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A Study on the Impact of Node Mobility on the Duration and Maximum Length of Multi-Hop Routes in Wireless Networks

Michael Pascoe Chalke

2010

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Universidad Nacional Autónoma de México, por mi raza hablará el espíritu.

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RESUMEN

Estudio sobre el Efecto de la Movilidad en la Duración y la Longitud Máxima de Rutas Multisalto en Redes Inalámbricas

Michael Pascoe Chalke

Una red móvil del tipo *ad-hoc* (MANET) está conformada por una colección de nodos móviles que crean una red temporal mediante interfaces inalámbricas y sin requerir el uso de cualquier otro tipo de infraestructura existente o administración centralizada. Debido a la limitación en el alcance de transmisión de las interfaces inalámbricas, podría requerirse la intervención de uno o múltiples nodos intermedios operando como relevos que permitan establecer una ruta de comunicación entre cualquier par de nodos fuente-destinatario presentes en la red.

Esta tesis presenta un modelo que permite estimar el tiempo de duración de rutas que involucran varios nodos intermedios en redes móviles del tipo *ad-hoc*. Primero se analiza una ruta formada por tres nodos, donde el nodo intermedio está en movimiento mientras que los nodos fuente y destinatario permanecen estáticos. A partir de este caso, se demuestra que la posición inicial del nodo intermedio y el tamaño de la región de traslape, en la cual se encuentra localizado, afectan directamente a la duración de la ruta. La región de traslape asociada a un nodo intermedio se forma por la intersección de las zonas de cobertura de sus nodos adyacentes, que también son miembros de la ruta en cuestión. A continuación se considera un segundo caso, en el cual las rutas están conformadas por tres nodos móviles. Con base en un análisis extenso de dichas rutas, se determina la función de densidad de probabilidad (PDF) asociada al tiempo de duración de ruta bajo dos diferentes modelos de movilidad. Esta función puede ser determinada, ya sea por métodos analíticos o estadísticos. Finalmente, se demuestra que el tiempo de duración de una ruta formada por N nodos intermedios, puede ser calculado de manera precisa al considerar el tiempo de duración mínimo de un conjunto de N rutas de tres

nodos cada una. Se desarrollaron una serie de simulaciones, utilizando el simulador de redes *NS-2*, para verificar la precisión del modelo propuesto y poder compararlo con otras propuestas halladas en la literatura. Los resultados de simulación demuestran que el modelo propuesto proporciona una mayor concordancia con respecto a los otros modelos. Los resultados obtenidos a partir de este trabajo podrían ser utilizados para calcular la sobrecarga en la señalización (*overhead signaling*) que puede presentarse durante el proceso de mantenimiento de rutas en los protocolos de encaminamiento *unicast* y *multicast* para redes del tipo MANET.

Esta tesis también establece un modelo para estimar un límite superior en la longitud de ruta para redes móviles del tipo *ad-hoc*. En las redes del tipo MANET, las rutas son descubiertas por lo regular mediante la inserción en la red de paquetes de descubrimiento por parte de nodos emisores. En el momento en el que cada uno de estos paquetes alcanza a su destinatario, este nodo debe utilizar la ruta seguida por el paquete de descubrimiento para enviar un paquete de respuesta hacia el nodo emisor. Una vez recibido el mensaje de respuesta, puede iniciarse la transferencia de datos entre los nodos emisor y destinatario. Sin embargo, la movilidad de los nodos afecta en forma negativa a la duración de la ruta descubierta, ya que los cambios de posición de los nodos podrían ocasionar interrupciones en la conectividad. Además, el proceso de descubrimiento de rutas se puede colapsar por completo cuando, debido a los cambios de posición de los nodos, ya que la ruta seguida tanto por un paquete de descubrimiento como por un paquete de respuesta podría no ser válida en algún momento, mientras alguno de estos paquetes se encuentra viajando a través de la ruta. En esta tesis se estudian las condiciones que ocasionan este efecto y se demuestra que éstas imponen un límite práctico sobre la máxima longitud que puede presentar una ruta. Esta tesis también introduce un modelo de retardo para rutas con saltos múltiples el cual es el resultado de extender un modelo, encontrado en la literatura, el cual permite estimar el retardo en el acceso a redes WLAN de un solo salto. Asimismo, se presenta otro modelo de duración de ruta que considera los retardos de reenvío de los paquetes involucrados durante en el proceso de descubrimiento de ruta. Partiendo de la combinación de ambos modelos, se encuentra una expresión matemática que permite calcular un límite superior en la longitud de ruta para redes del tipo MANET. El modelo se valida mediante simulaciones con diferentes escenarios. A partir de este modelo, se descubre que tanto el alcance de transmisión y la movilidad de los nodos, así como los retardos involucrados en el reenvío de paquetes definen el número máximo de saltos que puede alcanzar una ruta. Según el conocimiento del autor, este es un problema fundamental de escalabilidad de las redes móviles del tipo *ad-hoc* que no había sido analizado anteriormente desde una *perspectiva movilidad-retardo*.

ABSTRACT

A Study on the Impact of Node Mobility on the Duration and Maximum Length of Multi-Hop Routes in Wireless Networks

Michael Pascoe Chalke

A mobile ad-hoc network (MANET) is a collection of mobile nodes forming a temporary network by means of wireless interfaces and without use of any existing network infrastructure or centralized administration. Due to the limited transmission range of wireless radio transceivers, there may be a need for one or multiple nodes (intermediate nodes) working as relays to establish a communication path between source-destination pairs in a mobile ad-hoc network.

This thesis presents a model that estimates the time duration of routes formed by several intermediate nodes in mobile ad-hoc networks. First, a 3-node route is analyzed, where only the intermediate node is in movement while source and destination nodes remain static. From this case, it is shown how route duration is affected by the initial position of the intermediate node and the size of the overlapping region where it is located. The overlapping region associated to an intermediate node is formed by the intersection of the coverage zones between their adjacent route neighbors. A second case is also considered where all nodes of the 3-node routes are mobile. Based on extensive analysis of these routes, the PDF of route duration is determined under two different mobility models. This PDF can be determined by either analytical or statistical methods. Finally, this thesis shows that the time duration of a route formed by N intermediate nodes can be accurately computed by considering the minimum route duration of a set of N routes of 3 nodes each. Simulation work was conducted using the

NS-2 network simulator to verify the accuracy of the proposed model and to compare it with other proposals found in the literature. Simulation results show that the model is in better agreement as compared with other models. Results from this work can be used to compute overhead signaling during route-maintenance of unicast and multicast routing protocols for mobile ad-hoc networks.

This thesis also sets forth a model to compute an upper bound on route length in mobile ad-hoc networks. In MANETs, routes are usually found by means of discovery packets that are injected to the network by sender nodes. At the time of reaching an intended destination, the route followed by a discovery packet is used to send a reply packet back to the sender. Upon reception of the reply message, data transfer from sender to destination can initiate. Node mobility, however, negatively affects route duration time since position changes may lead to disruptions in connectivity. Furthermore, the whole route discovery process collapses when, due to position changes, the route followed by a discovery packet (or a reply packet) may not be valid at any time, while one of these packets is travelling across the route. This thesis examines the conditions leading to this effect and shows that they impose a practical limit on route length. This thesis also introduces a delay model for multi-hop routes which is extended from an access delay model for single-hop WLAN networks found in the literature. Another route duration model that considers forwarding delays involved during the route discovery phase is also derived in this thesis. By combining both models, a closed-form expression to compute maximum route length in MANETs is obtained. This model is validated by simulations with different network settings. From this model, it is found that the node transmission range, node mobility and forwarding delays actually define the maximum feasible number of hops in a route. To the best of the author's knowledge, this is a fundamental scaling problem of mobile ad-hoc networks that has not been analyzed before from a *mobility-delay perspective*.

Chapter 1

Introduction

1.1. Overview

An ad-hoc network is a collection of nodes forming a temporary network by means of wireless interfaces and without use of any existing network infrastructure or centralized administration. Different types of ad-hoc networks are becoming increasingly popular: Vehicular Ad-hoc Networks (VANETs), Wireless Sensor Networks (WSNs) and Mobile Ad-hoc Networks (MANETs).

A Mobile Ad-hoc Network (MANET) consists of a collection of mobile nodes connected by wireless links. In MANETs, nodes are free to move and organize without involving any infrastructure or centralized administration. As laptops and IEEE 802.11/Wi-Fi wireless networks became widespread in the late 1990s, MANETs also became a popular subject for research. Degree of mobility is an important factor and a key research issue in MANETs and VANETs. Although most sensor applications currently have zero or low mobility, in the future these applications can also be foreseen to involve some degree of mobility [1].

Due to the limited transmission range of wireless radio transceivers, there may be a need for one or multiple nodes (intermediate forwarding nodes) working as relays (multi-hop routing) to establish a communication path between source-destination pairs in an ad-hoc network. The number of intermediate nodes will depend on the distance between source and destination nodes, transmission range and node density. Usually, the presence of one or more intermediate nodes is necessary to allow the exchange of data between source and destination nodes across an ad-hoc network. Traffic relaying in mobile ad-hoc networks, however, is a difficult task. Node mobility, signal interference and power outages produce frequent changes in network conditions. As a result, any link along a route may fail at some point, forcing the nodes to find another route. It is clear that route duration strongly depends on the node mobility pattern, and that it would be convenient to compute this duration in advance. Node mobility causes frequent and unpredictable topology changes in the network. Routes, therefore, have a limited lifetime. In Fig. 1, we show an arbitrary route from a source node *S* to a destination node *D* involving several forwarding nodes. In this figure, each circle of radius *R* represents the transmission range of each node.

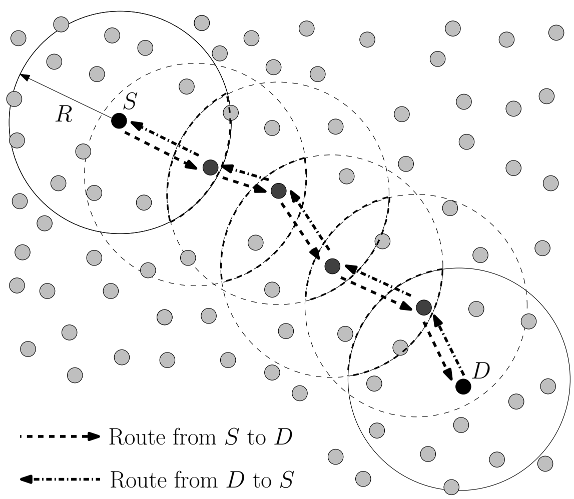

Figure 1-1: Multi-hop routing in MANETs.

1.2. Node Mobility Issues

The term *Node Mobility* in wireless networks refers to the network nodes' ability to move or change their relative position in the network area. Mobility can depend on different locomotion media, such as pedestrian or vehicular movement. In general terms, node mobility may be constrained and limited by the physical laws of acceleration, velocity and rate of change of direction.

Additionally, node mobility can be differentiated according to the nodes' spatial and temporal dependencies as well as their geographic restrictions. Spatial dependency is a measure of how two nodes are dependent on their motion. If two nodes are moving in the same direction then they have high spatial dependency. Temporal dependency is a measure of how current velocity (magnitude and direction) are related to previous velocity. Nodes having the same velocity have high temporal dependency. Geographic restrictions of movement express how bounded or freely the mobile nodes can move, i.e., with or without physical restrictions.

Numerous issues should be considered when deploying MANETs. We will now present a brief description of some limitations and challenges imposed by node mobility. Some of the main issues to be addressed are as follows:

1. Dynamic topology: Due to node mobility, the topology in ad-hoc networks may change constantly. As nodes move in and out of range of their neighboring nodes, some links will fail while new links between nodes are created. This issue is obviously greatly affected by node mobility. Node mobility causes position changes over time and these changes mainly determine route duration time. A route that is valid now, may not be valid at a later time. Degree of mobility directly affects the performance of routing protocols because they are expected to react more frequently at a higher nodal speed.

2. Environment unpredictability: Ad-hoc networks may be deployed in unknown terrains, hazardous conditions, and even hostile environments in which the nodes may be imminently endangered. Depending on the environment, node failures may occur frequently. Node mobility induces a dynamic environment. Obviously, when a node changes position, the environment around it might change as well, thus leading to dangerous or unexpected conditions.

3. Unreliability of wireless medium: Communication through the wireless medium is unreliable and subject to errors. The quality of the wireless links may fluctuate unpredictably over time due to varying environmental conditions such as high levels of electro-magnetic interference (EMI) and the presence of obstacles or inclement weather conditions, among others. Furthermore, in some applications, nodes may be resource-constrained and thus would not be able to support transport protocols necessary to ensure reliable communication on a lossy link. In some cases, node mobility may, directly or indirectly, cause fluctuations in link quality. For instance, node density, electro-magnetic and/or traffic conditions can differ significantly from one place to another within the network area.

4. Resource-constrained nodes: Nodes in a MANET are typically battery-powered as well as limited in storage and processing capabilities. Moreover, due to node mobility, they may be situated in areas where it is impossible to re-charge and thus have limited lifetime. Because of these limitations, they must have algorithms which are energy-efficient as well as operating with limited processing and memory resources. The available bandwidth of the wireless medium may also be limited because nodes may not be able to sacrifice the energy consumed by operating at full link speed. Although this issue may be less affected by node mobility, there might be some cases where node mobility may reduce energy capabilities. For instance, nodes that are equipped with self-motion devices and one energy-supply only, may

experience a significant lifetime reduction.

As a result of these issues, MANETs are vulnerable to several types of failures, including:

1. Route failures: A route failure occurs when any mobile node abandons the coverage zone of its adjacent nodes.

2. Transmission errors: The unreliability of the wireless medium and the unpredictability of the environment may lead to transmitted packets being garbled and thus received with errors.

3. Node failures: Nodes may fail at any time due to different types of hazardous conditions in the environment. They may also drop out of the network either if they are out of reach or when their energy supply is depleted.

4. Link failures: Node failures as well as changing environmental conditions (e.g., increased levels of EMI) may cause links failures.

1.3. Problem Statement

This thesis examines how node mobility affects route duration and route length in multi-hop MANETs and sets forth two models that can be used to improve the overall performance of mobile ad-hoc networks. One model can be used to determine the average route duration of multi-hop routes and the second to compute the maximum feasible number of hops in a route (maximum route length).

Since the origins of wireless networks, node mobility has been considered one of the most important factors that negatively affects route duration time as position changes may lead to disruptions in connectivity. While the effects of node mobility may not be easily tractable even under simple mobility patterns, an analysis of node mobility from different perspectives would be an important contribution for wireless ad-hoc networks. We are therefore interested in studying the impact of node mobility on the performance of MANETs primarily related to route duration and route length.

Since to a large extent, the degree of mobility determines route duration, it is crucially important to carry out an analytical study of route duration. Such a study can be used to anticipate route disruption and to avoid the degradation of system performance. Knowledge of route duration can be used to select an alternative route before the current one fails and it can also be used to decrease or limit packet losses and latency due to overhead signaling during route reconstruction. Because route duration decreases with route length, a route duration model could be used to scale the maximum network size up or down so as to meet minimum route duration requirements to ensure a satisfactory communication path between any pair of nodes.

Routing protocols for ad-hoc networks can be classified into different categories according to the methods used during route discovery and route maintenance. In *proactive* routing, routes from one node to all the other nodes in the network are discovered and maintained even when not needed. For *reactive* routing, nodes discover a route only when needed, usually by flooding the entire network with control packets. Although reactive protocols usually exhibit higher latency compared to proactive protocols, because the former usually generate less signaling, they are preferably used in many practical scenarios. This thesis applies directly to reactive unicast routing protocols, e.g., Dynamic Source Routing (DSR) [2] and Ad-hoc On Demand Distance Vector (AODV) [3].

In MANETs routes are usually found by means of discovery packets that are injected to the network by sender nodes. At the time of reaching an intended destination, the route followed by a discovery packet is used to send a reply packet back to the sender. Upon reception of the reply message, data transfer from sender to destination can initiate. Node mobility, however, negatively affects route duration time since position changes may lead to disruptions in connectivity. Furthermore, the whole route discovery process collapses when, due to position changes, the route followed by a discovery packet (or a reply packet) may not be valid at any time, while one of these packets is travelling across the route. In this thesis, we will examine the conditions leading to this effect. Based on this analysis, we proceeded to develop a model to compute an upper bound on route length in MANETs. This model could also be used to estimate the maximum network size.

1.4. Thesis Outline

In order to solve the problem stated above, we intend to make use of a combination of analytical and statistical modeling. We are also interested in the use of network simulations in order to validate the route duration and route length models in MANETs. We selected the *network simulator NS-2* [4] because it is a relatively simple and widely available open-source software that is commonly used to evaluate MANET performance. The outline of our study is as follows:

In Chapter 2, we set out to study the route duration of a 3-node route for a case in which only the intermediate node moves. This analysis explores some factors that affect route duration. This chapter also describes the procedure to obtain a route duration model, for routes with 3 mobile nodes, using two mobility patterns, i.e., Random WayPoint (RWP) and Random Walk (RW). Finally, the model is generalized in order to consider routes with N intermediate mobile nodes. We conducted a combination of theoretical and statistical analyses in order to formulate the proposed model. A series of simulations were conducted in order to compare and validate the route duration model versus simulation results.

In Chapter 3, we show that node transmission range, node mobility and forwarding delays actually define the maximum route length, measured by the number of intermediate nodes or hops, and therefore also define the maximum size of the network. Chapter 3 sets forth a procedure to compute the round trip time in multi-hop ad-hoc networks and it also presents another route duration model that considers forwarding delays involved during the route discovery phase. Additionally, this chapter presents the results obtained by simulation in order to validate the proposed model.

1.5. Thesis Contribution

The contribution this thesis makes can be summarized as follows:

This thesis presents a study that predicts route duration time in mobile ad-hoc networks. The study presented here can be used with different mobility models. Previous researchers have analyzed this issue, but their results have limited applicability. The approach hereby presented has a higher applicability than other models as it is not tied to any specific scenario or mobility pattern.

This thesis also sets forth a delay model for multi-hop routes which is extended from an access delay model for single-hop WLAN networks found in the literature. We also derive a route duration model that considers forwarding delays involved during the route discovery phase. By combining both models, we obtain a closed-form expression to compute maximum route length in mobile ad-hoc networks and therefore estimate the maximum network size. This expression considers node transmission range, node mobility and forwarding delays in the network. To the best of our knowledge, this is a fundamental scaling aspect of mobile ad-hoc networks that has not been analyzed before from a *mobility-delay perspective*.

Chapter 2

Route Duration Modeling for Mobile Ad-Hoc Networks

2.1. Introduction

An ad-hoc network is a collection of nodes forming a temporary network by means of wireless interfaces and without use of any existing network infrastructure or centralized administration. Different types of ad-hoc networks are becoming increasingly popular: Vehicular Ad-hoc Networks (VANETs), Wireless Sensor Networks (WSNs) and Mobile Ad-hoc Networks (MANETs). In MANETs, the nodes self-organize and are free to move randomly. The network topology may thus change rapidly and unpredictably. Such a network may operate in a standalone fashion, or may be connected to the Internet. As laptops and IEEE 802.11/Wi-Fi wireless networks became widespread in the late 1990s, MANETs also became a popular subject for research. Degree of mobility is an important factor and a key research issue in MANETs and VANETs. Although most sensor applications currently have zero or low mobility, in the future these applications can also be foreseen to involve some degree of mobility [1].

