobility, different modeling scenarios of path duration, etc. Chapter 3 shows a detailed analytical model for path duration.

Chapter 4 presents MATLAB results and a comparison with the experimental path

duration results of Sadagopan et al. [1]. Chapter 5 presents conclusions and future wok.

CHAPTER 2

LITERATURE SURVEY

Path duration has been studied in different contexts by many researchers. The motivation for analytically studying this subject is driven by these previous studies. The first attempt in correlating the path duration and performance of protocols appeared in a paper by Sadagopan et al. [1]. Here, the authors analyzed path duration, throughput, and overhead of the reactive routing protocol. The protocol chosen for this study was DSR. The results were shown across different mobility models such as RWP, RPGM, FW, and Manhattan mobility models. The parameters analyzed included relative velocity of nodes, number of hops, and transmission range. The analytical modeling for the path duration evolved basically on logical reasoning and the simulation results. Even though there was a constant that depended on node density, map layout, etc., there was no such model that could be validated with the simulation results. This forms the basis and motivation for analyzing the path duration by basing it on network parameters such as transmission range, average velocity, node density, and number of hops. The distribution of the path duration is approximated to an exponential distribution when the number of hops is greater than two.

A relation between the cumulative distribution function (CDF) of path duration in terms of link duration and number of hops was developed by Han et al. [2]. The basic expression for the path duration distribution is

$$F_l^{(n)}(x) = \frac{1}{m\left(G_l^{(n)}\right)} \int_0^x \left[1 - G_l^{(n)}(y)\right] dy \qquad\qquad if\ x > 0 \qquad (2.1)$$

$$F_l^{(n)}(x) = 0 \qquad\qquad if\ x \le 0 \qquad (2.2)$$

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where $F_l^{(n)}(x)$ is the CDF of path duration over different available links, and $G_l^{(n)}$ is the distribution of all available links in the network to reach a destination. The array of independent, monotonically independent, increasing random variables is $l = 1,2 \ldots \ldots . h^{(n)}$. This study developed a relationship between the excess lifetimes of two neighboring links for an on-demand routing protocol. The following are the major results of this analysis:

- The link excess lives, introduced by lack of the reachability process, are negligible for the RWP model.

- Using Palm's theorem, it was proven that the when the number of hops is large, the distribution of path duration can be accurately approximated by an exponential random variable under mild conditions.

- The inverse of the expected value of the path duration is approximately given by the sum of the inverses of expected link durations.

An analytical approach to finding limits on the number of hops for a given source to the destination Euclidean distance was evaluated by De et al. [3]. The least remaining distance approach was used for the analysis. The forwarding area was divided into a more probable area and a less probable area for the relay node selection. This division comes from the fact that the LRD is more in the less-probable area and vice versa. The analysis was basically for one-hop networks; the extension for multipath forwarding was not considered. Even though the underlying principle for the analysis was LRD forwarding, this is a relatively simple derivation for the path duration.

Tsao et al. evaluated the link duration of two mobile nodes [4]. Mobile nodes establish links if they come within the vicinity of their fields. More emphasis is given in

formulating the expression for probability distribution of the direct links. An expression was developed based on the assumption of unknown node velocity. Other assumptions in this model are listed below:

1. Each node has the same transmission range.

2. The link is active when the two nodes are within the transmission range of each other.

3. The magnitude of velocities of each node is the same.

The expected duration of the link duration is given by

$$E(T)=E(D/V)=E(D).E(1/V) \tag{2.3}$$

where "T" is the link duration, "V" is the relative velocity, and "D" is the active distance. The expressions for expected distance and expected velocity, respectively, are

$$f_d(d) = \frac{d}{2r\sqrt{4r^2 - d^2}}$$

$$f_v(v) = \frac{v}{2V_{fix}\sqrt{4V_{fix}^2 - v^2}} \tag{2.4}$$

From equation (2.4), the expected active link duration expression can be computed for two cases:

1. When $t \le \dfrac{r}{V_{fix}}$

$$f_v(v) = \frac{1}{2} - \frac{r^2 - V_{fix}^2 t^2}{2V_{fix}t} \ln \left| \frac{r + V_{fix}t}{\sqrt{r^2 - V_{fix}^2 t^2}} \right| \tag{2.5}$$

2. When $t > \dfrac{r}{V_{fix}}$

where V_{fix} is the magnitude of the velocity of the nodes.

From the equations derived, the simulation results show that the distribution of the active link duration decreases as the velocity increases.

Stability of the random waypoint mobility model was examined by Yoon et al. [5]. Node speed is the primary parameter in any mobility model. In this paper, the RWP model was analyzed. This model chooses a node independently and randomly, and then moves toward the destination at a certain speed. This speed is chosen randomly within the range $(0, V_{max}]$. The RWP model was expected to maintain the average speed of $V_{max}/2$; however, this did not occur. This feature was not noticeable when the simulations were run for a shorter period. But when the simulations were run for a longer duration, the average speed decayed slowly and tended to approach zero. The node speed is formally defined by

$$v(t) = \frac{\sum_{i=1}^{N} v_i(t)}{N} \tag{2.6}$$

This is attributed to the fact that, when the simulation periods are longer, the node speed progressively reduces as it approaches the destination. A formal approach to demonstrate this was attempted. The ratio of the average speed ($\vec{V}$) to the initial speed ($\vec{V}_{init}$) is given by

$$\frac{\vec{V}}{\vec{V}_{init}} = \frac{2(\alpha-1)}{(\alpha+1)\ln\alpha} = g(\alpha) \tag{2.7}$$

where $\alpha = \frac{V_{max}}{V_{min}} > 1$

Equation (2.7) can be expressed as

$$\lim_{\alpha \to 1} g(\alpha) = 1 \tag{2.8}$$

$$\lim_{\alpha \to \infty} g(\alpha) = 0 \tag{2.9}$$

From equations (2.8) and (2.9), it is quite clear that there will be certain decay in the average speed over time. The greater the value of α, the longer the decay period. In other words, the smaller the V_{min}, the longer the decay period.