Due to the limited transmission range of wireless radio transceivers, there may be a need for one or multiple nodes (intermediate forwarding nodes) working as relays (multi-hop routing) between source-destination pairs in an ad-hoc network. The number of intermediate nodes will depend on the distance between source and destination nodes, transmission range and node density. Traffic relaying in mobile ad-hoc networks, however, is a difficult task. Node mobility, signal interference and power outages produce frequent changes in network conditions. As a result, any link along a route may fail at some point, forcing the nodes to find another route. It is clear that route duration strongly depends on the node mobility pattern, and that it would be convenient to compute this duration in advance.

Since to a large extent, the degree of mobility determines route duration, it is crucially important to carry out an analytical study of route duration. Such a study can be used to anticipate route disruption and to avoid the degradation of system performance. Knowledge of route duration can be used to select an alternative route before the current one fails and it can also be used to decrease or limit packet losses and latency due to overhead signaling during route reconstruction. Because route duration decreases with route length, a route duration model could be used to scale the maximum network size up or down so as to meet minimum route duration requirements to ensure a satisfactory communication path between any pair of nodes.

The main contribution of this chapter is that it presents an analytical study that predicts the time duration of routes in mobile ad-hoc networks. The study presented in this chapter can be used with different mobility models. Previous researchers have analyzed this issue, but their results have limited applicability. The approach hereby presented has a higher applicability than other models as, it is not tied to any specific scenario or mobility pattern.

The rest of the chapter is as follows: Section 2.2. presents a description of previous work in this area. A study of route duration of a 3-node route is presented in Section 2.3.

for a case in which only the intermediate node moves. This analysis explores some factors that affect the route duration problem. Section 2.4. describes the procedure to obtain a route duration model, for routes with 3 mobile nodes, using two mobility patterns (Random WayPoint and Random Walk). In Section 2.5., the model is generalized in order to consider routes with *N* intermediate mobile nodes. Section 2.6. presents simulations using the *NS-2* network simulator to compare the analytical model versus simulation results. Finally, Section 2.7. presents some conclusions derived from this chapter.

2.2. Related Work

Work related to route duration in MANETs falls into two different categories according to the method followed by the authors, the experimental or analytical category.

Under the experimental category, simulation has been the main method through which route duration properties of mobile ad-hoc networks were analyzed in the past. Simulation-based studies consider several parameters like the mobility model, the traffic pattern, the propagation model, etc. The authors in [5] carried out one of the first studies concerning the analysis of route duration based on empirical results obtained by simulations. These authors examined detailed statistics of route duration considering several mobility models, i.e., Random WayPoint (RWP) studied in [6], Reference Point Group Mobility (RPGM) described in [7], Freeway (FW) and Manhattan (MH) introduced in [8]. In [5] the authors observed that, under certain conditions (i.e., a minimum speed and routes with several hops), the time duration of routes can be approximated by exponential distributions. They evaluated the effect of the number of hops, transmission range and relative speed of each mobility model on route duration. However, the authors did not consider the goodness of fit of any other probabilistic model. Moreover, they did not justify the selection of an exponential distribution with any mathematical validation. To deal with this limitation, the authors in [9] used Palm's theorem to state that, under some circumstances (e.g., infinite node density), the lifetime associated to routes with a large number of hops converges to an exponential distribution. These works provide a solution for the analysis of paths which is valid only for routes with a large number of hops. Their study could thus not be applied to many practical MANET applications where paths consist of few hops only. In spite of these limitations, the popularity of the exponential fitting has been used as a common approximation in some other works such as in [10]. In [10], the authors presented a statistical model for estimating route expiration time adaptively, in order to reduce the control traffic of on-demand routing protocols.

Under the analytical category, there are several studies related to route duration in the literature. Even though the authors of these works followed different approaches to solve the route duration problem, these results are of limited applicability since they did not provide an expression for modeling duration of routes with several intermediate nodes. The authors in [11], for example, presented a simplified model of link duration for a single-hop case. Based on this model, they tried to generalize a model for a multi-hop route, but they did not provide any closed-form solution for it. In [12], the authors presented an analysis of link duration for a two-hop MANET. In this study, the authors considered an exponential distribution of route duration and assumed that the source and destination nodes are static while the intermediate node is moving using the RWP mobility model. However, they did not extend their analysis to routes with several hops. The authors in [13] assumed that link durations are independent and exponentially distributed random variables with a known mean link duration. Based on these assumptions, the authors derived some expressions to estimate route duration for single and multiple routes. However, in most cases, it cannot be assumed that the mean link duration value is a known parameter. In [14], the authors presented a framework for studying route duration in mobile ad-hoc networks based on various mobility models, but they did not present any detailed analytical expressions. The authors in [15] presented some analytic expressions to characterize various statistics, such as: link lifetime, new link inter-arrival time, link breakage inter-arrival time and link change inter-arrival time, by probabilistic and geometrical methods. The authors in [16] presented statistical models to evaluate the lifetime of a wireless link in MANETs when nodes move randomly within constrained areas. Also in [16], it is shown that link lifetime can be computed through a two-state Markov model. In [17], the authors introduced a new metric named *Mean Residual Path Lifetime* which they used as a criterion to select routes with longer route duration times instead of the minimum number of hops, which is a criterion commonly used in MANETs. The mobility model considered in [18] used fluid-flow techniques to analytically model the average sojourn time of an intermediate node while it crosses the region formed by the intersection of the coverage zones between its adjacent nodes (overlapping region). This model was the first one to take into consideration the shape and size of the overlapping region. In [18], the authors assumed that intermediate nodes are found right after entering the overlapping region. But they did not reflect on the possibility that the forwarding node is already located within this region, which is the usual case, so route duration estimated by this model would be very different from the real value. Although this model assumed various intermediate nodes, because it considered all overlapping regions have similar size, the actual sojourn time for each forwarding node in the route would be the same, thus route duration predicted by this model will be the same for routes with one or several intermediate nodes, which is not realistic. In [19], the authors derived the joint probability distribution of route duration using discrete-time analysis for the Random Walk (RW) model. They based their analysis of route duration partitioning the MANET network into a number of hexagonal cells and assuming that mobile nodes roam around in a cell-to-cell basis. In [20], the authors described the probability distribution function of route duration assuming that nodes move according to a constant velocity model and derived the statistics of link and route duration in ad-hoc networks. It is worth mentioning that the analytical works presented in [19] and [20] are the closest studies to ours, in the sense that they tried to approach the problem by analytical means only and they presented comparable performance metrics, such as route length (number of hops), transmission range, etc. In Section 2.6., we will present a comparison between these models and ours.

Although a study of route duration is extremely difficult to carry out even under simple mobility patterns, in this chapter we present a route duration model aimed to remove some of the limitations found in previous works. It is important to point out that there is no general mobility model that foresees all possible dynamic behaviors of mobile nodes. The proposed model predicts the time duration of routes with an arbitrary number of intermediate nodes, the only assumption we make is that the PDF of route duration for a 3-node mobile case can be somehow obtained. This chapter considers two mobility models commonly used in MANETs studies, i.e., RWP and RW.

2.3. Route Analysis of 3-node Routes

Before we approach the route duration problem, it is important to analyze and understand a simple route scenario first, where a 3-node route will be analyzed, considering that only the intermediate forwarding node is moving while source and destination nodes remain static. Developing this analysis will allow us to observe the impact different factors have on route duration in MANETs, including intermediate node's initial position and the size of the overlapping region.

Due to the fact that the actual number of possible shapes for a coverage zone is endless, the most sensible approach to model it is by means of a circular area. In most papers attempting to model route duration by simulation, empirical or analytical means make use of this assumption or they at least use regular areas (e.g., hexagonal). In this work, the transmission range of each node is assumed to be constant, thus leading to circular coverage zones. Let us denote by R the transmission range. Fig. 2–1 shows a multi-hop route from a source node S to a destination node D involving several forwarding nodes. Each circle in Fig. 2–1 represents the constant transmission range for each node in this route.

In any route, intermediate nodes will be found inside the overlapping region formed by the intersection of the coverage zones between their adjacent route neighbors, see Fig. 2–1. As we stated before, the coverage zones are considered to be circular, thus leading to overlapping regions with an *oval-like* shape. Additionally, note that the size of the overlapping region changes for different intermediate nodes. Therefore, the sojourn time of a forwarding node within each region can thus vary significantly. To include these considerations in the analysis, it is necessary to consider all possible initial positions and trajectories of nodes in the route, as well as the different sizes of the overlapping regions. In order to illustrate this, in Fig. 2–1 we show a route from source node *S* to destination node *D* involving several forwarding nodes.

Let us fix the source and destination nodes at points $S(x_S,y_S)$ and $D(x_D,y_D)$, respectively (as shown in Fig. 2–2). As we stated before, the coverage zone of each node has the shape of a circle with radius *R*. As illustrated in Fig. 2–2, factor *h* is an indicator of the size of the overlapping region, where $h = R - d_{S-D}/2$ and $d_{S-D} = \sqrt{(x_S - x_D)^2 + (y_S - y_D)^2}$ is the Euclidean distance between nodes *S* and *D*. This factor plays a crucial role in the operation and performance of routing protocols for wireless ad-hoc networks. As shown in Fig. 2–2, each intermediate forwarding node must be located within the overlapping region. Let points $A(x_A,y_A)$ and $B(x_B,y_B)$ be the intersection points between both circles. It is easy to show that the coordinates of points *A* and *B* can be found by:

$$x_{A/B} = \frac{B' \pm \sqrt{B'^2 - 4A'C'}}{2A'}$$

where x_A and x_B are the abscissas of points *A* and *B*. The coefficients A', B' and C' are given by:

$$A' = 4\left[(x_S - x_D)^2 + (y_S - y_D)^2\right],$$

$$B' = -4\left[(x_S^2 - x_D^2)(x_S - x_D) + (y_S - y_D)^2 (x_S + x_D)\right],$$

$$C' = \left[(x_S^2 - x_D^2)(y_S - y_D)^2\right]^2 + 4\left[(x_S^2 - R^2)(y_S - y_D)^2\right],$$

and

$$y_{A/B} = \frac{2(x_D - x_S)x_{A/B} + (x_S^2 - x_D^2) + (y_S^2 - y_D^2)}{2(y_S - y_D)}$$

where y_A and y_B are the ordinates of points *A* and *B*.

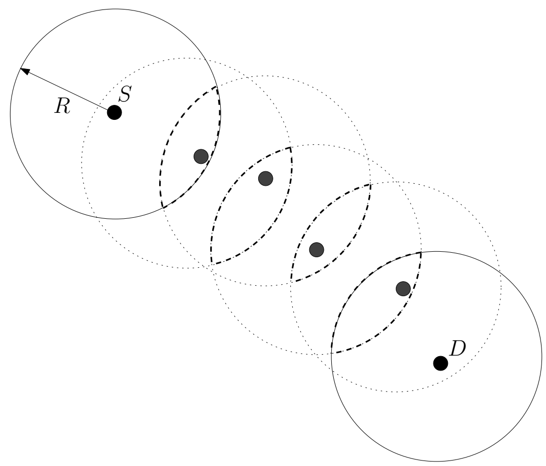

Fig. 2–1: Example of a route involving several intermediate nodes.

As shown in Fig. 2–2, point $I(x_I,y_I)$ is the initial position of the intermediate node and point $O(x_O,y_O)$ is the position where this node leaves the overlapping region. In this section, we are considering that intermediate node is following a rectilinear trajectory sloped α_I degrees, measured with respect to the horizontal axis, and moving at constant speed v_I. The distance travelled by an intermediate node moving from *I* to *O* (d_{I-O}) can be found by geometric analysis as:

$$d_{I-O}(\alpha_I) = \left| -\sqrt{a^2 + b^2}\sin(\alpha_I + \delta) + \sqrt{R^2 - (a^2 + b^2)\cos^2(\alpha_I + \delta)} \right|. \qquad (2.1)$$

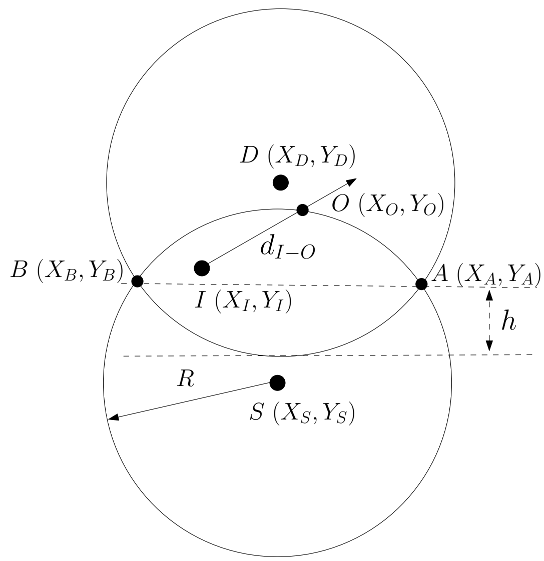

Fig. 2–2: Overlapping region of two adjacent nodes.

Parameters a, b and δ, found in (2.1), must be computed separately to analyze the link between source node - intermediate node and the link between intermediate node - destination node. When the intermediate node crosses over the border of the source node coverage zone, parameters a, b and δ are:

$$a = y_I - y_S \quad , \quad b = x_I - x_S \quad \text{and} \quad \delta = \arctan\left(\frac{b}{a}\right)$$

otherwise

$$a = y_I - y_D \quad , \quad b = x_I - x_D \quad \text{and} \quad \delta = \arctan\left(\frac{b}{a}\right).$$

Then, the average distance travelled by an intermediate node before leaving the overlapping region ($\bar{d}_{I-O}$), given its initial position $I(x_I,y_I)$, can be found using the Mean Value Theorem [21], this is:

$$\bar{d}_{I-O} = \frac{1}{\Delta\alpha_I}\int_{\alpha_m}^{\alpha_M} d_{I-O}(\alpha_I)\, d\alpha_I \ . \qquad (2.2)$$

where:

$$\Delta\alpha_I = \left|\alpha_M - \alpha_m\right| ,$$

$$\alpha_M = \arctan\left(\frac{y_B - y_I}{x_B - x_I}\right),$$

$$\alpha_m = \arctan\left(\frac{y_A - y_I}{x_A - x_I}\right)$$

and

$$\alpha_M = \arctan\left(\frac{y_A - y_I}{x_A - x_I}\right),$$

$$\alpha_m = \arctan\left(\frac{y_B - y_I}{x_B - x_I}\right).$$

Therefore, the average distance travelled by an intermediate node before leaving the overlapping region would be:

$$\bar{d}_{I-O} = \frac{1}{\Delta\alpha_I}\left[\sqrt{a^2+b^2}\cos(\alpha_I+\delta)\Big|_{\alpha_I=\alpha_m}^{\alpha_I=\alpha_M} + \int_{\alpha_m}^{\alpha_M}\sqrt{R^2-\left(a^2+b^2\right)\cos^2(\alpha_I+\delta)}\,d\alpha_I\right]. \quad (2.3)$$

In this analysis, we consider the angle α_I as an independent random variable uniformly distributed over the interval ($\Delta\alpha_I$) given by the difference between its maximum and minimum values (α_M and α_m, respectively). As well as the parameters *a*, *b* and δ, the angles α_m and α_M, must be computed separately for the link between source node - intermediate node and for the link between intermediate node - destination node.

Figures 2–3a and 2–3b show the angles involved in the links between source node - intermediate node and intermediate node - destination node, respectively. Fig. 2–3c shows some trajectories followed by an intermediate node from its initial to final positions. Each line in Fig. 2–3c represents a different trajectory.

Because it does not seem possible to integrate (2.3) algebraically, we use an approximation by replacing the square root in the integrand with a binomial series [21] and, after some algebra; it can be simplified as shown:

$$\sqrt{R^2-\left(a^2+b^2\right)\cos^2(\alpha_I+\delta)} \approx R\left(1-\sum_{j=1}^{\infty} k_j\left(u(\alpha_I)\right)^j\right) \qquad (2.4)$$

where:

$$u(\alpha_I)=\cos^2(\alpha_I+\delta) \qquad (2.5)$$

and

$$k_j = \frac{1}{(j)!}\left(\frac{a^2+b^2}{R^2}\right)^j\left[\prod_{l=1}^{j}\left(\frac{3}{2}-l\right)\right], \qquad (2.6)$$

then:

$$R\int_{\alpha_m}^{\alpha_M}\left(1-\sum_{j=1}^{\infty} k_j\left(u(\alpha_I)\right)^j\right)d\alpha_I = R\left(\alpha_I\Big|_{\alpha_I=\alpha_m}^{\alpha_I=\alpha_M} - \sum_{j=1}^{\infty} k_j\int_{\alpha_m}^{\alpha_M}\cos^{2j}(\alpha_I+\delta)d\alpha_I\right). \qquad (2.7)$$

The range of convergence for the binomial series used in the previous approximation is given by $\left(a^2+b^2\right)< R^2$. It is worth mentioning that the accuracy of the approximation is degraded as $\left(a^2+b^2\right)\to R^2$, which corresponds to the case when the nodes are located very close to the boundary of the overlapping region. In this case the approximation has to be used with care.

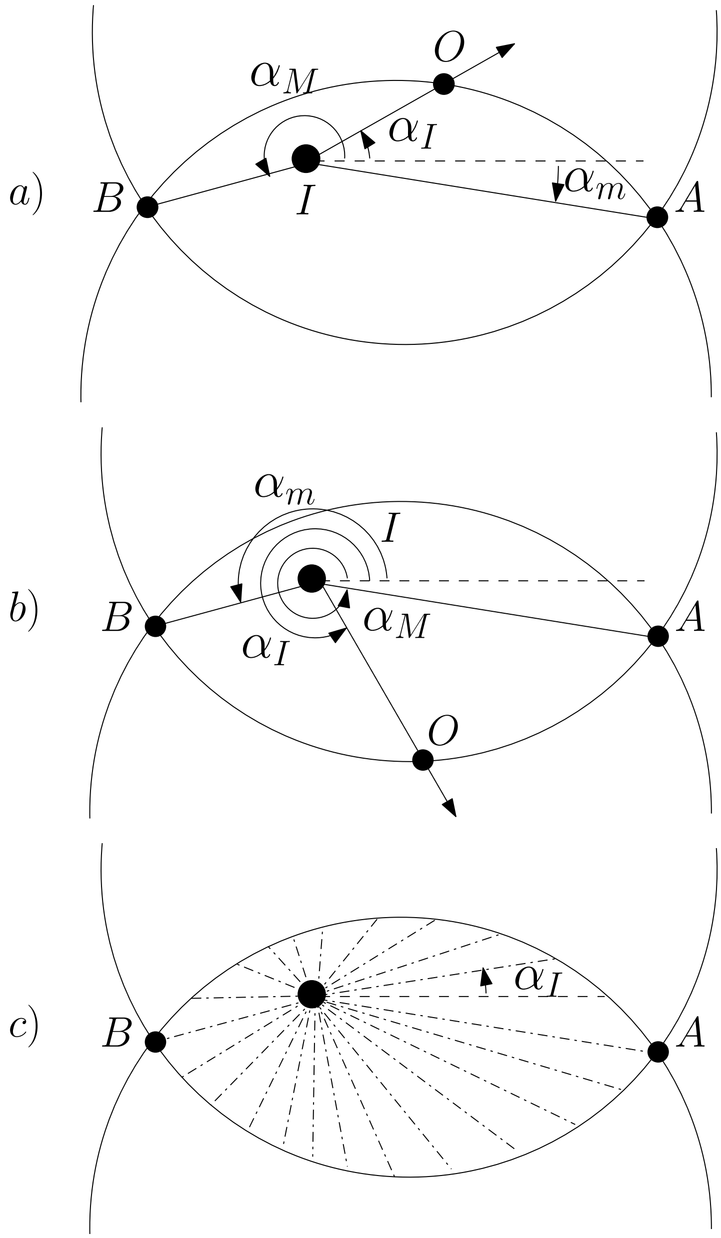

Fig. 2–3: (a) Angles involved while modeling link duration of source - intermediate node. (b) Angles involved while modeling link duration of intermediate node - destination. (c) Some trajectories followed by an intermediate node from its initial to final positions.

After replacing the integral found in (2.3) by (2.7), an approximation of the average distance will be:

$$\bar{d}_{I-O} \approx \frac{1}{\Delta\alpha_I}\left[\sqrt{a^2+b^2}\cos(\alpha_I+\delta)\Big|_{\alpha_I=\alpha_m}^{\alpha_I=\alpha_M} + R\left(\alpha_I\Big|_{\alpha_I=\alpha_m}^{\alpha_I=\alpha_M} - \sum_{j=1}^{\infty} k_j \int_{\alpha_m}^{\alpha_M} \cos^{2j}(\alpha_I+\delta)\, d\alpha_I\right)\right]. \quad (2.8)$$

The average sojourn time for a forwarding node within the overlapping region ($\bar{T}_I$) is directly proportional to the average distance travelled by the intermediate node ($\bar{d}_{I-O}$), and inversely proportional to its speed of movement (v_I). Therefore:

$$\bar{T}_I = \frac{\bar{d}_{I-O}}{v_I}. \quad (2.9)$$

This sojourn time defines the route duration for the 3-node route.

In (2.8) we can remove dependence on the initial position $I(x_I,y_I)$ by averaging the distance over all possible initial positions within the overlapping region, i.e.,

$$\bar{D}_{I-O} = \int_{y_m}^{y_M}\int_{x_m}^{x_M} f_{x_I y_I}(x_I, y_I)\,\bar{d}_{I-O}(x_I, y_I)\,dx_I dy_I\ . \qquad (2.10)$$

where $f_{x_I y_I}(x_I, y_I)$ represents the joint probability density function for the random variables x_I and y_I. This PDF depends on the spatial layout of intermediate nodes.

In order to illustrate the impact of the intermediate node's position on 3-node route duration, we conducted a series of calculations, using previous equations to evaluate the average distance ($\bar{d}_{I-O}$) and its standard deviation (σ_{I-O}) for a set of 1,000 intermediate forwarding nodes randomly placed in different positions inside the overlapping region. For each forwarding node, the average distance is obtained by using (2.8) and the standard deviation is evaluated using 3,600 values of the travelled distance obtained by (2.1). Each node was considered to move along 3,600 rectilinear trajectories, with a 0.1º difference. Figures 2–4a and 2–4b show the average distance ($\bar{d}_{I-O}$) and its standard deviation (σ_{I-O}), respectively. The *oval-like* shape on the XY plane of Figures 2–4a and 2–4b represents the overlapping region. In these figures, it is clear that the values of average distance and standard deviation depend on the position where the forwarding node is initially located. The closer the intermediate node is found to the border of the overlapping region, the lower the average distance (i.e., shorter route duration), and the higher its standard deviation. This behavior can be explained because, whenever the forwarding node is close to the boundary of the region, it will experience either very short times (i.e., when it leaves the overlapping region right away) or long times (i.e., when it crosses a large section of the overlapping region before leaving it).

We conducted similar tests considering four regular shapes of the overlapping region (i.e, oval, square, circular and rectangular) with equal areas. We found the same trends as the ones depicted in Figures 2–4a and 2–4b. However, independently of the shape, the bigger the overlapping region the longer the average sojourn time of the intermediate node in the overlapping region.

From the 3-node static case, we can conclude that the initial positions of source, intermediate and destination nodes impact route duration in MANETs. Also, the size of the overlapping region is a crucial factor that affects route duration. This justifies that route duration analysis should include node position and overlapping region size.

2.4. Route Duration Model

In this section, we define *Route Duration Time*, T_{RD}, as the instant in which a established route fails. Note that this concept assumes that the route discovery phase occurred at a previous moment (*Route Discovery Time*). In Chapter 3, we set forth another route duration model that considers forwarding delay involved during the route discovery phase. A multi-hop route would be valid as long as each node remains within the coverage zone of its adjacent nodes.

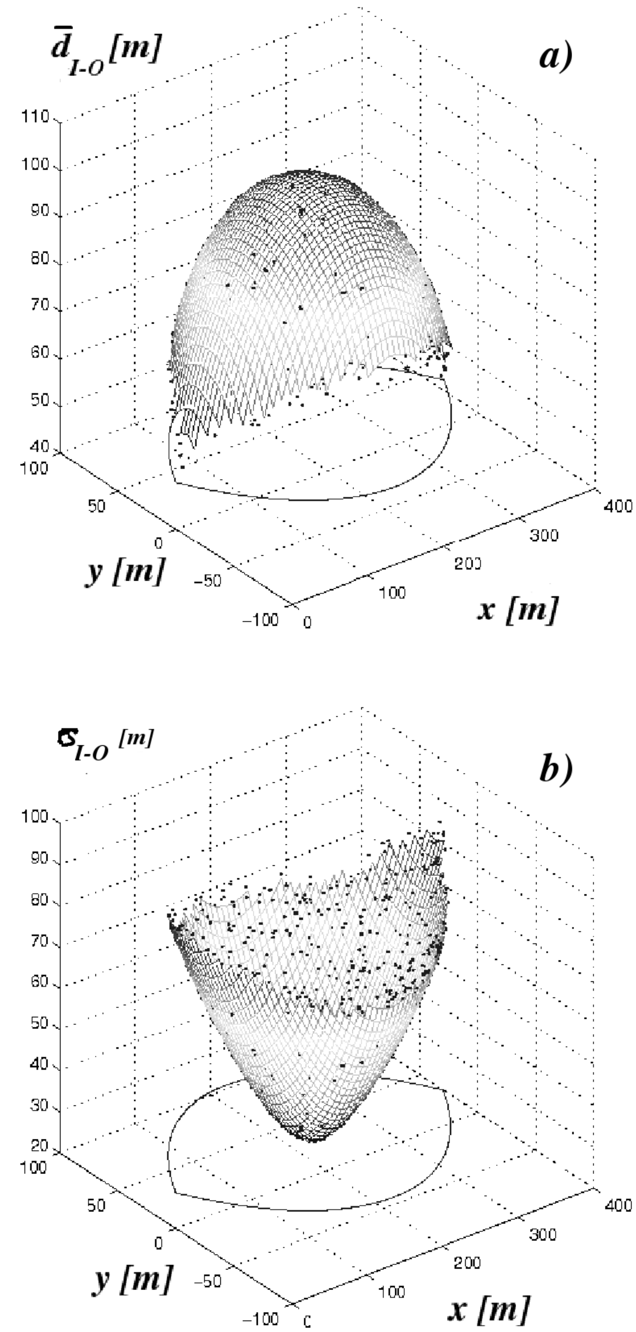

Fig. 2–4: (a) Average distance distribution as a function of the initial position of the intermediate node. (b) Standard deviation distribution as a function of the initial position of the intermediate node.

As described above, each intermediate node must be found inside the respective overlapping region, formed by the intersection of the coverage zones between their adjacent route neighbors in order to work as a relaying node, see Fig. 2–1. In this thesis, we consider that the coverage zone is circular and all nodes use the same transmission range (R = 250 [m]). In this thesis, we have considered the transmission range defined by the IEEE 802.11a standards, i.e., R = 250 [m] (outdoors), but any other transmission range might also be considered. More details about the IEEE 802.11a standards are given in appendix A-2. Note that the size of each overlapping region changes for different intermediate nodes, thus the sojourn time of each intermediate node within this region can vary significantly.

To include all these considerations in the analysis, it would be necessary to consider the mobility model that describes the movement behavior followed by mobile nodes in the network. It would also be necessary to take into consideration all possible initial positions and node trajectories. It is clear that to note this would imply an extremely complex analysis because the size and location of the overlapping region are constantly changing as time passes in a MANET.

In this chapter, we follow a method in which we first compute the PDF of route duration for routes formed by 3 mobile nodes only (*triplets*). Section 2.5. shows a general method to obtain the average route duration of routes formed by N intermediate mobile nodes.

2.4.1 PDF for Routes with 3 Mobile Nodes

We here analyze 3-node routes with all mobile nodes. Based on this specific scenario, we analyze how the relative movement of nodes affects route duration. We then determine the Probability Density Function (PDF) that describes the probability that a 3-node route could last a time longer than a given value. Based on this PDF, it is possible to find the average route duration for routes formed by several intermediate nodes, as will be shown in Section 2.5. This PDF can be determined by analytical or statistical methods depending on the mobility model followed by mobile nodes in the network.

In this section, we model how long it takes for the intermediate node to exit the overlapping region. But, in this case, we consider all nodes to be moving according to a random-based mobility model. In this kind of model, mobile nodes move randomly and freely without any restriction. To be more specific, the speed, destination and/or trajectory are all chosen randomly, independent from other nodes. This kind of model has been used in many simulation studies. In this section, we consider two random-based mobility patterns, i.e., the Random WayPoint and Random Walk models. However, other mobility patterns can also be considered, as long as the associated route duration PDF is provided.

2.4.1.1 Random WayPoint

Due to its simplicity and wide availability in network simulators, the Random WayPoint Model (RWP) is one of the mobility models most commonly used to evaluate MANET performance. For instance, in the network simulator *NS-2* [4], the *setdest* tool may be used to generate RWP traces. There are two versions of this tool. In version 1, various parameters are established, i.e., the number of mobile nodes, pause time, maximum speed, simulation time and size of the simulation field. In version 2, other parameters are added or changed, i.e., speed type, minimum and maximum speeds and pause type.

The implementation of this mobility model is as follows: as the simulation starts, all nodes are randomly placed within the network area. Then, each mobile node randomly selects one location in the simulation field as the first destination point. It then travels towards this destination point with a constant velocity chosen uniformly and randomly from [0, V_{max}] or [V_{min}, V_{max}] (depending on the *setdest* version), where the parameters V_{min} and V_{max} are the minimum and maximum allowable velocities for every mobile node, and $V_{min} < V_{max}$. The velocity and direction of each node are chosen independently from other nodes. Upon reaching its destination point, each node stops for an interval, defined by the *pause time* parameter T_{pause}. If T_{pause} = 0 [*s*], this leads to continuous mobility. As soon as the pause time expires, each node chooses another destination point and moves towards it with a different speed. The whole process is repeated again until the simulation ends.

In the RWP model V_{min}, V_{max} and T_{pause} are the key parameters that determine the mobility behavior of nodes. Additionally, if V_{max} is small and T_{pause} is long, the topology of ad-hoc networks becomes relatively stable. On the other hand, if the nodes move fast (i.e., V_{max} is large) and T_{pause} is small, the topology is expected to be highly dynamic. Varying these parameters, especially V_{max}, the RWP model can generate various mobility scenarios with different levels of nodal speed. Therefore, it seems necessary to quantify the nodal speed.

Intuitively, one such notion is the average node speed. If we could assume that the pause time T_{pause} = 0 [*s*], considering that nodal speed is uniformly and randomly chosen from [0,V_{max}] or [V_{min}, V_{max}], we can easily find that the average nodal speed is V_{max} / 2 or (V_{min} + V_{max})/2. However, in general, the pause time parameter should not be ignored. In addition, it is the relative speed of two nodes that determines whether the link between them breaks or forms, rather than their individual speeds. Thus, average node speed seems not to be the appropriate metric to represent the notion of nodal speed.

It is important to point out that the scenarios considered in this work can be made more complex in many different ways. In this work, however, we have mainly attempted to study the effect of mobility patterns and spatial layout of nodes on route duration. For this reason, we did not conduct experiments with heterogeneous speeds since we consider that, by itself, this is material of future work. Nevertheless, at this point we would like to mention that other authors have investigated this very same issue in the cases where each node chooses a speed at random between V_{min} and V_{max}. For instance, the authors in [22], calculated $\overline{M}$ as the measure of relative speed averaged over all node pairs and over all time. Using this mobility metric, it is possible to roughly measure the level of nodal speed and differentiate the different mobility scenarios based on the level of mobility. Additionally, the authors of [8] showed that the *Average Relative Speed* increases linearly and monotonically with the maximum allowable speed. Based on these results we speculate that our scenario would be equivalent to one with random speed and an average relative speed whose value equals the constant value we used.

2.4.1.2 Random Walk

The Random Walk Model (RW) has similarities with the RWP model because the node movement has strong randomness in both models. However, in the RW model, nodes change their speed and direction at specific intervals only. In the RW model, each change of trajectory occurs after a fixed time interval t_x or after a fixed traveled distance d_x, at the end of which a new direction and speed are calculated. For every new interval, each node randomly and uniformly chooses its new direction $\theta(t)$ from $(0, 2\pi]$. In a similar way, the new speed $v(t)$ follows a uniform distribution or a Gaussian distribution within $[V_{min}, V_{max}]$. Therefore, during the interval, a node moves with a velocity vector $(v(t) \cos \theta(t), v(t) \sin \theta(t))$. Also, there is a discrete version of the RW mobility model where the trajectory randomly changes among 4 different angles only, $[0, \pi/2, \pi, 3\pi/2]$. This version can be used to emulate a node moving on a reticulated area.

The RW model is a memory-less process, because the information about the previous status is not used for future trajectory decisions. That is to say, the current velocity is independent from the previous velocity and the future velocity is also independent from the current velocity. However, that is not the case of mobile nodes in many real life applications.

2.4.1.2 PDF Generation

As aforementioned, we need to model how long it takes for the intermediate node to exit the overlapping region in a 3-node route. But, in this case, we consider that all nodes in the 3-node route move according to a random-based mobility model (RWP or RW mobility models). Let us identify the source, intermediate and destination nodes with indexes *S*, *I* and *D*, respectively. Let us denote such index with *k*, thus $k = S, I$ or D. Each node's position is described by the coordinates $(x_k(t), y_k(t))$. Let $\vec{v}_k(t)$ be the velocity vector of node *k*, i.e.,

$$\vec{v}_k(t) = \left[v_{x_k}(t)\right]\hat{i} + \left[v_{y_k}(t)\right]\hat{j} \qquad (2.11)$$

where $\hat{i}$ and $\hat{j}$ are the unit vectors.

Each node *k* moves according to a random-based mobility model, then it follows a trajectory sloped at α_k degrees and it moves at a speed v_k for a period of time that depends on the mobility model (for the RWP model, any node keeps moving with the same direction and speed upon reaching its destination; for the RW model, any node keeps moving with the same direction and speed for a constant travelled distance). The behavior of α_k and v_k, as time passes, would be described according to the selected mobility model. Then, the velocity vector for node *k* ($\vec{v}_k(t)$), would be given by:

$$\vec{v}_k(t) = \left[v_k \cos(\alpha_k)\right]\hat{i} + \left[v_k \sin(\alpha_k)\right]\hat{j} \qquad (2.12)$$

where

$$|\vec{v}_k(t)| = v_k \qquad [m/s]$$

Now, let $\vec{r}_k(t)$ be the vector that describes the position of node *k*, that is:

$$\vec{r}_k(t) = \vec{r}_k(0) + \int_0^t \vec{v}_k(t)dt \qquad (2.13)$$

where the initial vector position of node *k*, $\vec{r}_k(0)$, is given by

$$\vec{r}_k(0) = [x_k(0)]\hat{\imath} + [y_k(0)]\hat{\jmath}$$

It is important to point out that in the general case, the slope of trajectory, given by α_k, is not constant with respect to *t*. However, in this analysis we are considering that the probability of having direction changes is negligible (a node moving in the overlapping region will not change its current direction). If direction changes are rare events, α_k can be considered as constant in the analysis of a node roaming in the overlapping region and (2.13) reasonably holds.

Substituting (2.12) in (2.13), we get:

$$\vec{r}_k(t) = [v_k t\cos(\alpha_k) + x_k(0)]\hat{\imath} + [v_k t\sin(\alpha_k) + y_k(0)]\hat{\jmath} \qquad (2.14)$$

which can be represented by

$$\vec{r}_k(t) = [x_k(t)]\hat{\imath} + [y_k(t)]\hat{\jmath} \qquad (2.15)$$

where

$$x_k(t) = v_k t\cos(\alpha_k) + x_k(0)$$

is the abscissa of position of node *k* and

$$y_k(t) = v_k t\sin(\alpha_k) + y_k(0)$$

is the ordinate of position of node *k*.

Now, let $d_{S-I}(t)$ be the distance between the source and intermediate nodes and let $d_{I-D}(t)$ be the distance between the intermediate and destination nodes. Distances $d_{S-I}(t)$ and $d_{I-D}(t)$ can be found by the Euclidean distance formula, so:

$$d_{S-I}(t) = \left|\vec{r}_I(t) - \vec{r}_S(t)\right| \qquad (2.16)$$

and

$$d_{I-D}(t) = \left|\vec{r}_D(t) - \vec{r}_I(t)\right| . \qquad (2.17)$$

When either distance $d_{S-I}(t)$ or $d_{I-D}(t)$ exceeds the transmission range (*R*), the communication between the respective adjacent node pair [*S*,*I*] or [*I*,*D*] is interrupted. Route disruption happens when either:

$$d_{S-I}(t) \geq R \qquad (2.18)$$

or

$$d_{I-D}(t) \geq R . \qquad (2.19)$$

Let $T_{[S,I]}$ and $T_{[I,D]}$ be the rupture time of communication between adjacent node pairs [*S*,*I*] and [*I*,*D*], respectively. Then, route duration time (T_I), for a 3-node route, will be found by:

$$T_I = \min\left(T_{[S,I]}, T_{[I,D]}\right) \qquad (2.20)$$

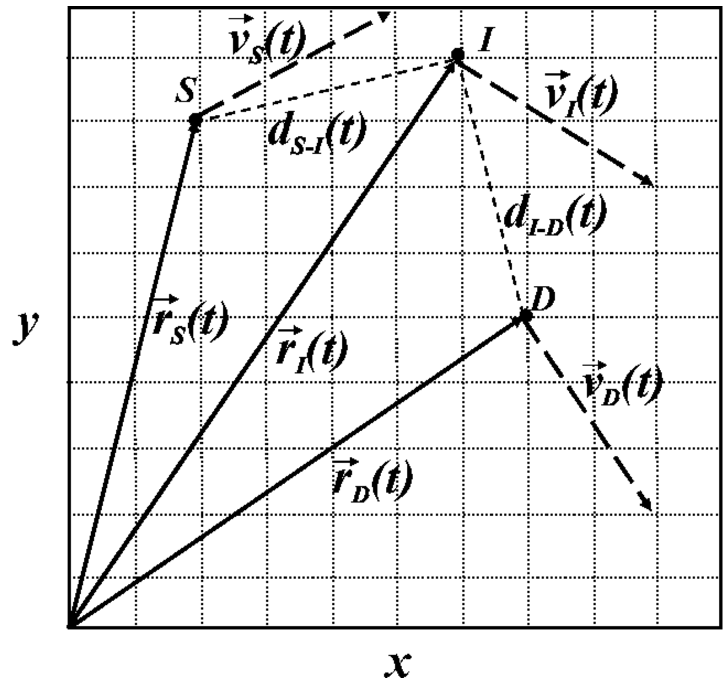

Fig. 2–5: Position and velocity vectors for source, intermediate and destination nodes.