In order to overcome this drawback, Yoon et al. suggested the following measures:

1. Specify a positive minimum speed for the mobility model. This cannot be too close to zero, as it may affect the stability of the model.

2. Calculate average speeds carefully rather than using a simple arithmetic average.

3. Warm up the simulations in order to eliminate the initial drop in the average speed.

When these changes were incorporated, simulation results showed that the speed was maintained consistently over time. The new run showed an increase in overhead packets and dropped packets.

Mobility models form the major crux of simulations in wireless networks. These mobility models were dealt with by Bettstetter [6]. The movement patterns of users are important in analytical and simulation studies of these networks. These models help in updating the user location and allocating radio resources, especially in a cellular network environment, and are called microcellular environments. In general, macro mobility models do not give the correct results when applied to micro environments, since the choice of speed and direction are not correlated to the previous values.

In this paper, Bettstetter attempted to introduce the micro mobility patterns in the random mobility model, which is used for mobile and wireless networks. This is called the smooth Random Mobility model.

This model is basically addresses the two dimensional movement on a minute level. Speed and direction are considered independent and random. There are no restrictions applied for the movement of nodes is not restricted. Speed and direction are modeled as two stochastic processes in the simulation environment. They are changed in incremental steps, which are auto correlated to the previous values.

The speed profile of the node at any time is given by the following:

- Current speed

- Current acceleration

- Current target speed

The node moves with a constant speed until a target speed is decided. Once it fixes the target speed, the node accelerates or decelerates in steps. The speed-change events follow Poisson's process. The direction change is similar to speed change. The node moves in a straight line until there is a change in direction. The direction change events follow an exponential process.

Simulations of wireless networks rely on the mobility models. The author derives a general framework for random mobility models and proves that any model that chooses the distance or destination independently suffers from average speed decay. Recommendations to avoid this were made by Yoon et al. [7].

Random mobility models are a collection of a set of nodes placed randomly within a confined simulation space, U. Every node selects two or more of the following parameters:

- Speed, "v"

- Angle, "α'"

- Distance, "d"

- Travel time, "t"

In this paper, Yoon et al. considered only temporal properties of the node. Since the angle affects only the spatial distribution, this was not considered. Also, since choosing the destination is equivalent to choosing distance, this leaves the selection of models with two of the three parameters, i.e., models with (speed, time) and (speed, distance).

From the expressions developed in this model, the following were concluded:

- The steady state speed distribution is always different from the initial speed distribution.

- The steady state distribution and the expectation of the node speed are dependent on the initial speed distribution, average distance, and average pause time.

- The steady state average node speed is always less than the initial average speed.

The performance of a mobile node highly depends on its movement. Therefore, a stable node movement is most critical in analyzing any mobility model. In order to avoid the decay in the average velocity of the node, there are a few alternatives:

A. Narrowing the range from which the speeds are selected, which can minimize the decay, but the core problem remains the same. Moreover, the variety of speeds cannot be achieved by this.

B. Initially warming up the simulations, and when the steady state is reached, removing the initial period for the analysis. However, this is a tedious process in analyzing mobility models.

C. Using the composite method by selecting the speed from the steady state values.

Considering the disadvantages of the above methods, Yoon et al. suggested a composite procedure to minimize this by a methodical analysis. Conventionally, the speed of the initial trips is selected independent of the travel times, but the average steady state speed is calculated from the travel times. If the initial speeds are chosen from a steady state distribution and the speeds for the later part are chosen from the original speed distribution, this problem can be completely eliminated.

A stability-based routing approach was introduced by Sridhar et al. [9]. This type of routing was proposed as the improved version of conventional hop count-based routing. Stability metric employed in this approach was link residual time. The difference of average link duration and current age of the link is defined as the link residual time. Similar to proactive routing protocols, each node is proposed to maintain the state information of all its neighbors. This approach concludes that stability is not dependent on the age of the link. In other words, older links are not necessarily the stable. Associativity-based routing (ABR), which is also called the stability-based routing protocol, on the contrary, proposes that older links are more stable.

The degree of mobility was measured by Kwak et al. [10]. This is linearly dependent on the rate of network link changes and is useful to measure routing protocols' performance with different mobility models. Along with the physical properties of the network, such as the dimensions, node density is considered the parameter that affects the mobility along with range and velocity of nodes.

CHAPTER 3

THEORETICAL MODEL

3.1 Modeling and Assumptions

As discussed earlier, in mobile ad hoc networks, the topology changes with time. There are many strategies to select the best route in such a dynamically changing environment. One such technique is the least remaining distance forwarding model. LRD basically selects the shortest path to reach the destination, in other words, the shortest path duration.

3.1.1 Least Remaining Distance Model

As in any forwarding, the LRD model has a source node and a destination node. Another node, called the relay node is selected by the source node to forward the packet. Consider a simple scenario of a single-hop distance from the source node to reach the destination. The source node's transmission range contains a number of nodes that can reach the destination. Let the distance from these nodes to the destination be d_1, d_2, d_3.....d_n. The source node will select the node that has the minimum distance to the destination. This behavior is analogous to the shortest path technique in wired networks. In the case of MANETs, this is called LRD forwarding. In order to implement this routing technique, every node should be able to assess the least remaining distance of the other nodes in order to reach the destination. The aim of this modeling is to probabilistically assess the link duration and hence the path duration to reach a specific destination. After assessing all possible path durations, the node selects the least path duration among all the possibilities.