Fig. 2–5 illustrates the position and velocity vectors of a route with 3 mobile nodes (source *S*, intermediate *I* and destination *D*). This figure shows the position of the corresponding nodes (*S*, *I* and *D*) at instant *t* when each node moves in the direction described by its velocity vector.

In order to get an average value of route duration for any route, it would be necessary to consider all possible trajectories and initial positions for the three nodes involved in the route. It is clear to note that this case is far more complex to analyze than the 3-node static case because the size and location of the overlapping region are constantly changing as time passes and, consequently, the factor *h* varies in the same way.

Route duration is given by the minimum time that each forwarding node remains inside of its associated overlapping region (using (2.20)). In order to obtain a mathematical model to calculate the average duration of a given route formed by 3 nodes, we constructed different histograms using the data provided by (2.20). Each histogram represents the relative frequency of time durations of a set of routes for a specific initial h value which corresponds to a particular overlapping region. Additionally, each histogram considers all possible initial positions of the intermediate node and all the possible initial trajectories followed by the three nodes, according to the selected random-based mobility model.

In this study, we analyze the cases for three initial h values corresponding to different overlapping regions. These values are $h = \{R/10, 0.28R, R/2\}$ [m]. An overlapping region with an initial $h = R/10$ takes into account an overlapping region with a small size. On the other hand, an overlapping region with $h = R/2$ represents the maximum size of the overlapping region. Finally, h = $0.28R$ [m] corresponds to a typical overlapping region. The later value was obtained by means of an exhaustive analysis of 10,000 routes formed by 3 nodes (*triplets*). These routes were selected from all possible *triplets* found from a set of nodes randomly placed into several network scenarios with different size and node densities. The *triplets* were discovered using the Dijkstra's Shortest Path Algorithm [23]. The shortest route between any pair of the nodes will be formed by the set of intermediate nodes with the minimum number of links (hops). The routes discovered by this procedure are independent from any routing protocol or simulation software. In fact, it is expected that an efficient routing protocol will find such routes.

In order to obtain these histograms, we developed a statistical analysis, following this procedure: 1) At time zero, we selected source and destination nodes so the size of the overlapping region (described by the factor h) was constant. 2) A node was randomly placed as forwarding node between source and destination. 3) We assigned random trajectories (described by a random-based mobility model) for the three nodes involved and let the nodes move at a constant speed $v_k = 1$ [m/s]. 4) We used (2.20) to calculate the instant when the distance between either source-forwarding nodes or forwarding-destination nodes exceeded the transmission range R. 5) we repeated the same procedure 10,000 times for multiple positions and trajectories of the three nodes. This number of experiments was necessary in order to obtain an experimental PDF function whose statistical properties did not change significantly with more experiments. We found that performing more experiments did not significantly change the results.

In Figures 2–6a-c, we show the histograms for the three different values of h for the RWP mobility model. Each histogram graphically summarizes and displays the relative distribution of the data set provided by (2.20). The vertical axis of each histogram represents the relative frequency (the number of data that corresponds to a specific route duration time interval divided by the total number of data). The horizontal axis of each histogram corresponds to the route duration time, divided into intervals of 1 second each. As shown in Figures 2–6a-c, there is a relationship between the size of the overlapping region and the relative frequency of route duration times. Longer route duration happens more frequently when the overlapping region is larger. In a similar way, in Figure 2–7, we show the histogram for a typical h value ($h = 0.28R$ [m]) but for the RW mobility model.

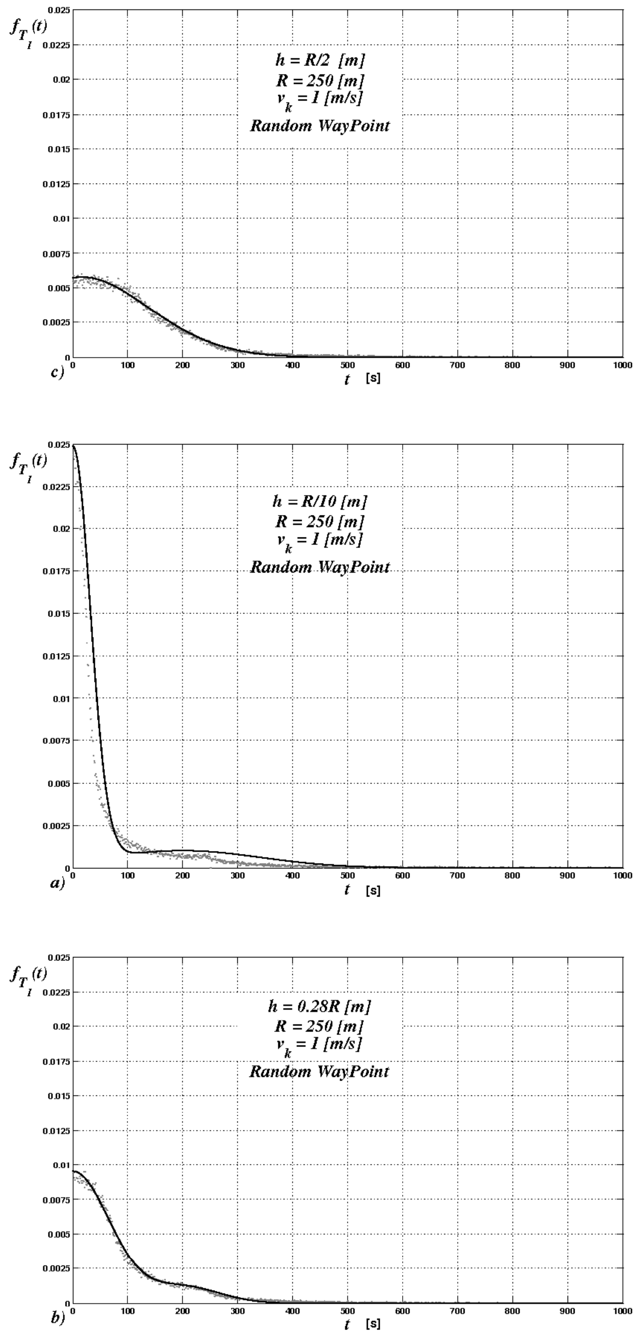

Figure 2-6: Results with the Random WayPoint mobility model a) PDF for h = R/10 [m]. b) PDF for h= 0.28R [m]. c) PDF for h = R/2 [m].

These histograms can be converted to Probability Density Functions (PDFs). We use a curve fitting method to find the mathematical expression that represents these PDFs. For the RWP mobility model, we selected two truncated Gaussian distributions. On the other hand, for the RW mobility model, we use two exponential distributions. These distributions were used as it was experimentally found that they accurately represent the histograms (see solid curves in Figures 2–6a-c and Fig. 2–7). Based on these distributions, the PDFs could be expressed as:

$$f_{T_I}(t)=\begin{cases}\alpha_1 e^{-\left(\frac{t-\beta_1}{\delta_1}\right)^2}+\alpha_2 e^{-\left(\frac{t-\beta_2}{\delta_2}\right)^2} & ; \quad t>0\\ 0 & ; \quad t\le 0\end{cases} \qquad (2.21)$$

or

$$f_{T_I}(t)=\begin{cases}\alpha_1 e^{-(\beta_1 t)}+\alpha_2 e^{-(\beta_2 t)} & ; \quad t>0\\ 0 & ; \quad t\le 0\end{cases} \qquad (2.22)$$

The first curve fitting corresponds to the RWP mobility model. where, parameters α_i, β_i, and δ_i, for i = 1,2, were found by using the Robust Non-Linear Least Squares Fitting Method applying the Trust-Region Algorithm. A parameter of goodness of fit for this curve fitting method is: *R-Square* ≈ 0.99. Table 1 shows the values of the statistical parameters α_i, β_i, and δ_i obtained for three initial values of $h = \{R/10, 0.28R, R/2\}$ [*m*]. The second curve fitting corresponds to the RW mobility model. where, parameters α_i, and β_i for i =1,2 were found by using the same method. Table 2 shows the values of the statistical parameters α_i, and β_i obtained for an initial value of $h = 0.28R$ [*m*]. Given a different initial h value, it is possible to find its parameters.

From this section, we can conclude that the 3-node mobile case allows us to observe how the relative movement between source, intermediate and destination nodes affects route duration in MANETs.

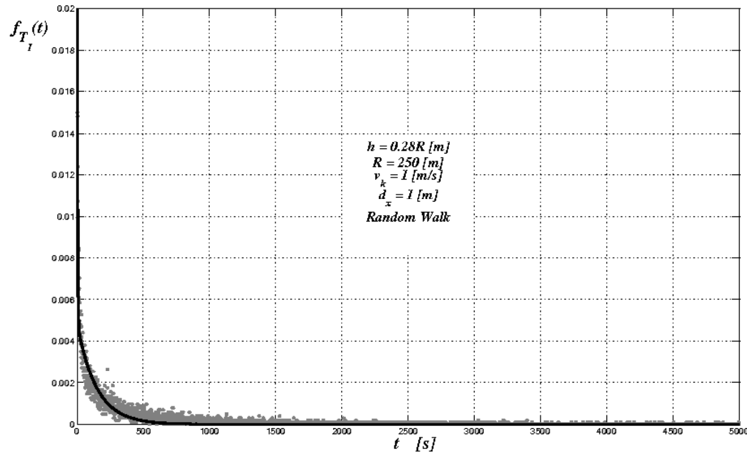

Figure 2-7: Probability Density Function for *h* = 0.28*R* [*m*] using RW.

It is important to point out that this model considers all possible initial positions of the forwarding node and all possible initial trajectories followed by the source, intermediate and destination node, for a specific *h* value when the route was discovered.

Table 2.1: Statistical Parameters for PDFs for RWP model shown in Figures 2–6a-c.

PDFs Statistical Parameters						
h [*m*]	α_1	β_1	δ_1	α_2	β_2	δ_2
R/10	0.0050	0.0000	155.00	0.0013	125.00	160.00
0.28*R*	0.0095	0.0000	95.000	0.0012	200.00	95.00
R/2	0.0245	0.0000	45.000	0.0010	200.00	200.00

Table 2.2: Statistical Parameters for PDFs for RW model shown in Figure 2–7.

PDFs Statistical Parameters				
h [*m*]	α_1	β_1	α_2	β_2
0.28*R*	0.00515	0.05867	0.00068	0.00096

2.5. Route Analysis of *K*-node Routes

The previous section showed how the relative movement between source, intermediate and destination nodes affects route duration in MANETs. Finally, in this section, we will analyze a general case considering a route formed by *K* nodes, $K \geq 3$.

For convenience, we will not use the notation of nodes that we used previously. Each node will be identified by an integer number *k*, ($k = 0,1,2, \ldots , K-1$, where the source node is $k = 0$ and the destination node is $k = K-1$). Thus, the route will have $N = K-2$ intermediate nodes. Therefore, we could use (2.20) to calculate the time interval during which each forwarding node remains inside its associated overlapping region, but replacing the indexes *S*, *I* and *D* for the corresponding *k* values of each node of the *N* *triplets* and by computing route duration as the minimum value of the *N* time intervals. This case, however, would be even more complex to analyze than a 3-node case because the overlapping region associated to each intermediate node has a different size and position that are changing as time passes.

In order to simplify the analysis of routes involving *N* intermediate nodes, we present a method to estimate the average route duration for a route formed by *K* nodes by taking *N* samples of a single PDF, defined by (2.21) or (2.22) and using the typical overlapping region size only ($h = 0.28R$ [*m*]). By using this method, we are assuming that the times that the intermediate nodes remain in their overlapping regions are mutually independent. Therefore, it is valid to divide the route into *N* simpler 3-node-mobile routes or *triplets*.

The PDF samples generate *N* random variables, given by $[T_1', T_2', \ \ldots \ , T_n', \ \ldots \ , T_N']$. Then, we compute the duration of a route involving *K* nodes, T_{R_k}', as:

$$T_{R_k}' = \min[T_1', T_2', \ \ldots \ , T_n', \ \ldots \ , T_N']$$

where:

T_n' : are independent and identically distributed random variables, each one representing the time that the intermediate node remains in its corresponding overlapping region.
n : identification number of each intermediate node, $n = 1,2, \ldots , N$; $N = K - 2$.
N : maximum number of intermediate nodes in the route.

We developed an exhaustive study for different routes with N intermediate nodes using (2.23) and we estimated the average route duration on each case. In the following section, we show the results obtained from this study. We also demonstrate the precision of the proposed method, by comparing it with simulations and other analytical models found in the literature.

We should say that another method to compute route duration would be to select a different PDF associated to the exact h value for each intermediate node in the route and then sample it. However, we found that sampling one PDF only, with a typical h value ($h = 0.28R$ [m]), provides a good precision compared with simulations.

We also performed experiments with a model consisted of 3 PDFs related to the h values $R/10$, $0.28R$ and $R/2$. We found that, using a 3-PDF model, slightly increases the precision of the average route duration computation. We, therefore, consider that using this method is not justified because it has a higher complexity with a negligible improvement.

2.6. Simulation and Results

Network simulations are used to represent the different operation conditions of wireless networks. The simulations have several key parameters, including mobility models, propagation models and communicating traffic patterns, among others. Before showing the results we obtained from the proposed model, we want to show some tests we developed to verify how the network simulator *NS-2* behaves. First, we started a simulation test, without any modification, to verify that the intermediate nodes, chosen by the routing protocol as forwarding nodes in routes of three nodes, were randomly distributed within the overlapping region. In these simulations we used Ad-hoc On Demand Distance Vector (AODV) as the routing protocol. Figure 2–8a graphically shows the random location of forwarding nodes (each intermediate node is represented by a little circle).

We then performed a series of simulation tests to validate the proposed model. Several scenarios were created using the *NS-2* simulator. The simulation settings consisted of a network in a rectangular area with the following dimensions X_{sc} = 2000 [m] and Y_{sc} = 2000 [m] with 400 nodes. In this thesis, we considered the transmission range defined by the IEEE 802.11a standards in *NS-2*, i.e., R = 250 [m] (outdoors). Table 3 summarizes the main parameters of our simulation scenarios.

Table 2.3: Simulation Settings

Simulation Settings	
Parameter	*Value*
Range of Transmission (R [m])	250
Simulation Area Length (X_{sc} [m])	2000
Simulation Area Width (Y_{sc} [m])	2000
Number of Nodes (M)	400
Routing Protocol	AODV
Mobility Models	RWP / RW
Speed (v_k [m/s])	1

6.1 Random WayPoint

We selected a large network size to minimize the probability of having trajectory changes in any intermediate node within the overlapping region while they move according to the RWP mobility model. The probability that an intermediate node changes its trajectory within its associated overlapping region, can be found by: $P_I = A_{or}(h)/A_{sc}$, where: $A_{or}(h) = 2R^2 \arccos((R-h)/R) - 2(R-h)\sqrt{R^2 - (R-h)^2}$ is the area of the overlapping region and $A_{sc} = X_{sc} \cdot Y_{sc}$ is the rectangular area of the scenario. If we consider our network settings, we would have $P_I < 1\%$.

We simulated 3-node static and mobile cases by placing source and destination nodes with a fixed initial position, such that $h = (0.28)R$. As explained before, this value of h represents a typical overlapping region. Finally, we registered how long it took for a set of intermediate nodes, chosen randomly as forwarding nodes, to leave the overlapping region. Fig. 2–8b shows the initial positions and trajectories followed by each intermediate forwarding node before leaving the overlapping region in a 3-node route, when source and destination are static. The initial positions are represented by little circles and trajectories are represented by line segments with variable length. From Fig. 2–8b, it is clear to note that the initial positions and trajectories of the intermediate nodes, as well as the size of the overlapping regions are among the factors affecting route duration.

We developed another set of simulations in order to discover several routes involving K mobile nodes with N intermediate nodes while moving according to the Random WayPoint mobility model. We then let the simulation run until the first intermediate node left the route and we registered the time interval the route was available (i.e., $T_R = T_F - T_D$; where: T_R: route duration time, T_F: route failure time, T_D: route discovery time). We performed 1,000 simulations using these routes to obtain sufficient data to validate the proposed model. We used the results provided by this set of simulations to generate the simulation curve presented in Fig. 2–9.

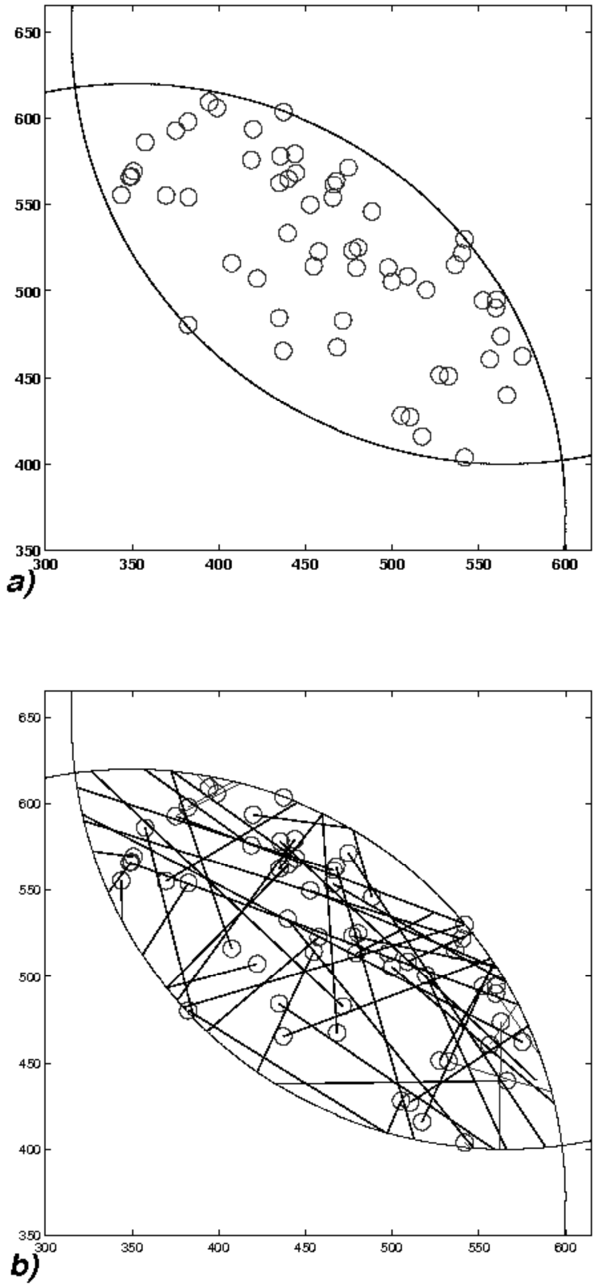

Figure 2-8: a) Spatial layout of initial positions of some intermediate nodes. b) Trajectories followed by each intermediate nodes according to RWP mobility model.

From Fig. 2–9, we can see that relative errors between the proposed model and simulation data were found around 20% for routes with 2 intermediate forwarding nodes, whereas relative errors oscillated between 6% and 3% for routes with 4, 8 and 16 intermediate nodes. We consider that the main reason why relative errors are larger for routes with small *N* is due to the variability of overlapping regions at time zero that we did not consider, since, we only used a typical value of *h* in the model; whereas relative errors for routes with larger values of *N* are smaller because the average *h* value for their overlapping regions is closer to the typical value we used. It is important to point out that the fact of having a maximum margin of error of 20% may be acceptable for many applications due to the complexity of this problem. As we expected, Fig. 2–9 shows that the time duration of routes decreases as the number of intermediate nodes increases. It is important to point out that the precision improves as the number of intermediate nodes increases.

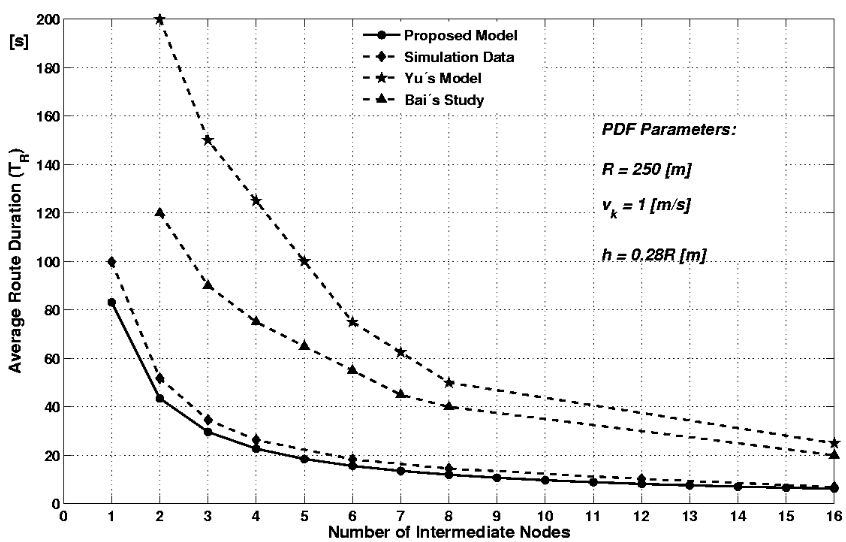

Figure 2-9: Average route duration versus number of intermediate nodes for Random WayPoint mobility model.

In addition, Fig. 2–9 compares the results presented in this study with the analytical model presented by Yu et al. [20]. We selected this study, because we considered that the authors were addressing the same problem and provided a solution through different approaches. They also presented analytical expressions and displayed curves related to route duration, so they can be easily compared with our model. In [20], Yu et al. provided a graph with normalized values of average route duration time versus number of hops in the route. In this study, the authors indicated that normalized values of average route duration time must be multiplied by factor (R/v) to adjust them to any specific scenario. A comparison between this analytical study and our model is presented in Fig. 2–9. Fig. 2–9 clearly shows that the proposed model has a greater accuracy than the one in [20].

Also, in Fig. 2–9 we compare the proposed model with the empirical study presented by Bai et al. in [5]. In [5], the authors introduced an approximate function to estimate route duration (i.e., $T_R \approx R/(\lambda_0 N_h v)$; where: T_R: route duration, R: transmission range, λ_0: experimental parameter (determined by network layout, node density and other parameters related to mobility models or scenarios), N_h: number of hops, v: speed) but they did not justify this function with any mathematical means. A comparison between this experimental study and our model is also shown in Fig. 2–9. It is clear that the proposal has better accuracy than the function presented in [5].

To give more validity to the proposed model and results, we repeated previous simulations but with a higher node density scenario (i.e., 1000 [m] × 1000 [m] network with 300 nodes). It is important to note that we obtained consistent results with this simulation scenario within 5% variations with respect to the results shown in Fig. 2–9.

2.6.1 Random Walk

In a similar way, we also developed a set of simulations in order to discover several routes involving K mobile nodes with N intermediate nodes while moving according to the RW mobility pattern. Also, we let the simulation run until the first intermediate node left the route and we registered the time interval the route was available. We performed the same number of simulations (1,000 simulations) using these routes to obtain sufficient data to validate the proposed model. We used the results provided by this set of simulations to generate the simulation curve presented in Fig. 2–10.

In Fig 2–10, we compare our results with the analytical model for RW mobility pattern presented by Tseng et al. Briefly, in [19], the authors presented a graph with the expected values of route duration versus route length and we used these results to compare them with our model and simulations. A comparison between this analytical study and the proposed model is presented in Fig. 2–10. Clearly, it shows that the proposal outperforms the one provided by [19].

2.6. Conclusions

This chapter has presented a model to estimate route duration in wireless ad-hoc networks when nodes move according to a random-based mobility model. This model analyzes a route formed by N intermediate nodes. The problem was first approached by studying simpler 3-node routes. From the 3-node static case, it has been demonstrated that the initial positions of source, intermediate and destination nodes have a great impact on route duration in MANETs. From the 3-node mobile case, the PDF of route duration of 3-node routes for Random WayPoint and Random Walk models have been obtained. Finally, it has been shown that, regardless of the mobility pattern considered, route duration of routes formed by N intermediate nodes can be computed as the

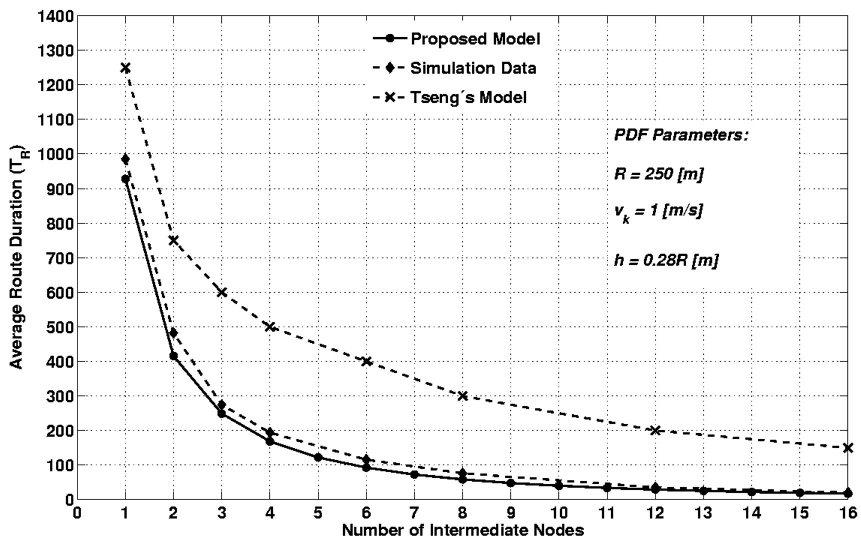

Figure 2-10: Average route duration versus number of intermediate nodes for Random Walk mobility model.

minimum route duration of N 3-node routes. Theoretical analyses and simulations have been developed to validate this study. In general, simulation results were very close to the results obtained by the proposed model with an acceptable margin of error. Results from this work can be used to compute the overhead signaling of unicast and multicast routing protocols for mobile ad-hoc networks since every time a route fails, the routing protocol needs to either repair the route locally or find a new route. It is important to point out that the analysis presented in this chapter is also an integral part of the work included in [24].

Chapter 3

A Mobility-Based Upper Bound on Route Length in MANETs

3.1. Introduction

A Mobile Ad-hoc Network (MANET) consists of a collection of mobile nodes connected by wireless links. In MANETs, nodes are free to move and organize without involving any infrastructure or centralized administration. Due to the limited transmission range of wireless radio transceivers, there may be a need for intermediate nodes, working as relays, to establish a communication path between source-destination airs in the network. In Fig. 3-1 we can observe an arbitrary route from a source node S to a destination node D involving several relaying nodes. In this figure, each circle of radius R represents the transmission range of each node. Node mobility causes frequent and unpredictable topology changes in the network. Routes, therefore, have a limited lifetime.

Routing protocols for ad-hoc networks can be classified into different categories according to the methods used during route discovery and route maintenance. In *proactive* routing, routes from one node to all the other nodes in the network are discovered and maintained even when not needed. For *reactive* routing, nodes discover a route only when needed, usually by flooding the entire network with control packets. Although reactive protocols usually exhibit higher latency compared to proactive protocols, because the former usually generate less signaling, they are preferably used in many practical scenarios. The model we present in this chapter applies directly to reactive unicast routing protocols, e.g., Dynamic Source Routing (DSR) [2] and Ad-hoc On Demand Distance Vector (AODV) [3].

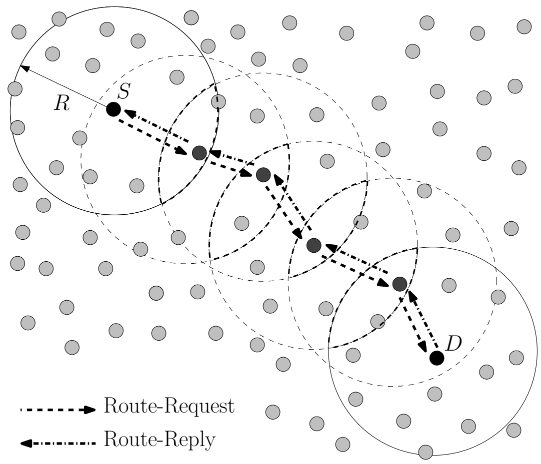

Figure 3-1: Mulit-hop routing in MANETs.

In general terms, reactive routing protocols are constituted by two main mechanisms. Route Discovery is the mechanism by which a source node *S* attempting to send data packets to a destination node *D* discovers a route to node *D*. Route Maintenance is the mechanism by which nodes detect and locally attempt to repair any broken route that had been initially discovered and established by the route discovery mechanism. When local route maintenance is not possible, node *S* should attempt to discover another route to node *D*. Source-destination pairs in MANETs should discover at least one valid route before the first transmission. Such routes must ensure that data transfer can take place, at least for a short period of time, even if both ends are located at the farthest opposite boundaries of the network. Based on this criterion, we can assume the existence of an upper limit on route length.

In order to determine an upper bound on route length in MANETs, from a *mobility-delay perspective*, we need to analyze how the route discovery process works for reactive routing protocols. The route discovery goes through the following phases: When node *S* attempts to send data packets to node *D*, it floods the network with control packets. The flooding begins when node *S* broadcasts a route-request packet. Neighbors of node *S* receiving this packet will relay it once. This procedure continues until the entire network is flooded. The way MANETs work causes that control and data packets may experience queueing delays, channel contention and transmission latencies at each relaying node, especially during the flooding. Let us consider a *per-hop forwarding delay* composed of such delays. In spite of forwarding delays and under some channel conditions (e.g., full network connectivity, absence of hidden stations and transmission errors), at least one route-request packet will reach node *D* at a later time. When node *D* receives the route-request packet, it sends a route-reply packet back to node *S* using the same route; but in the opposite direction. *From the source perspective*, a route from node *S* to node *D* will be established only when node *S* receives the route-reply packet from node *D*. However, due to node mobility, the route from node *D* to node *S* may fail before the route-reply packet reaches node *S*. This is a fundamental issue in the route discovery process for reactive routing protocols. This situation is illustrated in Fig. 3-1, where we can observe that it takes some time for node *S* to find node *D* and also for node *D* to reply back to node *S*. If, by the time the reply travels back to node *S*, one of the intermediate nodes has already moved out of the route, the reply will not reach node *S*. In absence of a response, node *S* will again attempt to discover a route to node *D*. At this point, the operation of the routing protocol can be said to collapse because no valid routes can be found to carry information.

In this chapter we show that node transmission range, node mobility and forwarding delays actually define the maximum route length, measured by the number of intermediate nodes or hops, and therefore also define the maximum size of the network. Previous studies related to scaling properties of ad-hoc networks have mostly analyzed the traffic carrying capacity at the physical and MAC layers. We argue that for the network's traffic carrying capacity to be useful, we should have valid routes for a time interval that allows successful packet delivery between any source-destination pair. We believe this is a fundamental scaling problem in ad-hoc networks that has not been looked at before from a *mobility-delay perspective*.

This chapter makes a twofold contribution. First, we extend an access delay model for single-hop WLAN networks, found in [25], in order to obtain a delay model for multi-hop routes. Second, we derive a route duration model that considers forwarding delays involved during the route discovery phase. To the best of our knowledge, route duration studies available in the literature did not consider the route discovery phase, e.g., [11, 12, 13]. By combining both models, we obtain a closed-form expression to compute the maximum route length in mobile ad-hoc networks and therefore, the maximum network size.

The rest of the chapter is organized as follows: Section 3.2. summarizes some works found in the literature related to scaling properties in ad-hoc networks. Section 3.3. presents the round trip time and route duration models. Section 3.4. presents an analysis to obtain the maximum length of routes in ad-hoc networks given the node transmission range, node mobility and forwarding delays in the network. Section 3.5. presents the results obtained by simulation in order to validate the proposed model. Finally, Section 3.6. presents some conclusions derived from this chapter.

3.2. Related Work

In this section, we present some works that can be found in the literature related to the scaling properties of ad-hoc networks from different perspectives. These works have mostly analyzed the traffic carrying capacity of wireless networks at the physical and MAC layers for unicast or multicast transmissions. In [26] the authors investigated the traffic carrying capacity at the physical layer under different network conditions. In [18] and [27], the authors studied the impact of individual variable-range power control on the physical and network connectivity, network capacity, and power savings of wireless multi-hop networks. In [28], the authors examined the capacity of wireless ad-hoc networks at the MAC layer via simulations and analysis from basic principles. In [29], the authors studied the capacity of large-scale random wireless networks. They also derived matching asymptotic upper bounds and lower bounds on multicast capacity of random wireless networks.

Various authors have studied the performance of routing protocols in ad-hoc networks under different network conditions, such as the number of contending stations, network size and mobility patterns. Most of these works were based on simulations, e.g., [30, 31, 32]. However, they have not considered the existence of an upper bound on route length in mobile ad-hoc networks.

Another issue that has been studied in the literature is the route duration problem of MANETs. Although it can be intuitively inferred that route duration time directly affects route length, to the best of our knowledge, there is no work related to the establishment of maximum route length from a *mobility-delay perspective*. Available studies on route duration in MANETs fall into two different categories depending on whether the authors follow an experimental or analytical method. Under the experimental category, simulation has been the main method through which route duration properties of mobile ad-hoc networks have been analyzed. Simulation-based studies consider several parameters, such as the mobility model, the traffic pattern and the propagation model, among others, e.g., [5, 8]. The authors of these papers observed that under certain conditions (i.e., minimum speed and routes with several hops), the route duration can be approximated by exponential distributions, although they did not provide any mathematical validation to justify the selection of these distributions. They also evaluated the effect of the number of hops, the transmission range and the relative speed of the mobility model on route duration. The authors in [9] used Palm's theorem to state that, under some circumstances (such as infinite node density) the lifetime associated to routes with a large number of hops actually converges to an exponential distribution. Under the analytical category, the literature includes several studies related to route duration. Even though the authors of analytical studies have followed different approaches to solve the route duration problem, the results are of limited applicability since they have only modeled route duration with a limited number of intermediate nodes, e.g., [11, 12]. In other analytical studies, the authors have analyzed the route duration problem by considering one or few mobility patterns, e.g., [14, 16, 19, 20]. In general, both experimental and analytical studies have not considered the existence of an upper bound on route length in MANETs.

3.3. Model Components

In this section we summarize the round trip time and route duration models required for the derivation of an upper bound on route length. First, we extend an access delay model for single-hop WLAN networks introduced in [25] in order to derive a delay model for multi-hop routes. Related details will be given below. Second, we deduce a route duration model in terms of the number of nodes involved in the route, node transmission range and speed of movement. This model also considers route discovery time because it cannot be ignored when obtaining maximum route length. From the combination of these models we obtain an upper bound on route length, discussed below in Section 3.4.

3.3.1 Round Trip Time

We define Round Trip Time, T_{RTT} , as the time required for a packet to travel from a specific source node *S* to a specific destination node *D* and back again, through a multi-hop route. Round trip time depends on many factors including: the data transfer rate of the network links, the number of intermediate nodes between source and destination nodes, the amount of traffic in the network, the MAC protocol. Additionally, round trip time must consider the queueing delay for each relaying node of the route.

We derive the round trip time for a route formed by *N* intermediate nodes from an access delay model for a single-hop route presented in [25] and also from a simplified queueing delay model. Assuming that the route experiences practically the same average per-hop access delay $\overline{T}_{\Delta}$, due to channel contention and transmission delays at each relaying node, and also the same average queueing delay on each hop $\overline{T}_{Q}$ As previously stated, *forwarding delays* correspond to the sum of queueing delays, channel contention and transmission latencies experienced by any packet at each relaying node Then, the average round trip time for multi-hop routes, $\overline{T}_{RTT}$, would be proportional to the number of hops (N + 1), and could be computed by means of:

$$\overline{T}_{RTT} = 2(N+1)\left(\overline{T}_{\Delta} + \overline{T}_{Q}\right). \qquad (3.1)$$

where factor 2(N + 1) corresponds to the number of hops in a route formed by *N* intermediate nodes, counted in both directions. In order to obtain the average per-hop access delay $\overline{T}_{\Delta}$, we use a model found in [25], which will be discussed below.