3.2   Link Duration

If two nodes are within each other's transmission range, the link between them is considered active. The duration of this active link is known as the link duration. Fundamentally, the expression for this is given by

$$t = \frac{d}{v_r} \tag{3.1}$$

where "d" is the distance that the node has to travel to go out of the transmission range, and "v_r'" is the relative velocity between the two nodes. Since the MANET dynamically changes with time, the probability distribution of link duration is derived by determining the probability distributions of "d" and "v_r." The following sections deal with the analysis of these two quantities.

3.2.1 Link Distance

As pointed out earlier, the analysis of "d" is based on the shortest-path technique. Most of the routing protocols having an on-demand nature use this technique. The nodes are assumed to follow Poisson distribution with node density (λ) as the parameter. The suitability of this distribution has been discussed by Sadagopan et al. [1] and Han et al. [2].The following variables for analyzing the link distance are illustrated in Figure 3.1

l: Distance between source (S) and destination (D).

x: Distance between relay node (R) and D. I is a point of intersection between the two circles—one drawn at S with radius r and the other drawn at D with radius x. Then $ID = RD = x$.

y: Distance between S and R.

r: Transmission range of nodes. This is considered uniform for all the nodes.

θ: Angle between the two straight lines SR and SD.

Δx: Width of the strip shown in Figure 3.1. This strip is formed by two arcs drawn from D with radius x and $x +\Delta x$, respectively. Δx is chosen such that the probability of finding at least one node in the strip is non-zero.

$a_{int}(x)$:   Width of the strip shown with stripes in Figure 3.1. The strip is formed by two arcs drawn from D with radius x.

$a_{arc}(x, \Delta x)$:   Area of the strip formed by Δx as described earlier.

x: distance between I and D, same as the distance between R and D
y: distance between S and R
l: distance between S and D
r: transmission range of S
θ : angle between SR and SD
z: straight line distance between S and R
A1+A2: area of intersection between circles drawn at S and D
θ_1: angle between SI and SD
θ_2: angle between ID and SD

S: source
D: destination
R: relay
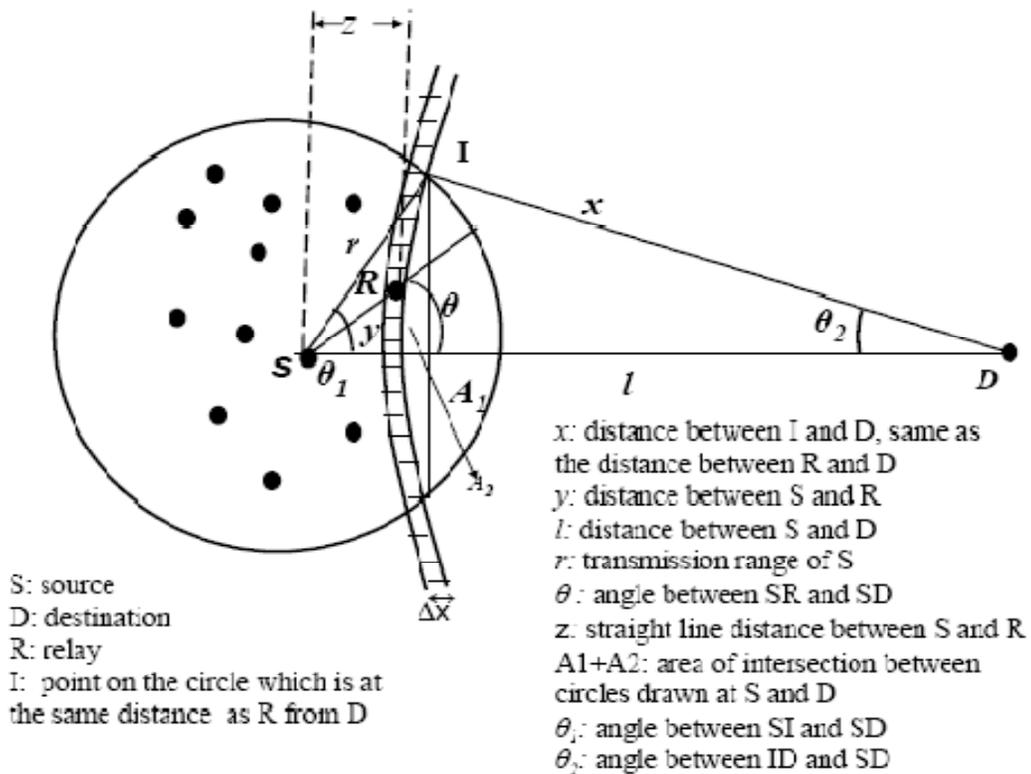I: point on the circle which is at the same distance as R from D

Figure 3.1. Selection of a relay node based on the principle of shortest path or least remaining distance. The location of nodes are assumed to follow Poisson distribution with parameter λ, representing the node density [11].

Figure 3.1 illustrates the scenario of the LRD forwarding technique. Let X represent the distance between the relay node and destination node which is $RD \ or \ ID$. The PDF $f_x(x)$ corresponding to X can be computed based on both of the following conditions:

- The source node selects a node at a distance x from the destination, if it cannot find any other node within the area $a_{int}(x)$.

- If there is at least one node within the strip, then $a_{arc}(x, \Delta x)$.