3.3.1.1 Average Per-Hop Access Delay Model

The authors in [25] introduced a model to compute the average per-hop access delay (average service time), $\overline{T}_\Delta$, due to channel contention and transmission delays. A packet transmitted by a node in a single-hop route, will experience an access delay in the presence of *c* contending nodes in a saturated situation (i.e., all nodes always have at least one packet to transmit). This model relies on the work presented by Bianchi in [33], which provides a model to evaluate the saturation throughput of the IEEE 802.11 MAC protocol under some channel conditions (e.g., full network connectivity, absence of hidden stations and transmission errors). In this chapter we focus on IEEE 802.11 MAC protocol because it has become the *de facto standard* in wireless ad-hoc networks. In case a different radio technology is used, a different access delay model should be considered. The expression to compute the average access delay for single-hop routes, $\overline{T}_\Delta$, is given by [25]:

$$\overline{T}_\Delta = \overline{T}_B + \overline{T}_S, \quad (3.2)$$

where: $\overline{T}_B$ is the average contention time and is given by $\overline{T}_B = \left(\alpha\left(W_{\min}\beta - 1\right)\right)/\left(2q\right) + \left[\left(1-q\right)/q\right]\overline{T}_C$. Parameter $\overline{T}_S$ is the average time that the channel is busy due to a successful transmission given by $\overline{T}_S = T_{DIFS} + 3T_{SIFS} + 4T_\sigma + T_{RTS} + T_{CTS} + T_H + T_P + T_{ACK}$. Parameter $\overline{T}_C$ is the time in which a collision on the channel occurs given by $\overline{T}_S = T_{DIFS} + T_{RTS} + T_\sigma$. The terms T_{DIFS} and T_{SIFS} TSIF*S* correspond to the inter-frame spaces used during transmission. The terms T_{RTS}, T_{CTS}, T_H, T_P and T_{ACK} correspond to the time intervals allocated for the transmission of *RTS*, *CTS*, *H* (headers), *P* (payload or data) and *ACK* packets, respectively. T_σ is the slot-time. Additionally, $\alpha = \left(1-P_T\right)T_\sigma + P_T P_S \overline{T}_S + P_T\left(1-P_S\right)\overline{T}_C$ and $\beta = \left(q - 2^m\left(1-q\right)^{m+1}/1-2\left(1-q\right)\right)/\left(1-2\left(1-q\right)\right)$, where $q = 1-p$ and p is the collision probability. P_T is the probability that there is at least one transmission in the time slot. P_S is the probability associated to a successful transmission on the channel. $W_{\min}$ is the minimum congestion window, m is the maximum back-off stage. Probabilities P_S and P_T, involved in this model can be derived from the collision probability p. For more details, refer to [25] and [33]. The authors in [25] found an approximation for the collision probability p in terms of the minimum congestion window ($W_{\min}$) and the number of contending stations (c), i.e.,

$$p \approx \frac{2W_{\min}(c-1)}{(W_{\min}+1)^2 + 2W_{\min}(c-1)}. \quad (3.3)$$

In many cases, queueing delays contribute significantly to forwarding delays. In the next section, we thus present a simplified model to compute the average queueing delay for a multi-hop route in mobile ad-hoc networks.

3.3.1.2 Queueing Delay

In MANETs each network node can be considered as a network router. When a packet arrives at a node, it has to be processed and, if that is the case, retransmitted to another node. We define *Queueing Delay*, $\overline{T}_Q$, as the time a packet waits in the buffer until it begins contending for the channel. The maximum queueing delay depends on the buffer size. If the expected number of packets in the buffer, defined as $\overline{B}$, is a known parameter, then the average per-hop queueing delay ($\overline{T}_Q$) can be computed by:

$$\overline{T}_Q = \overline{B} \cdot \overline{T}_\Delta + \overline{T}_R, \qquad (3.4)$$

where, $\overline{T}_R$ corresponds to the average residual time for a packet that is currently in service and $\overline{B}$ is the average number of packets in the buffer. Parameter $\overline{T}_\Delta$ is the average per-hop access delay.

The average number of packets in the buffer ($\overline{B}$) could be determined by either analytical or statistical methods. Analytical methods would involve a queueing model for MANETs. This model should describe mathematically the general behavior of queues in MANETs. Although there are several studies related to queueing models in the literature for the Internet, none of them provides a general solution that could be applied to MANETs. Statistical methods would involve extensive network simulations to study the behavior of parameter $\overline{B}$. However, in both methods, the behavior of $\overline{B}$ would strongly depend on many factors including node density, mobility patterns, network dimensions, physical and network connectivity, transmission range, routing protocols, among others.

In particular, a queueing delay model would require a characterization of both the applications using the ad-hoc network and the traffic associated to them. Unfortunately, both applications for ad-hoc networks and the real traffic associated to them are yet to emerge. Due to these conditions, it would be highly complex and unrealistic to set forth a queueing model for MANETs. In this work, let us assume that on average each contending node has $\overline{B}$ packets in its buffer. By replacing (3.4) in (3.1), we obtain that the average round trip time for multi-hop routes is given by:

$$\overline{T}_{RTT} = 2(N+1)\left(\overline{T}_{\Delta} + \overline{B}\cdot\overline{T}_{\Delta} + \overline{T}_{R}\right), \qquad (3.5)$$

where: factor 2(N + 1) corresponds to the number of hops in a route formed by N intermediate nodes, counted in both directions. $\overline{B}$ is the average number of packets in the buffer. Parameter $\overline{T}_{R}$ is the average residual time for a packet that is currently in service and $\overline{T}_{\Delta}$ is the average per-hop access delay.

3.3.2 Route Duration Model

In this section, we define *Route Duration Time*, T_{RD}, as the interval measured from the instant a valid route is discovered to the instant the route fails. This period of time specifies how long a route can be used to transfer data. Now, we define *Route Discovery Time*, T_D, as the interval measured from the instant in which the source node sends the initial route request to the instant in which it receives the route reply from the destination node. Once the source node receives the route reply, a route has been established between the source-destination pair. Additionally, we define *Route Failure Time*, T_F, as the time measured from the instant in which the source node sends the initial route request to the instant in which the established route fails. Note that both concepts share the same time origin (i.e., the instant in which the source node sends the initial route request), see Fig. 3-2. This figure corresponds to a time diagram illustrating the instants in which route discovery and route failure occur. We then formally define route duration as:

$$T_{RD} = \begin{cases} T_F - T_D & ; \quad T_F \geq T_D \quad [s] \\ 0 & ; \quad T_F < T_D \quad [s] \end{cases} \qquad (3.6)$$

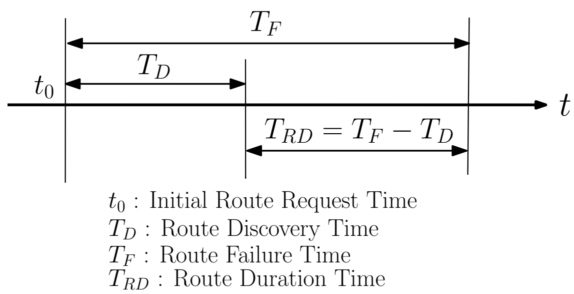

Figure 3-2: Time diagram for route discovery, route failure and route duration times.

In the previous definition, we consider that when any mobile node, which is a member of the route in the process of being discovered, abandons the coverage zone of any of its neighboring nodes before the route is completely established, then there would be no route duration time for this *hypothetical route*. Therefore, route duration time would be valid only for scenarios where the route failure time (T_F) is longer than the route discovery time (T_D). Otherwise, a long route discovery time might considerably reduce the route duration time at a certain point where the route would be useless to transfer data or it would make impossible to discover it.

A typical route is formed by a source node, a variable number of intermediate nodes and a destination node. The number of intermediate nodes depends on many factors, such as the distance between source and destination nodes, node transmission range and node density.

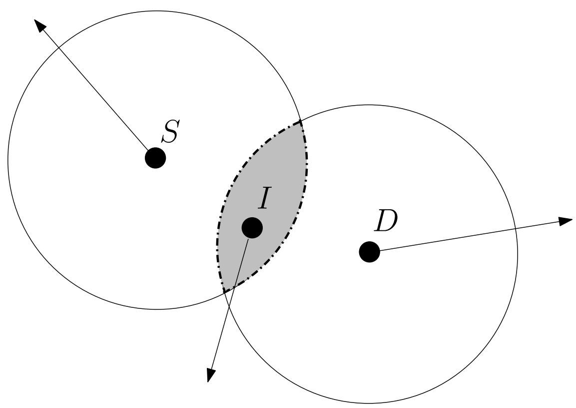

Figure 3-3: Route formed by 3 mobile nodes.

As illustrated in Fig. 3-3, let us consider a route formed by 3 mobile nodes, source node *S*, intermediate node *I* and destination node *D*. In order for node *I* to work as a relaying node, it should be located within the intersection of the coverage zones of nodes *S* and *D* (overlapping region), represented by the shaded area in Fig. 3-3. Note that the size of the overlapping region depends on the distance between nodes *S* and *D*. The time that node *I* remains within this region can vary significantly because of the different sizes of the overlapping regions and it also depends on the positions, trajectories and relative speeds of the 3 nodes involved. The route from node *S* to node *D* will be valid as long as node *I* remains within the overlapping region. In the same way, a route formed by *N* intermediate nodes will be valid as long as all the intermediate nodes remain within their respective overlapping regions, see Fig. 3-1. In a route, formed by one or many intermediate nodes, the first intermediate node that abandons its overlapping region will cause a route failure.

Chapter 2 presented a route duration model for ad-hoc networks in terms of the number of nodes involved in the route, node transmission range and speed of movement. In Chapter 2, we performed an exhaustive data analysis of routes with 3 mobile nodes, as the one shown in Fig. 3-3. Based on this analysis, we concluded that a statistical model for the probability density function (PDF) of the route duration time, $f_T(t)$, can be well represented by:

$$f_T(t) = \begin{cases} \alpha_1 e^{-\left(\frac{t-\beta_1}{\delta_1}\right)^2} + \alpha_2 e^{-\left(\frac{t-\beta_2}{\delta_2}\right)^2} & ; \quad t > 0 \quad [s] \\ 0 & ; \quad t \leq 0 \quad [s] \end{cases} \tag{3.7}$$

where, parameters α_j, β_j, δ_j, for *j* = 1, 2, can be found by fitting the analyzed data to the previous model. The expression shown in (3.7) considered all possible initial positions and trajectories followed by the 3 mobile nodes (*S*, *I* and *D*), which are moving according to the Random WayPoint (RWP) mobility model. Figure 3-4a illustrates the PDF given by (3.7). We then analyzed routes formed by *N* intermediate nodes as a concatenation of *N* 3-node routes (*triplets*). We found that the route duration time for a route formed by *N* intermediate nodes can be obtained by determining the minimum of *N* i.i.d. random variables defined by (3.7). Finally, in Chapter 2, we numerically evaluated the route duration time for thousands of route sets formed by a different number of intermediate nodes on each set and computed their average route duration. More details were given in Chapter 2.

The route duration model that we set forth in this chapter extends the one presented in Chapter 2 in two ways. First, we provide a closed-form expression to compute the average route duration, and second, we take the route discovery time into consideration.

In order to find the upper bound on route length, we need to analyze the case in which the route failure time is about the same order of magnitude as the route discovery time, $T_F \cong T_D$. After a careful inspection of Fig. 3-1, we can observe that it takes some time for node *S* to find node *D*, and also some time for node *D* to reply back to node *S*. It is also discernible that the average route discovery time is proportional to the route length. If we assume that each hop experiences the same average per-hop access delay $\overline{T}_\Delta$ in both ways, the average route discovery time ($\overline{T}_D$), for routes formed by *N* intermediate nodes, can be approximately found by computing the average round trip time, given by (3.5) , i.e.,

$$\overline{T}_D = 2(N+1)(\overline{T}_\Delta + \overline{B} \cdot \overline{T}_\Delta + \overline{T}_R), \qquad (3.8)$$

as above-mentioned, factor 2(*N* + 1) corresponds to the number of hops in a route formed by *N* intermediate nodes, counted in both directions. $\overline{B}$ is the average number of packets in the buffer. Parameter $\overline{T}_R$ is the average residual time for a packet that is currently in service and $\overline{T}_\Delta$ is the average per-hop access delay. The derivation of the route duration model, presented in this chapter, differs from other route duration models found in the literature as it considers hop by hop forwarding delays in the computation. In Fig. 3-4b, we show a route formed by 3 intermediate nodes. It illustrates how route discovery and route duration are affected by forwarding delays. The clocks shown in Fig. 3-4b represent the instant the route request reaches each intermediate node. For instance, by the time the third intermediate node receives the route-request packet, the route duration associated to the first *triplet* has already consumed 2Δ time units. We take this situation into consideration by shifting each PDF in time, as it is also depicted in this figure.

In order to consider these delays in the analysis, we must apply different time shifts to the PDF, given by (3.7). Each time shift corresponds to an individual access delay $\overline{T}_{\Delta}$ experienced by each intermediate node during the route discovery process, see Fig. 3-4b. A time shift represents a time difference on the time of arrival of the route-request packet for each intermediate node. Time shifts applied to (3.7) can be mathematically expressed by:

$$f_{T_n}(t) = f_T(t - t_n) \qquad ; \qquad \text{for } n = 1, 2, \cdots, N, \qquad (3.9)$$

where, $t_n = nT_{\Delta}$ and $\overline{T}_{\Delta}$ is the individual average per-hop access delay that corresponds to a specific intermediate node, denoted by *n*, for *n* = 1, 2, … ,*N*.

The PDF associated to the new route duration model, would then be:

$$f_{T_n}(t) = \begin{cases} \alpha_1 e^{-\left(\frac{(t-t_n)-\beta_1}{\delta_1}\right)^2} + \alpha_2 e^{-\left(\frac{(t-t_n)-\beta_2}{\delta_2}\right)^2} & ; \quad t > t_n \quad [s] \\ 0 & ; \quad t \le t_n \quad [s] \end{cases} \qquad (3.10)$$

where, parameters α_j, β_j, δ_j, for *j* = 1, 2, can be found by the same method, as used before for (3.7). T_n, for *n* = 1, 2, · · · ,*N*, represents the time that a specific intermediate node remains within its overlapping region, $T_n \ge 0 \quad [s]$.

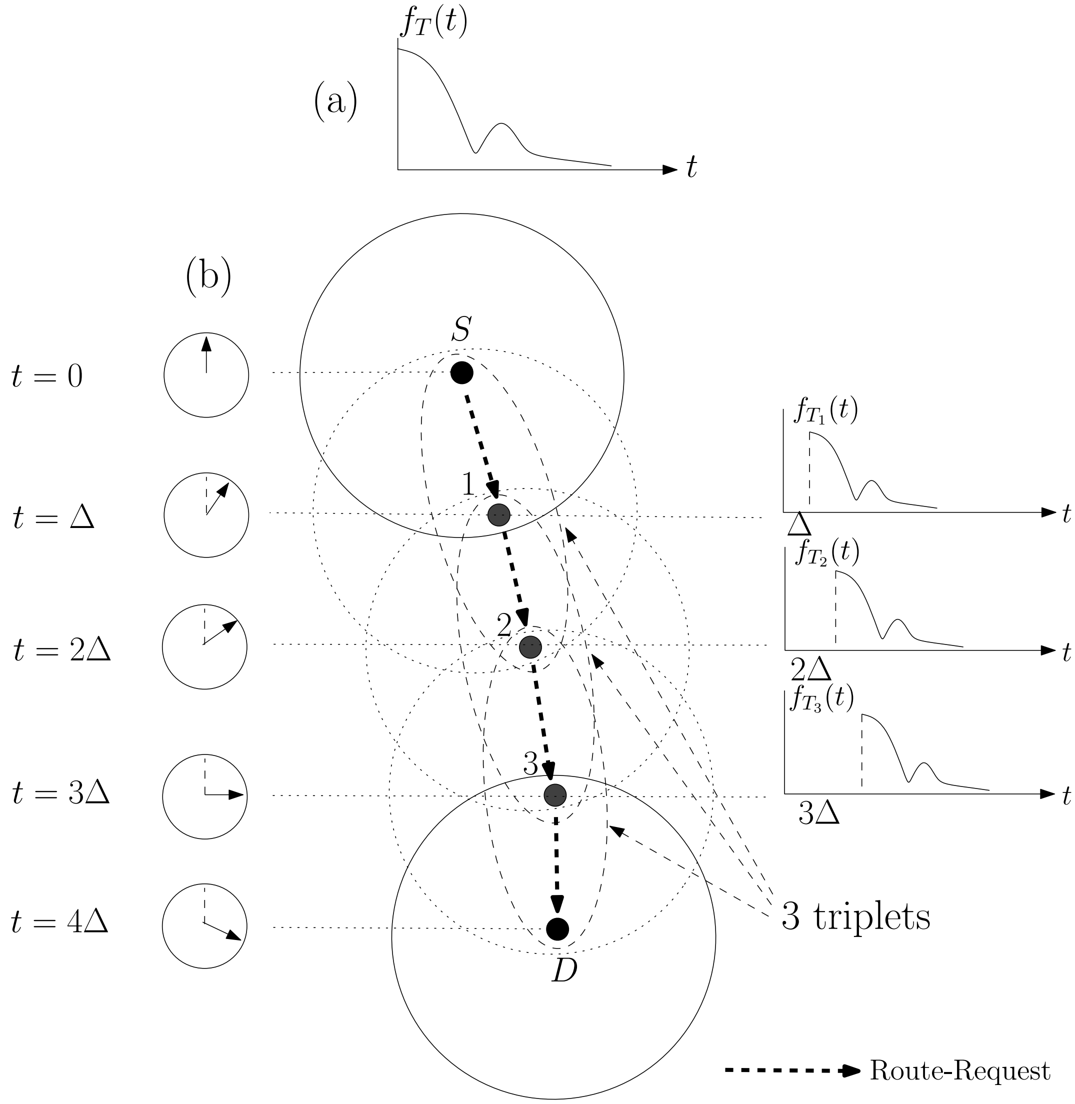

Figure 3-4: (a) The PDF given by (3.7). (b) Impact of forwarding delays on route discovery and on route duration.

Now, we obtain a closed-form expression that allows us to compute the average route failure time (T_F). By definition, the cumulative distribution function (CDF) associated to a PDF represents the probability that an intermediate node remains within its overlapping region a period of time within the interval $T_n \leq t \quad [s]$. Let us denote such CDF by $F_{T_n}(t)$. In consequence, the probability that an intermediate node remains within its overlapping region for a time $T_n > t \quad [s]$ would be given by the complementary cumulative distribution function (CCDF), i.e.,

$$C_{T_n}(t) = P(T_n > t) = 1 - F_{T_n}(t). \qquad (3.11)$$

We assume that the time each intermediate node remains within its respective overlapping region is an independent random variable. If the route is formed by N intermediate nodes, the probability that the route failure time (T_F) be within the interval $T_F \leq t \quad [s]$, would be given by:

$$P(T_F \leq t) = 1 - \prod_{n=1}^{N} P(T_n > t), \quad (3.12)$$

or

$$P(T_F \leq t) = 1 - \prod_{n=1}^{N} C_{T_n}(t) = F_{T_F}(t), \qquad (3.13)$$

where $F_{T_F}(t)$ is the CDF associated to the failure time for a route formed by N intermediate nodes.

Since the route failure time is a positive and continuous random variable, its average value ($\overline{T}_F$) could be found by using [34]:

$$\overline{T}_F = \int_0^{\infty} \left(1 - F_{T_F}(\tau)\right) d\tau . \qquad (3.14)$$

If we replace (3.13) in (3.14), we obtain:

$$\bar{T}_F = \int_0^{\infty} \prod_{n=1}^{N} C_{T_n}(\tau) d\tau \,. \quad (3.15)$$

Apparently, the integral shown in (3.15) can only be solved by numerical methods for different values of *N*. When solving (3.15) numerically, it can be observed that the average route duration time is inversely proportional to the number of intermediate nodes, *N*, and speed of movement, *v*. We performed an extensive analysis of node mobility by considering all possible trajectories followed by the nodes involved in the route. The data obtained by this analysis were then fitted in order to find an experimental model that represents the average failure time, in terms of *N* and *v*. For this purpose, we select an expression with two terms, because we found experimentally that a two-term expression is an accurate representation of the average failure time.

An approximation of the average failure time, $\bar{T}_F$, could thus be expressed as:

$$\bar{T}_F = \frac{\kappa}{Nv} + \gamma(N+1), \quad (3.16)$$

where parameters κ and γ can be found by means of a fitting process.[1]

Finally, if we replace (3.8) and (3.16) in (3.6), we can compute the average route duration time ($\bar{T}_{RD}$) by means of:

$$\bar{T}_{RD} = \begin{cases} \dfrac{\kappa}{Nv} + \left(\gamma - 2\left(\bar{T}_\Delta + \bar{B}\cdot\bar{T}_\Delta + \bar{T}_R\right)\right)(N+1) & ; \quad T_F \geq T_D \quad [s] \\ 0 & ; \quad T_F < T_D \quad [s] \end{cases} \qquad (3.17)$$

[1] Some statistical parameters related to the goodness of fit obtained for (3.17) are: *SSE* ≈ 10^{-4} and *R−square* ≈ 0.99. Similar values were obtained when fitting (3.7). The term *SSE* corresponds to the Sum of Squares due to Error and *R−square* is defined as the ratio of the Sum of Squares of the Regression (*SSR*) and the Total Sum of Squares (*SST*).

3.4. Maximum Route Length

As aforementioned, a route would be useful if, and only if, route failure time is longerthan the time interval required to discover the route. In Section 3.3., we mentioned that route duration decreases with route length and that the round trip time increases with route length. The routes should therefore have a maximum length that meets both time conditions and assures a satisfactory communication path between any pair of nodes of the network. The previous statements can be expressed analytically as:

$$\overline{T}_{RD} \geq \overline{T}_{RTT} . \quad (3.18)$$

If we replace (3.17) and (3.5) in (3.18), we obtain:

$$\frac{\kappa}{Nv} + \left(\gamma - 2\overline{T}_{\Delta}\right)\left(N+1\right) \geq 2\left(N+1\right)\overline{T}_{\Delta} . \quad (3.19)$$

In order to compute the maximum route length from (3.19), we must consider that all nodes involved in the route have empty buffers, i.e., $\overline{B} = 0$ packets, and also they do not have packets in service, therefore $\overline{T}_R = 0 \quad [s]$. It is evident that, when the buffers are not empty, forwarding delays experienced by a packet at each intermediate node will be increased. This issue affects the maximum route length that can be obtained during the route discovery process. In Fig. 3-5 we can observe two sets of four curves each. The first set displays the average route duration time model versus number of intermediate nodes and the second set the average round trip time versus number of intermediate nodes. In these curves, we consider two different values of contending stations per sensing range area, i.e., c = 10, 20 nodes, and two different packet sizes, given by P = 1500 bytes and P = 368 bytes (average IP packet size [35]). In these computations, we consider the node transmission range, i.e., R = 250 [m] (outdoors), and the node sensing range, i.e., R_s = 550 [m], both parameters are defined by the IEEE 802.11a standards. More details about the IEEE 802.11a standards are given in appendix A.-2. The speed of movement used in these computations is v = 1 [m/s].

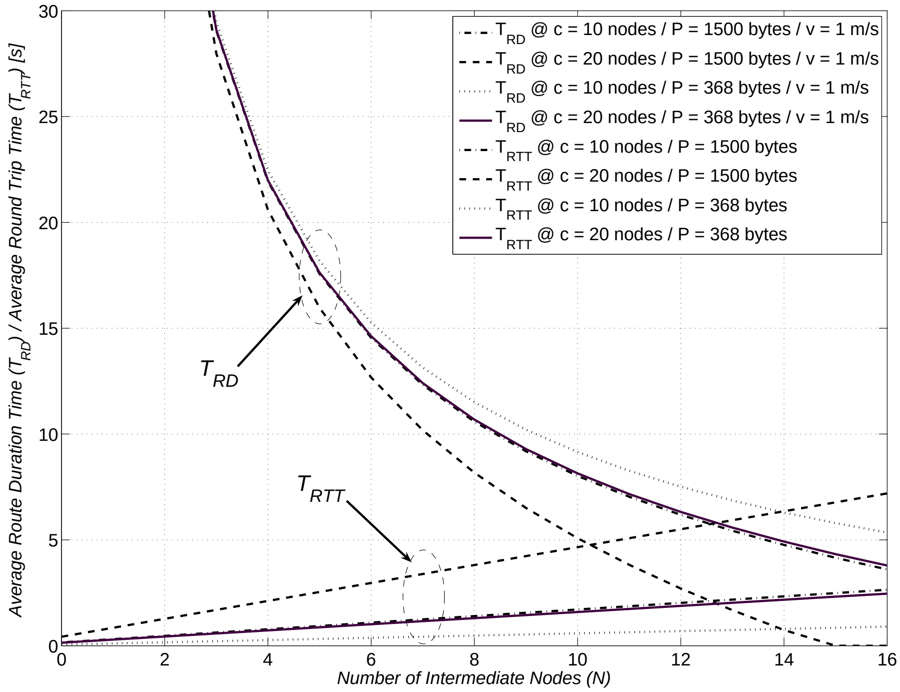

Figure 3-5: Average route duration and average round trip time versus number of intermediate nodes in MANETs.

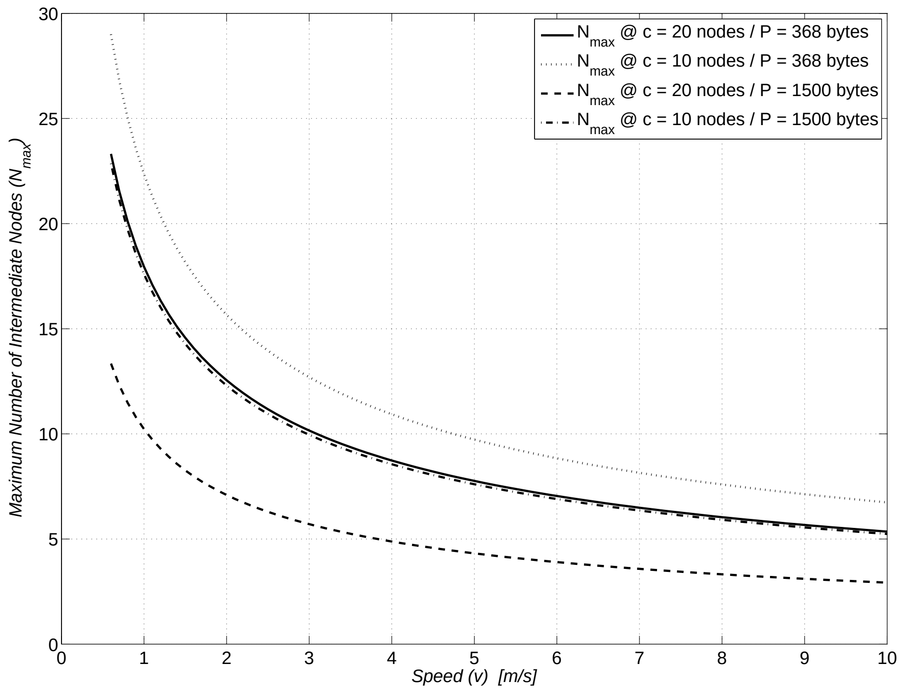

Figure 3-6: Maximum number of intermediate nodes versus speed of movement in MANETs.

From Fig. 3-5, we can infer that there is one intersection point on each pair of curves ($\overline{T}_{RD}$ and $\overline{T}_{RTT}$) with the same network conditions, i.e., contending nodes (c) and packet size (P). The abscissa of the intersection point corresponds to the maximum number of intermediate nodes, N_{max}, given the network conditions. As long as $N \leq N_{max}$, it is guaranteed that useful routes can be discovered. When we equal both sides in (3.19) and solve the resulting equation for N, we obtain the maximum value N_{max}, given by:

$$N_{\max} = \left\lfloor \frac{1}{2}\left[-1 + \sqrt{1 + \frac{4\kappa}{v\left(4\overline{T}_{\Delta} - \gamma\right)}}\right]\right\rfloor, \quad (3.20)$$

where $\lfloor x \rfloor$ is the floor function of a real number x.

In Fig. 3-6 we can observe a set of four curves displaying the maximum number of intermediate nodes, computed from (3.20), versus node speed of movement. Upon comparing these curves, we can infer that the maximum number of intermediate nodes is inversely proportional to the packet size and node speed. As above-mentioned, by limiting the maximum route length to a hop-count under N_{max}, given by (3.20), a communication path would be ensured for any source-destination pair in the network. So, if we assume that the maximum route length corresponds to the maximum diagonal of the network, we can easily compute the equivalent maximum network size. The maximum diagonal of the network, D_{max}, can be found by multiplying the mean distance between two adjacent nodes, $\overline{d}$, by (N_{max} + 1), i.e.,

$$D_{\max} = \left(N_{\max} + 1\right)\overline{d}\,. \quad (3.21)$$

According to (3.20), factor (N_{max} + 1) corresponds to the maximum feasible number of hops in a route (maximum route length).

A simple method to obtain the mean distance between two adjacent nodes $\overline{d}$, used in (3.21), is to analyze a route with one intermediate node only, as the one shown in Fig. 3-3. If the distance between any source-destination pair, given by d_{SD}, is within the interval $R < d_{SD} < 2R$, then one intermediate node I would be needed as a relay. If the distance between nodes *S* and *D* is uniformly distributed in the interval $R < d_{SD} < 2R$, its average value would be given by $\bar{d}_{SD} = (R + 2R)/2 = 1.5R$. Finally, the mean distance between either *S-I* or *I–D* corresponds to $\bar{d} = \bar{d}_{SD}/2 = 0.75R$. Other methods to find $\bar{d}$ would be to compute the average length of a MST (Minimum Spanning Tree) or by extensive network simulations.

3.5. Simulations and Results

This section presents the main results that we obtained through a series of simulation tests. We used the network simulator *NS-2* to conduct these simulations in order to validate the models presented in this chapter. First, we conducted a series of simulations to test the round trip time through multi-hop routes. Next, we performed a second series of simulations to test the route duration model. Finally, we conducted a third series of simulations to examine and test the accuracy of the maximum route length predicted by the proposed model.

3.5.1 Round Trip Time

We conducted some simulations in order to study the round trip time experienced by multi-hop routes. The simulation settings consisted of a square network with the following dimensions X_{sc} = 2000 [*m*] and Y_{sc} = 2000 [*m*], with 400 nodes randomly placed within this area. In these simulations, network nodes had no mobility. We subdivided the network nodes into two sets of nodes. The first group (background traffic group) consisted of nodes generating background traffic. The second group included nodes involved in multi-hop routes. From the first group, we selected a specific number of source-destination pairs, formed by two adjacent nodes needing no intermediate nodes to communicate with each other. On each pair, we defined a connection to transmit packets, each one corresponding to a CBR traffic source with a fixed packet size of 368 bytes (average IP packet size [35]). The number of connections were set in order to assure a uniform distribution of contending stations in the network area, i.e., approximately $c = 20$ nodes per sensing range. In these simulations, we considered the transmission range and the sensing range defined by the IEEE 802.11a standards in *NS-2*, i.e., $R = 250$ [m] and $R_s = 550$ [m], respectively.

We also selected a packet rate high enough to guarantee that all contending nodes in the network always had at least one packet in the buffer. These connections generated background traffic to ensure that simulations are operating under a controlled number of contending stations, as required by the model.

Once we generated the background traffic, we performed the following experiment. From the second group of nodes, we chose another set of source-destination pairs ($S-D$) such that there was a specific number of intermediate nodes (N) in the route. The intermediate nodes also belonged to the second group of the nodes. On each $S-D$ pair, we defined a connection to transmit packets, then we let the simulation run for 200 seconds. We divided the nodes in the network into two groups because it was the only way to guarantee that, on one hand, we could control the number of contending stations per attempted transmission (first group of nodes) and, on the other hand, we could anticipate the number of packets in the buffer for the second set of nodes (in this case, $\overline{B} \approx 0$). The values of c and $\overline{B}$ are both key parameters in order to compare simulation tests with the proposed model. We monitored the round trip time experienced by each packet on each route, by registering the instant in which each packet was generated by node S and the instant in which it was received by node D. In the same way as the background traffic, each connection of the second group of nodes corresponded to a

CBR traffic source with a fixed packet size of 368 bytes. In this case, we selected a packet rate that assured a uniform average buffer occupancy at each intermediate node in the route. This condition can be easily fulfilled by controlling that all intermediate nodes have empty buffers, i.e., $\overline{B} = 0$ packets, over long periods of time. In the case where $\overline{B} \neq 0$ packets, forwarding delays experienced by a packet at each intermediate node will be longer than the scenario presented here. As aforementioned, if the buffers are not empty, it would require a longer time to transmit each packet through the route and the maximum obtainable route length would be affected. We performed 1,000 simulations to obtain enough data over different routes with similar lengths to compute the average round trip time and compare it with the proposal. We used the results provided by these simulations to generate the curve presented in Fig. 3-7. In this figure, we can also compare the simulation results with the proposed model. Simulation results are very close to the results obtained by the model. Additionally, Fig. 3-7 includes 95% confidence intervals for the average round trip time obtained by the simulations.

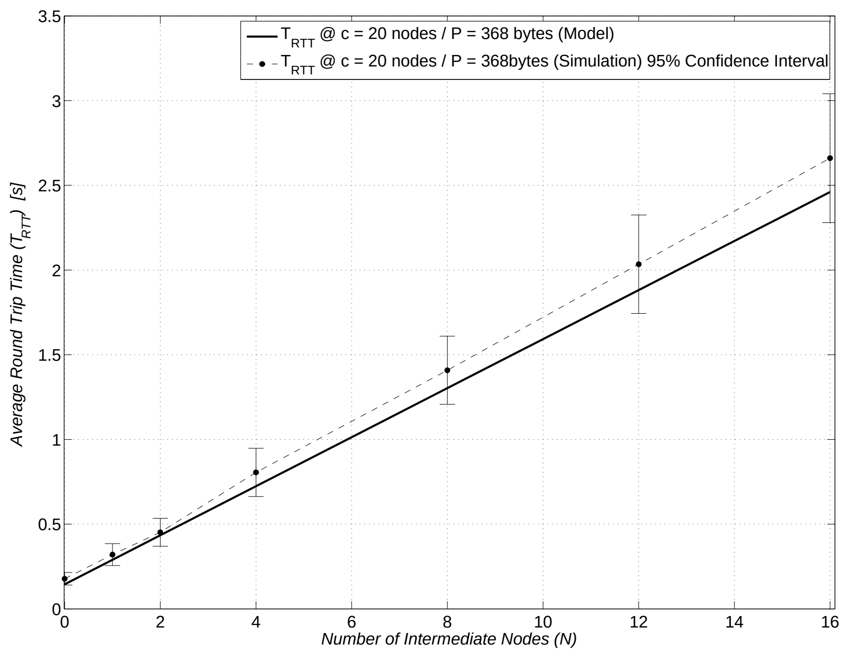

Figure 3-7: Average Round Trip Time for a wireless network with 20 contending stations.

3.5.2 Route Duration

We performed another series of simulations in order to validate the route duration model for routes involving *N* intermediate nodes. As in the previously, the simulation settings consisted of a square network with the following dimensions X_{sc} = 2000 [*m*] and Y_{sc} = 2000 [*m*] and again 400 nodes were randomly placed within this area. In this set of experiments, we also subdivided the network nodes into two sets of nodes. The first set of nodes had no mobility (static-node group). The second set of nodes (mobile-node group) moved according to the RWP mobility model at a constant speed (v = 1 [m/s]). We again considered the transmission range and the sensing range defined by the IEEE 802.11a standards in *NS-2* , i.e., R = 250 [m] and R_s = 550 [m], respectively. Briefly, the implementation of the RWP mobility model is as follows: as the simulation starts, all nodes are randomly placed within the network area. Each mobile node then randomly selects one location within the simulation field as first destination point and travels towards it with a constant velocity v. Upon reaching its destination point, each node stops for an interval. As soon as the pause time expires, each node chooses another destination point and moves towards it at a different speed. The whole process is repeated again until the simulation ends. We selected a large network size to minimize the probability of having trajectory changes of any intermediate node before it leaves its associated overlapping region. The probability that an intermediate node changes its trajectory within its overlapping region can be found by: $P_I = A_{or}(h)/A_{sc}$, where: $A_{or}(h) = 2R^2 \arccos((R-h)/R) - 2(R-h)\sqrt{R^2-(R-h)^2}$ is the area of the overlapping region and $A_{sc} = X_{sc} \cdot Y_{sc}$ is the area of the scenario. If we consider our network settings, we have that $P_I < 1\%$.

From the mobile-node group, we chose a collection of routes involving *N* intermediate nodes. These routes were discovered using the Ad-hoc On Demand Distance Vector (AODV) as the routing protocol. The choice of a specific routing protocol, however, is not relevant to this study. For each route involving *N* intermediate nodes, we let the simulation run until one intermediate node left the route and we registered the time interval during which the route was available. Route duration simulation results were obtained for v = 1 [*m*/*s*], although they can be scaled to a different speed (v') by simply multiplying the values obtained for 1 [*m*/*s*] by factor (v/v'). We used the results provided by these simulations to generate the curves presented in Fig. 3-8. In this figure, we present the average route duration time for a MANET where nodes move at two different speeds, i.e., 1 and 5 [*m*/*s*], and there is no background traffic in the network. In this figure, we can make a comparison between the simulation results and the route duration model. It is important to point out that simulation results are very close to the results obtained by the route duration model with an acceptable margin of error. Additionally, Fig. 3-8 includes 95% confidence intervals for the average route duration time obtained through simulation.