This can be represented mathematically as

$P(x \leq X < x + \Delta x)$

$$= P_r[number \ of \ nodes \ in \ a_{int}(x)] * P_r[atleast \ one \ node \ in \ a_{arc}(x, \Delta x)]$$

$$= e^{-\lambda a_{int}(X)}[1 - e^{-\lambda a_{arc}(x, \Delta x)}] \qquad l - r \leq x \leq r \qquad (3.2)$$

Let the PDF of $X = f_X(x)$. This can be mathematically expressed as

$$f_X(x) = e^{-\lambda a_{int}(X)}[1 - e^{-\lambda a_{arc}(x, \Delta x)}] \quad \forall \ (l - r) \leq x \leq l \qquad (3.3)$$

$$f_x(x) = 0 \quad elsewhere$$

Generally, it is implied that the routing protocol is assumed to know the distance of the relay nodes in terms of hops. Evaluating the above expression for $l = 500m$ and $r = 250m$ is shown in Figure 3.2

From Figure 3.1, $a_{int}(x)$ and $a_{arc}(x, \Delta x)$ can be computed as

$$a_{int}(x) = A_1 + A_2 \qquad (3.4)$$

$$a_{int}(x) = r^2\left[\theta_1 - \frac{\sin 2\theta_1}{2}\right] + x^2\left[\theta_2 - \frac{\sin 2\theta_2}{2}\right] \qquad (3.5)$$

$$a_{arc}(x, \Delta x) = \left[\frac{2\theta_2}{2\pi}\right][\pi(x + \Delta x)^2 - \pi x^2] \qquad (3.6)$$

and can be calculated as

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$$a_{arc}(x, \Delta x) = \theta_2[2x + \Delta x]\Delta x \tag{3.7}$$

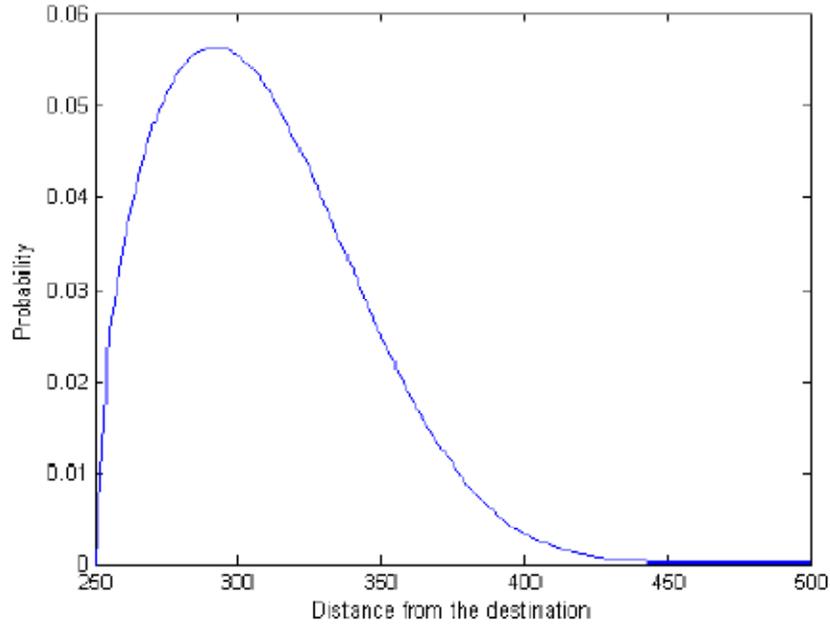$$a_{arc}(x, \Delta x) = \cos^{-1}\left[\frac{x^2 + l^2 - r^2}{2xl}\right][2x + \Delta x]\Delta x \tag{3.8}$$

Figure 3.2. Probability density function of the random variable X. The curve is plotted for $l = 500$m and $r = 250$m. The range of random variable X is from $l = r$ to l.

The terms θ_1 and θ_2 can be derived as illustrated below,

From Figure 3.1, consider the triangle SID formed by the source, relay, and destination node. This is illustrated in Figure 3.3
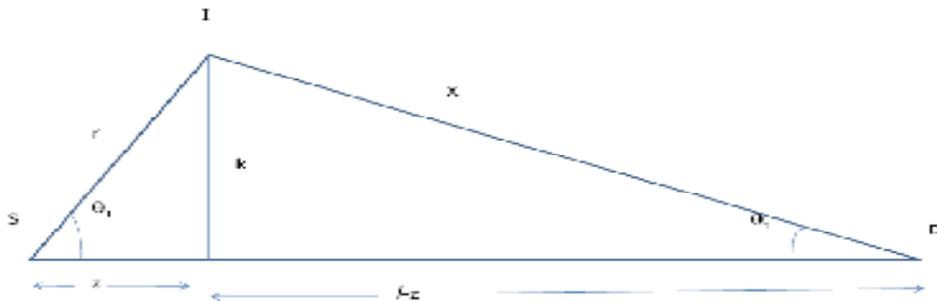

Figure 3.3. Triangle formed by source node (S), relay node (I), and destination node (D).

From Figure 3.3, it can be seen that

$$k^2 = r^2 - z^2 \tag{3.9}$$

$$k^2 = x^2 - (l - z)^2 \tag{3.10}$$

Deducing from equations (3.9 and (3.10), we get

$$r^2 - z^2 = x^2 - (l - z)^2 \tag{3.11}$$

$$r^2 - z^2 = x^2 - (l^2 + z^2 - 2lz) \tag{3.12}$$

Solving for z,

$$z = \frac{l^2 + r^2 - x^2}{2l} \tag{3.13}$$

From Figure 3.3,

$$\cos \theta_1 = \frac{z}{r} \tag{3.14}$$

$$\cos \theta_1 = \frac{l^2 + r^2 - x^2}{2lr} \tag{3.15}$$

Similarly, $\cos \theta_2$ is computed. The final expressions for θ_1 and θ_2 are given as

$$\theta_2 = \cos^{-1}\left[\frac{x^2 + l^2 - r^2}{2xl}\right] \tag{3.16}$$

$$\theta_1 = \cos^{-1}\left[\frac{r^2 + l^2 - x^2}{2rl}\right] \tag{3.17}$$

From $f_X(x)$, the expected distance from the relay node to the destination can be computed as

$$E[X] = \frac{1}{A}\int_{l-r}^{l} x f_X(x) dx \tag{3.18}$$

$$E[X] = \frac{1}{A}\int_{l-r}^{l} x e^{-\lambda a_{int}(X)}\left[1 - e^{-\lambda a_{arc}(x,\Delta x)}\right] dx \tag{3.19}$$

Let z be defined as the progress per hop toward the destination made by the choice of the relay node. From figure 3.1, this can be defined as

$$z = l - x \cos \theta_2 \tag{3.20}$$

Substituting the value of $\cos\theta_2$ from the equation gives

$$z = l - x\,\frac{x^2 + l^2 - r^2}{2xl} \tag{3.21}$$

This leads to

$$x^2 = l^2 + r^2 - 2lz \tag{3.22}$$

Therefore,

$$x = \sqrt{l^2 + r^2 - 2lz} = g^{-1}(z) \tag{3.23}$$

and

$$z = \sqrt{\frac{l^2 + r^2 - x^2}{2l}} = g(x) \tag{3.24}$$

In order to compute $f_Z(z)$ from $f_X(x)$,

$$f_Z(z) = f_X[g^{-1}(z)]\,\frac{dg^{-1}(z)}{dz} \tag{3.25}$$

Differentiation of $g^{-1}(z)$ with respect to z gives

$$\frac{dg^{-1}(z)}{dz} = \frac{-l}{\sqrt{l^2 + r^2 - 2lz}} \tag{3.26}$$

Since r and l are constants with respect to z, we get,

$$dx = \frac{-l}{\sqrt{l^2 + r^2 - 2lz}}\,dz \tag{3.27}$$

Therefore,

$$\Delta x = \frac{-l}{\sqrt{l^2 + r^2 - 2lz}}\,\Delta z \tag{3.28}$$

From equations (3.17) and (3.16), θ_1 and θ_2 can be expressed, respectively, in terms of

z as

$$\theta_1(z) = \cos^{-1}\left[\frac{z}{r}\right] \tag{3.29}$$

$$\theta_2(z) = \cos^{-1}\left[\frac{l-z}{\sqrt{l^2 + r^2 - 2lz}}\right] \tag{3.30}$$

Therefore,

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$$a_{arc}(z, \Delta z) = \left[2 - \frac{l\Delta z}{l^2 + r^2 - 2lz}\right] \cos^{-1}\left[\frac{l-z}{\sqrt{l^2 + r^2 - 2lz}}\right](-l\Delta z) \qquad (3.31)$$

and

$$a_{int}(z)$$

is given by

$$a_{int}(z) = r^2\left[\theta_1(z) - \frac{\sin 2\theta_1(z)}{2}\right] + (l^2 + r^2 - 2lz)\left[\theta_2(z) - \frac{\sin 2\theta_2(z)}{2}\right] \qquad (3.32)$$

This leads to

$$a_{int}(z) = r^2\left[\theta_1(z) - \frac{\sin 2\theta_1(z)}{2}\right] + (l^2 + r^2 - 2lz)\left[\cos^{-1}\left[\frac{l-z}{\sqrt{l^2 + r^2 - 2lz}}\right] - \sqrt{\frac{r^2 - z^2}{l^2 + r^2 - 2lz}}\right] \qquad (3.33)$$

Also,

$$f_X[g^{-1}(z)] = e^{-\lambda a_{int}(z)}\left[1 - e^{-\lambda a_{arc}(z, \Delta z)}\right] \qquad (3.34)$$

Substituting expressions for $\frac{dg^{-1}(z)}{dz}$ and $f_X[g^{-1}(z)]$ into equation (3.26) gives

$$f_Z(z) = \frac{-l}{\sqrt{l^2 + r^2 - 2lz}} e^{-\lambda a_{int}(z)}\left[1 - e^{-\lambda a_{arc}(z, \Delta z)}\right] \qquad (3.35)$$

Once $f_Z(z)$ is known, the expected value of this length is calculated by

$$E[Z] = \int_0^r z\, f_Z(z)\, dz \qquad (3.36)$$

3.2.2 Relative Velocity

Relative velocity is considered with respect to relay node and source node. The expression for the relative velocity with S fixed is

$$v_r = \sqrt{v_1^2 + v_2^2 - 2v_1 v_2 \cos\alpha} \qquad (3.37)$$

where α is the angle between v_1 and v_2. If the magnitude of velocity is assumed constant as v, then $v_1 = v_2 = v$. Therefore,

$$v_r = v\sqrt{2 - 2\cos\alpha} = 2v\sin\frac{\alpha}{2} \qquad (3.38)$$

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Here α varies from 0 to 2π. Since the position of the source node is fixed, the relay node may move toward the source node or away from it with equal probability of 0.5. Since α is assumed to vary within $(0,2\pi)$, it is fair to assume that $\frac{\alpha}{2}$ would vary from $(0,\pi)$. The PDF of $f_{\frac{\alpha}{2}}\left(\frac{\alpha}{2}\right)$ can be given by