Additionally, we performed more simulations under different traffic conditions. These simulations are intended to study the impact of node mobility and background traffic on route duration separately. In order to generate the background traffic in the network, from the static-node group, we selected another set of source-destination pairs, formed by two neighboring nodes needing no intermediate nodes to communicate with each other. On each pair, we again defined a connection to transmit packets, each one corresponding to a CBR traffic source with a fixed packet size of 368 bytes (average IP packet size). The number of connections were set in order to guarantee a uniform distribution of contending nodes in the network area, i.e., approximately c = 20 nodes per sensing range. As previously stated, we selected a packet rate high enough to assure that all background traffic nodes in the network always had at least one packet in the buffer. We performed 1,000 simulations, with and without the presence of background traffic, then we computed the average route duration time and compared it with our route duration model. This number of experiments offered enough data to obtain a reliable average route duration time. We found that performing more experiments did not significantly change the results. In Fig. 3-9, we show the impact of the presence of

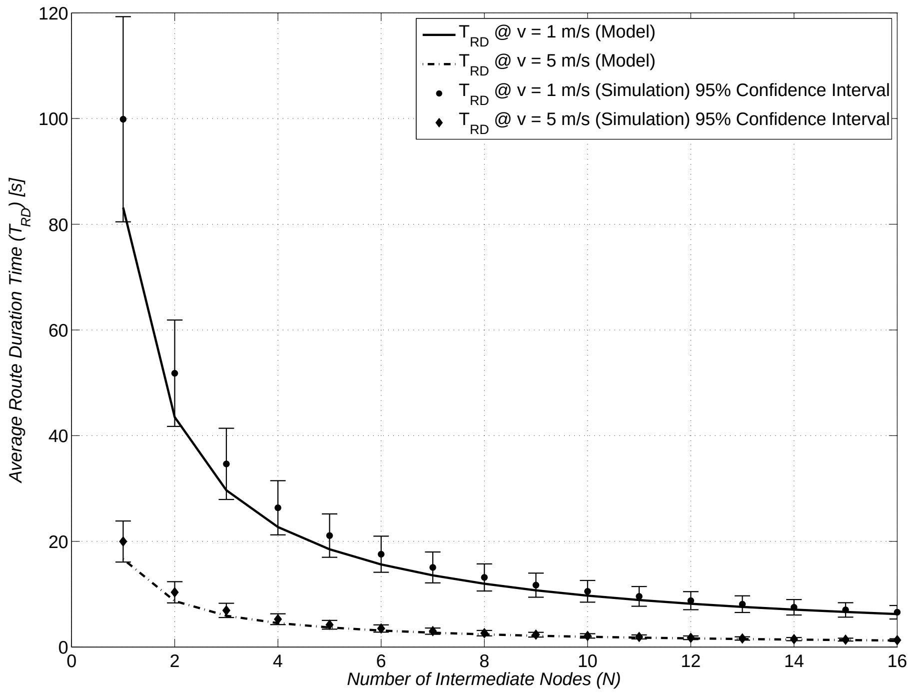

Figure 3-8: Average Route Duration Time for a MANET where nodes move at speeds of 1 and 5 [m/s].

background traffic on route duration. In this figure, we present the average route duration time for a MANET where nodes move at a speed of 1 [*m*/*s*] with and without the presence of background traffic. Additionally, we can also compare the simulation results with the route duration model, given by (3.17). It is evident that they closely match up within a satisfactory margin of error. This figure also includes 95% confidence intervals for the average route duration time obtained by the simulations.

3.5.3 Maximum Route Length

Finally, we conducted another series of simulations in order to validate the maximum route length model using the same network scenarios described previously and, again, we subdivided the network nodes into two sets of nodes. The first set of nodes had no mobility (static-node group) and the second set of nodes moved according to the RWP mobility model (mobile-node group) at constant speeds. Again, from the static-node group, we selected a specific number of source-destination pairs, formed by two adjacent nodes needing no intermediate nodes to communicate with each other. The number of connections were set in order to ensure a uniform distribution of contending nodes in the network area, i.e., approximately $c = 20$ nodes per sensing range. Each connection corresponded to a CBR traffic source with a fixed packet size of 368 bytes. As previously indicated, we selected a packet rate high enough to assure that all background traffic nodes in the network always had at least one packet in the buffer.

Once we generated the background traffic, we performed the following experiment. From the mobile-node group, we chose a series of source-destination pairs ($S{-}D$). Each pair was selected according to a specific route length, defined by the number of intermediate nodes (N) needed to communicate them. We defined a connection on each $S - D$ pair. For each connection, we let the simulation run for 200 seconds. We checked then whether the routing protocol was able to discover and associate a route to connect each source-destination pair. Again, we used AODV as the routing protocol. We also

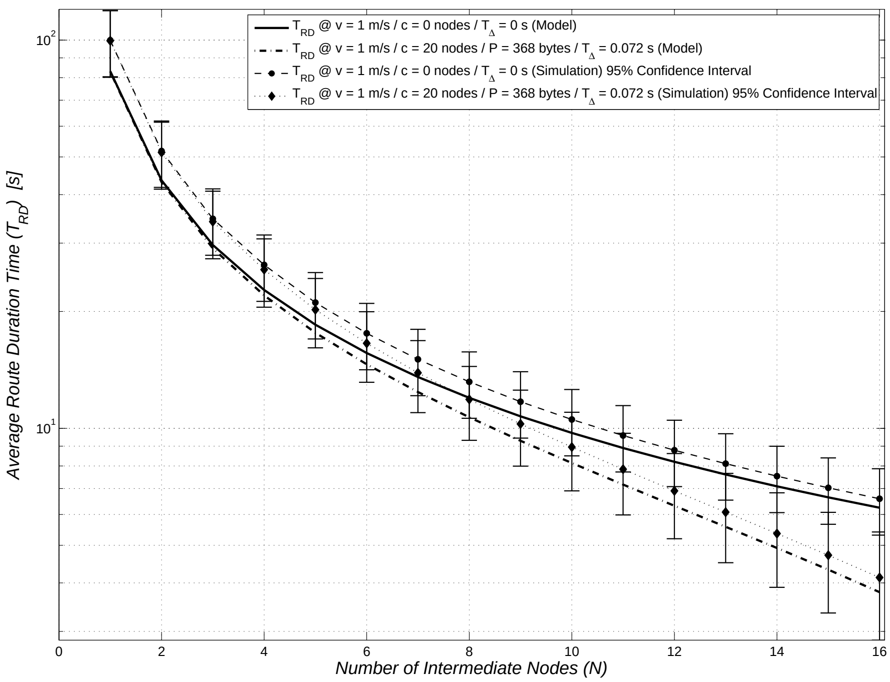

Figure 3-9: Average Route Duration Time for a MANET with and without the presence of background traffic.

monitored the instant in which each route-request packet was sent by node *S*, the instant in which it was received by node *D*, the instant in which each route-reply packet was sent by node *D* and the instant in which it was received by node *S*. We considered that a route from node *S* to node *D* was established if, and only if, node *S* received the route-reply packet from node *D*. We registered the results of these experiments as two possible events: a successful route-discovery if the route was discovered, otherwise, we registered a route-discovery failure. We repeated the previous experiment several times with various $S-D$ pairs in the network with the same route length. As a result, we obtained enough routes to evaluate the success rate of the route-discovery process for different route lengths. The results of these experiments are presented in Fig. 3-10. In this figure, we can make a comparison between the simulation results and the maximum route length, computed by means of (3.20). Figure 3-10 shows a set of two curves displaying the maximum number of intermediate nodes versus the speed of movement. The first curve (solid line) is computed by means of the proposed model. The simulation results correspond to the second curve (dashed line) presented in Fig. 3-10. These results were obtained under the same network conditions, i.e., $c = 20$ contending nodes and a packet size $P = 368$ bytes for different speeds. It is important to note that we obtained consistent results between the proposal and the simulations with 95% confidence intervals. Upon comparing these results, we can observe that the maximum number of intermediate nodes slightly fluctuates around one intermediate node.

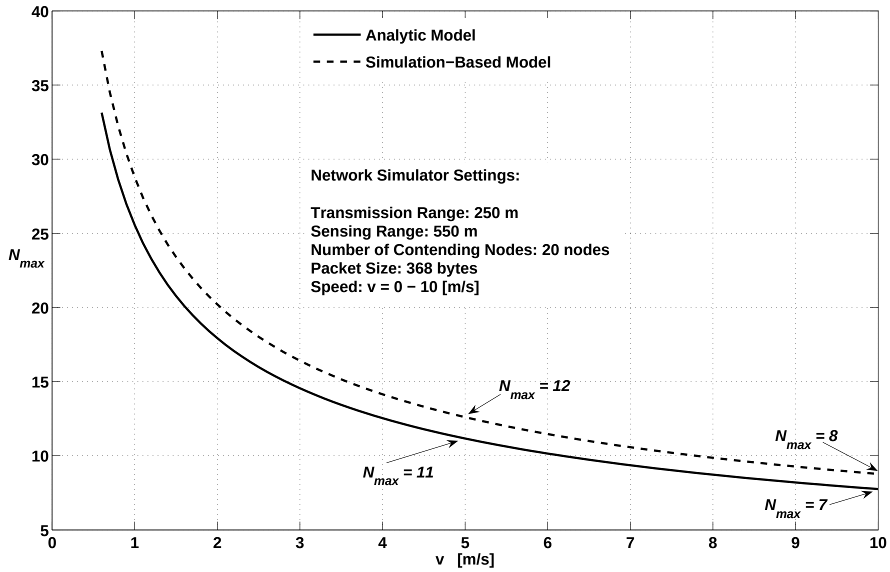

Figure 3-10: Maximum number of intermediate nodes for a wireless network with 20 contending nodes and a packet size of 368 bytes.

3.6. Conclusions

This chapter has presented a model to determine the upper bound on route length of wireless ad-hoc networks. The upper bound on route length has been found by determining the maximum feasible number of intermediate nodes, N_{max}, in any route of a mobile ad-hoc network. The problem was first approached by using an average access delay model for single-hop routes, found in the literature, to derive the round trip time for multi-hop routes. Second, based on the route duration model presented in chapter 2, a new route duration model for routes formed by N intermediate nodes has been established. This model takes the average route discovery time into account. Based on this model, an approximation to compute the average route failure time is provided and the average route duration time can therefore be estimated. A closed-form expression to compute the maximum feasible number of intermediate nodes (maximum route length) in mobile ad-hoc networks has been derived from these two models. An upper bound on route length guarantees a reliable communication path for any source-destination pair. The maximum network size can thus be estimated. Numerical calculations and simulations were developed to evaluate and validate this study for different network conditions. In general, simulation results were very close to the results obtained by the proposed model with an acceptable margin of error. From this analysis, we concluded that the maximum number of intermediate nodes is inversely proportional to packet size and node speed. This model can be used to scale network size up or down so as to meet minimum route duration requirements to ensure a communication path for any source-destination pair in mobile ad-hoc networks.

Chapter 4

Conclusions

This thesis established a model to estimate route duration in wireless ad-hoc networks when nodes move according to a random-based mobility model. This model analyzed a route formed by N intermediate nodes. The problem was first approached by studying simpler 3-node routes. From the 3-node static case, it was demonstrated that the initial positions of source, intermediate and destination nodes have a great impact on route duration in MANETs. From the 3-node mobile case, the PDF of route duration of 3-node routes for Random WayPoint and Random Walk mobility models were obtained. Finally, it was shown that, regardless of the mobility pattern considered, route duration of routes formed by N intermediate nodes can be computed as the minimum route duration of N 3-node routes. Theoretical analyses and simulations were developed to validate this study. In general, simulation results were very close to the results obtained by the proposed model with an acceptable margin of error. Results from this work can be used to compute the overhead signaling of unicast and multicast routing protocols for mobile ad-hoc networks since every time a route fails, the routing protocol needs to either repair the route locally or find a new route. Based on the work presented in this thesis, it would be possible to study the behavior of the proposed model with different mobility models, variable speeds and other heterogeneous conditions. Additionally, the relationship between route duration and system performance (throughput and overhead signaling) could also be analyzed, since this has not been established yet.

This thesis also set forth a model to determine the upper bound on route length of wireless ad-hoc networks. The upper bound on route length was found by determining the maximum feasible number of intermediate nodes, N_{max}, in any route of a mobile ad-hoc network. This problem was first approached by using an average access delay model for single-hop routes, found in the literature, to derive the round trip time for multi-hop routes. Second, based on the route duration model presented in Chapter 2, a new route duration model for routes formed by N intermediate nodes was established in Chapter 3. This model takes the average route discovery time into account. Based on this model, an approximation to compute the average route failure time was provided and the average route duration time can therefore be estimated. A closed-form expression to compute the maximum feasible number of intermediate nodes (maximum route length) in mobile ad-hoc networks was derived from these two models. An upper bound on route length guarantees a reliable communication path for any source-destination pair. The maximum network size can thus be estimated. Numerical calculations and simulations were developed to evaluate and validate this study for different network conditions. In general, simulation results were very close to the results obtained by the proposed model with an acceptable margin of error. From this analysis, we concluded that the maximum number of intermediate nodes is inversely proportional to packet size and node speed. This model can be used to scale network size up or down so as to meet minimum route duration requirements to ensure a communication path for any source-destination pair in mobile ad-hoc networks.

A . 1 – Publication List

The PhD student has participated in the writing of the following papers:

1. Conference Papers

- Authors: **M. Pascoe**, J. Gomez, V. Rangel and M. Lopez-Guerrero
  Title: "Route Duration in Mobile Ad-Hoc Networks"
  Conference: *In Proceedings of the IEEE 20th CCECE 2007,* Vancouver B. C., Canada
  Date: April, 2007.
- Authors: **M. Pascoe**, J. Gomez, V. Rangel and M. Lopez-Guerrero
  Title: "Modeling Route Duration in Mobile Ad-Hoc Networks"
  Conference: *In Proceedings of The Fourth IEEE International Conference on Mobile Ad-Hoc and Sensor Systems (MASS 2007),* Pisa, Italy,
  Date: October, 2007.
- Authors: **M. Pascoe**, J. Gomez, V. Rangel and M. Lopez-Guerrero
  Title: "An Upper Bound on Network Size in Mobile Ad-Hoc Networks"
  Conference: *In Proceedings of IEEE Global Communications Conference (GLOBECOM 2008)*, New Orleans, USA
  Date: December, 2008.

2. Journal Papers

- Authors: **M. Pascoe**, J. Gomez, V. Rangel, M. Lopez-Guerrero
  Title: "Route Duration Modeling for Mobile Ad-Hoc Networks"
  Journal: *ACM Wireless Networks Journal (WiNet)*
  Publisher: Springer

ISSN: 1022-0038 (printed version) / 1572-8196 (electronic version)
Impact Factor: 1.194 (2008)[1]
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Date: February, 2009

[1] Journal Citation Reports ®, Thomson Reuters

A . 2 – Transmission Range Calculation in *NS-2*

Network simulations are used to represent the different operation conditions of wireless networks. The simulations have several key parameters, including mobility models, propagation models and communicating traffic patterns, among others. We selected the network simulator *NS-2* [4] because it is a relatively simple and widely available open-source software that is commonly used to evaluate MANET performance. In Chapter 2 and Chapter 3, simulation work was developed to validate the route duration and route length models for different network conditions.

In this thesis, we have considered the transmission range defined by the IEEE 802.11a standards, i.e., $R = 250$ [*m*] (outdoors), but any other transmission range might also be considered. The main reason of considering this transmission range is intended to be consistent with the default values in *NS-2*. For instance, the transmitted signal power, P_{Tx}, for $R = 250$ [*m*] is $P_{Tx} = 0.28183815$ [*W*]. The frequency $f = 914 \cdot 10^6$ [*Hz*] - Lucent WaveLAN DSSS radio interface and the bandwidth is $B = 2$ [*MHz*]. Therefore, the wavelength would be $\lambda = c / f = 0.328$ [*m*]. The system loss factor is $L = 1.0$ [–]. The received signal power threshold is $P_{Rx\_\{Th\}} = 3.652 \cdot 10^{-10}$ [*W*]. The carrier sense threshold is $C_{S\_\{Th\}} = 1.559 \cdot 10^{-11}$ [*W*], thus leading to a sensing range $R_S = 550$ [*m*]. Most of these values are described in the IEEE 802.11a standards and some others are hardware and/or driver specific.

The transmitter and receiver antennas are both considered to be omni-directional with unit gain, i.e., $G_{Tx} = G_{Rx} = 1$. The antennas are centered at the transmitter and receiver coordinates, i.e., (X_t, Y_t, Z_t) and (X_r, Y_r, Z_r) with an elevation $Z_e = 1.5$ [*m*], i.e.,

$$X_{Tx} = X_t \text{ and } X_{Rx} = X_r$$

$$Y_{Tx} = Y_t \text{ and } Y_{Rx} = Y_r$$

$$Z_{Tx} = Z_t + Z_e \text{ and } Z_{Rx} = Z_r + Z_e$$

Since $Z_t = Z_r = 0$ [m], the height of receiver and transmitter antennas would be: $h_{Tx} = h_{Rx} = 1.5$ [m].

The distance between any transmitter-receiver pair, d, would be given by:

$$d = \sqrt{(X_{Tx} - X_{Rx})^2 + (Y_{Tx} - Y_{Rx})^2 + (Z_{Tx} - Z_{Rx})^2}$$

The cross-over distance, d_0, would be:

$$d_0 = \frac{4\pi h_{Tx} h_{Rx}}{\lambda} \text{ ; (} d_0 = 86.20 \text{ [}m\text{])}$$

If $d \le d_0$, then the Friis Free Space Propagation Model must be used, i.e.,

$$P_{Rx} = \frac{P_{Tx} G_{Tx} G_{Rx}}{L} \left(\frac{\lambda}{4\pi d} \right)^2$$

If $d > d_0$, then the Two-Ray Ground Propagation Model must be used, i.e.,

$$P_{Rx} = \frac{P_{Tx} G_{Tx} G_{Rx} h_{Tx}^2 h_{Rx}^2}{(d)^4 L}$$

Additionally, the IEEE 802.11 MAC defines the following parameters and settings: The slot-time is $T_{\blacklozenge}$ = 16 - 20 [μs]. The minimum contention window is W_{min} = 32. The maximum contention window is W_{max} = 1024. The inter-frame spaces used during transmission are T_{SIFS} = 8 - 10 [μs] and T_{DIFS} = 16 - 50 [μs]. The basic transmission rate is R_b = 1 [$Mbps$] (rate for control frames). The data transmission rate is R_d = 2 [$Mbps$] (rate for data frames).

A . 3 – Glossary

Abbreviations and Acronyms

ACK – ACKnowledgement packet

AODV – Ad-hoc On Demand Distance Vector

CBR – Constant Bit Rate

CCDF – Complementary Cumulative Distribution Function

CDF – Cumulative Distribution Function

CTS – Clear-To-Send packet

DIFS – Distributed Inter-Frame Space

DSR – Dynamic Source Routing

EMI – Electro-Magnetic Interference

FW – FreeWay (mobility model)

IEEE – Institute of Electrical and Electronics Engineers

i.i.d. – independent and identically distributed (random variables)

IP – Internet Protocol

MANET – Mobile Ad-hoc NETwork

MH – ManHattan (mobility model)

MST – Minimum Spanning Tree

NS-2 – Network Simulator (Second Version)

PDF – Probability Density Function

RPGM – Reference Point Group Mobility (mobility model)

RTS – Ready-To-Send packet

RTT – Round Trip Time

RW – Random Walk (mobility model)

RWP – Random WayPoint (mobility model)

SIFS – Short Inter-Frame Space

SSE – Sum of Squares due to Error

SSR – Sum of Squares of the Regression

SST – Total Sum of Squares

VANET – Vehicular Ad-hoc NETwork

Wi-Fi – Wireless Fidelity

WLAN – Wireless Local Area Network

WSN – Wireless Sensor Network

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