$$f_{\frac{\alpha}{2}}\left(\frac{\alpha}{2}\right) = \frac{1}{\pi} \tag{3.39}$$

From equation (3.40), $f_{v_r}(v_r)$ can be expressed as

$$f_{v_r}(v_r) = \frac{1}{\sqrt{4v^2 - v_r^2}} \cdot \frac{1}{\pi} \tag{3.40}$$

3.2.3 Expression for Link Duration

As discussed earlier, the link residual life is given by

$$t = \frac{d}{v_r} \tag{3.41}$$

where $d = r - z$, is a straight line that the relay needs to travel to move out of the transmission range. Hence, $f_T(t)$ is given by

$$f_T(t) = \int_0^{v_{max}} v_r f_{dv_r}(v_r t, v_r) dv_r \tag{3.42}$$

$$f_T(t) = \int_0^{v_{max}} [f_d(d)]_{d=v_r t} \left[\frac{v_r}{\sqrt{4v^2 - v_r^2}} \cdot \frac{1}{\pi}\right] dv_r \tag{3.43}$$

where v_{max} is the maximum velocity, and v is the velocity of the node. The equation shown for $f_T(t)$ is the equation for one-hop residual life of the link.

3.2.4 Path Duration

Path duration is derived from the PDF of the link duration. If there are h hops to reach the destination, then the path duration can be written as

$$t_{path} = \min(t_1, t_2, t_3 \ldots \ldots \ldots t_h) \tag{3.44}$$

where t_i is the link residual time corresponding to the ith link. Using Baye's theorem [2] and Chapter 6 in the work of Xu et al. [16], the path duration T_{path} can be expressed as

$$f(T_{path}) = hf_{T_{path}}(T_{path})C_{T_{path}}^{h-1} \qquad (3.45)$$

where $C_{T_{path}} = 1 - f_{T_{path}}$ is the complementary CDF of T_{path}.

Expanding $f_{T_{path}}(T_{path})$ gives

$$f_{T_{path}}(T_{path}) =$$

$$h\left[\int_0^{v_{max}}[f_d(d)]_{d=v_r t}\left[\frac{v_r}{\sqrt{4v^2-v_r^2}} \cdot \frac{1}{\pi}\right]dv_r\right]\left[1 - \right.$$

$$\left.\int_0^{t_{path}}\left\|\int_0^{v_{max}}[f_d(d)]_{d=v_r t}\left[\frac{v_r}{\sqrt{4v^2-v_r^2}} \cdot \frac{1}{\pi}\right]dv_r\right\|dt_{path}\right]^{h-1} \qquad (3.46)$$

The average path duration is given by

$$E[T_{path}] = \int_0^\alpha t_{path} f_{T_{path}}(t_{path})dt_{path} \qquad (3.47)$$

The average number of hops to reach the destination is given by $E[H]$. This quantity can be expressed as

$$E[H] = \frac{E[L]}{E[Z]} \qquad (3.48)$$

where $E[L]$ is the average distance between the source and destination, or the average path length, and $E[Z]$ is the average distance progress per hop.

From the work of Sridhar et al. [9]

$$E[L] = \frac{128}{45\pi}r \qquad (3.50)$$

CHAPTER 4

RESULTS AND DISCUSSION

This chapter provides an overview of the simulations run for the model presented in Chapter 3. These results are compared with the results of Sadagopan et al. [1] for the random waypoint model. MATLAB was used to simulate the proposed analytical model. In the following sections, the results for average path duration are presented for various parameters that affect the path duration. These parameters are transmission range, average velocity, number of hops, and node density. The objective of finding the accuracy in the proposed analytical model was achieved by providing the same values for input parameters to MATLAB as used by Sadagopan et al. [1].

4.1 Average Path Duration vs. Transmission Range

Figure 4.1 shows the relationship between the average path duration and the transmission range. It can be seen that as the transmission range increases, the average path duration also increases linearly. The maximum transmission range is varied in steps from 50 m to 250 m. The average velocity "v" is 10 m/s, and the maximum velocity "vmax" is 5 m/s.

If the transmission range is high, then the room for the relay node to travel is also high. This means that the probability of finding the node within the range is also more. Intuitively, the distance the relay node needs to travel to go out of range is higher. All of these imply that as the transmission range increases, the average path duration also increase.

If the relative velocity increases, the average path duration decreases. This can be attributed to the fact that the nodes move faster and go out of range in a much

shorter period of time, and the average path duration consequently decreases. Optimum values that follow the experimental results are v = 10 and vmax = 5.
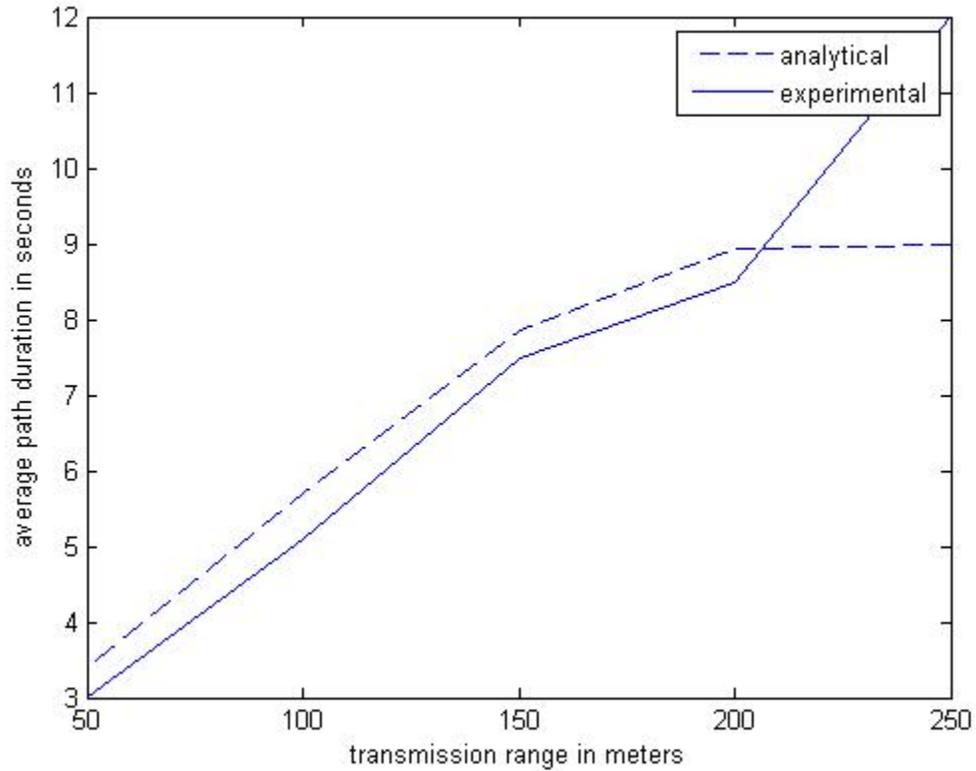

Figure 4.1. Average path duration vs. transmission range.

For a given average velocity of 10, if the relative velocity is changed from 1 to 10 it can be observed that the average path duration gradually decreases. This can be attributed to the fact that the nodes take a longer time to go out of range for lesser relative velocities ,and vice versa.

4.2 Average Path duration vs. Relative Velocity

Figure 4.2 shows the variation of the average path duration with respect to maximum velocity. The plot can be approximated to exponential distribution when V >= 15 m/s. Also, the average path duration has a multimodal distribution when V <= 15 m/sec, as mentioned by Sadagopan et al. [1].

For a give transmission range, the average path duration will be approximately a straight line. For the graph shown in Figure 4.2, this velocity is 15 m/s. The transmission range chosen for this particular scenario is 250 m. As the transmission range decreases, the average path duration also decreases.
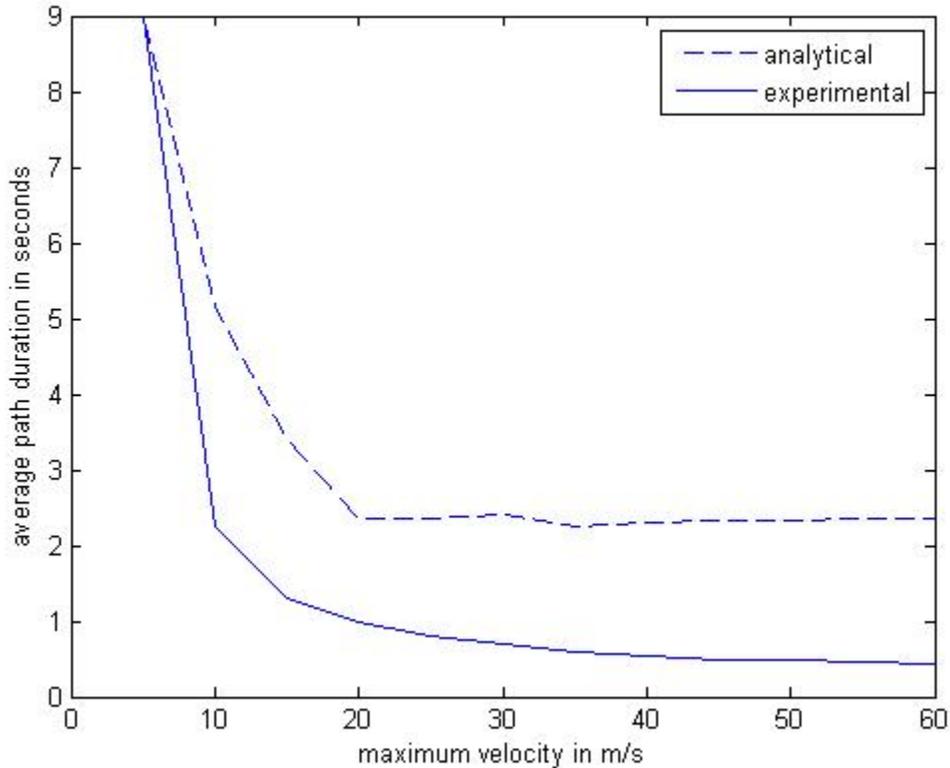

Figure 4.2. Average path duration vs. maximum velocity.

4.3   Average Path Duration vs. Number of Hops

Figure 4.3 shows the plot between number of hops and average path duration. As can be seen, the path duration is large for one hop. The path duration of one hop is nothing other than the link duration, which can be anywhere from 0 to R. A steep fall of path duration occurs from one hop to two hops. This distribution after two hops can be approximated to exponential distribution, as mentioned by Sadagopan [1].
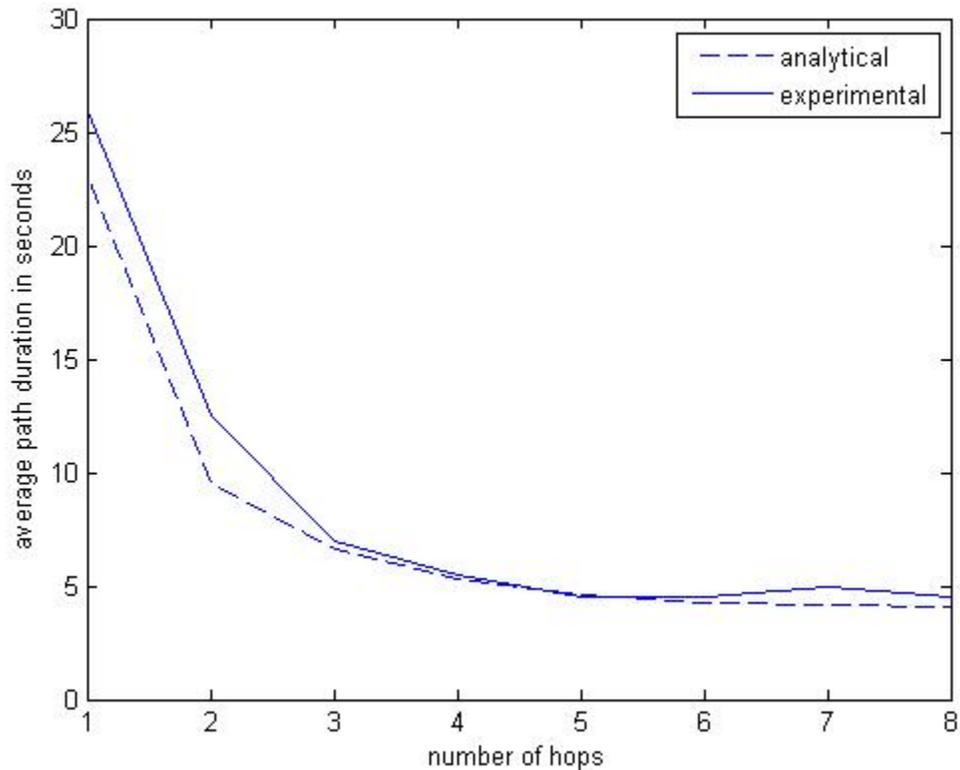
Figure 4.3. Average path duration vs. number of hops.

4.4 Average Path Duration vs. Number of Nodes

Figure 4.4 shows the plot between the average path duration and the node density λ. It can be seen that the average path duration increases with the node density. The parameters for this graph are transmission range of 220 m, relative velocity of 8 m/s, average velocity of 10 m/s, and node density varying between 10 and 100 nodes per the given transmission area. The transmission area is 1,000 by 1,000 cm. Some observations from the graph are as follows:

- Node density can be varied until a threshold value. This value for the graph in Figure 4.4 is approximately 140.

- As the relative velocity increases, the average path duration decreases, and vice versa. This is due to the fact that the nodes travel slower and hence takes more time to go out of range.

- If the transmission range is increased, the average path duration is increased. This is due to the fact that the relay nodes have to travel a longer distance to move out of range, and hence the average path duration increases.
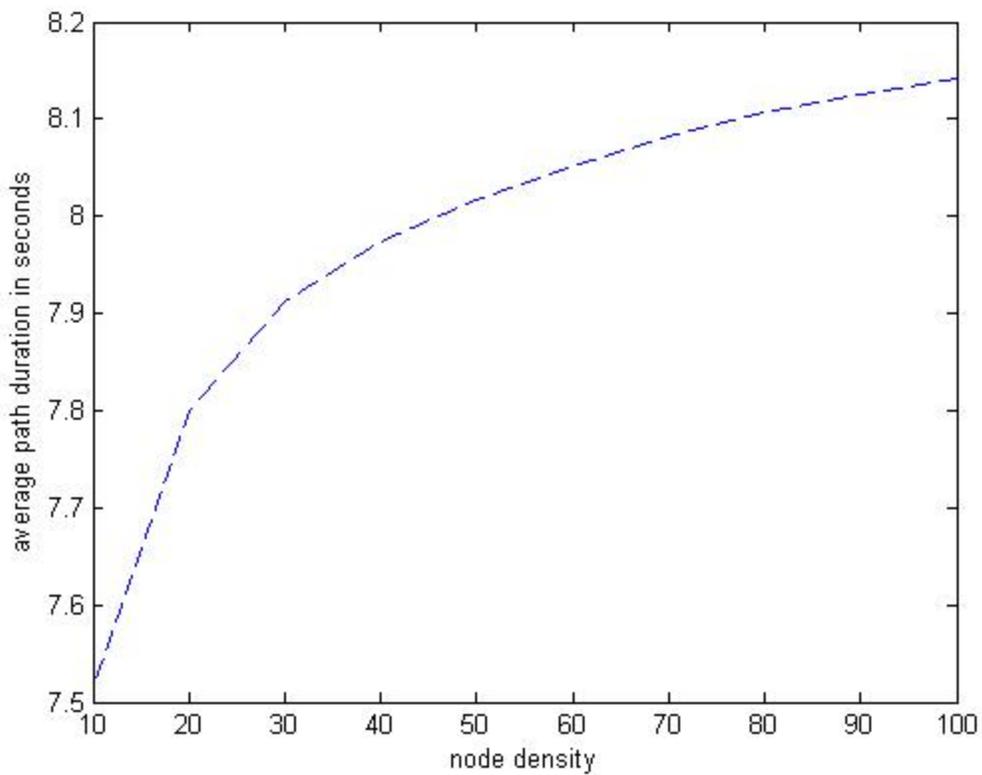

Figure 4.4. Average path duration vs. node density.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The demonstrated analytical model provides the expressions for predicting the path duration of the MANETs employing LRD forwarding. Although there are other routing strategies for MANET path selection, this technique is widely used. All the on-demand routing protocols employ this procedure for path selection. Analytical estimation of path duration is quite useful when employed for routing decisions made by the given routing protocols.

5.2 Future Work

Future work for this subject would be to incorporate the path duration feature into routing protocols. If this is successfully implemented, the nodes would have a clear understanding of the time taken to reach a destination, thus contributing to precise routing decisions.

The average path duration is primarily dependent on the mobility of the nodes. Other factors contribute to this quantity. Future work on this subject would be to investigate other mobility parameters that affect the average path duration.

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