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Analysis of Route Stability in Mobile Multihop Networks Under Random Waypoint Mobility

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ABSTRACT Analytical performance evaluation is crucial in designing mobile multihop networks under different operational conditions. It provides the best insight into the effects of various network parameters and their interactions. The route and link lifetime in mobile multihop networks under a random mobility environment have significant effects on network performance. Many analytical studies have been introduced to the body of work concerned with the link and route lifetime in mobile multihop networks. However, there is no closed-form analytical study for link and route stability in MANETs under any random mobility model. In addition, to simplify the analysis, one or more network characteristics were not considered in most of related studies. This work presents a closed-form analytical model for the link and route lifetime in mobile multihop networks, where nodes move according to the random waypoint mobility model. The proposed model can capture the effects of most network characteristics including the number of mobile nodes, the number of hops, the network area size, the transmission range, and the speed of nodes. In addition, we used the proposed model to derive expressions for the bounds of the link and route lifetime under different network characteristics. The proposed model can help characterize the network performance, analyze the network as to meet a certain level of quality-of-service, and design better routing protocols to cope with link breakage caused by node mobility. To verify the proposed model, extensive simulations were performed under different network characteristics.

INDEX TERMS Link lifetime, mobile ad hoc networks, multihop networks, random waypoint mobility, route lifetime, vehicle ad hoc networks.

I. INTRODUCTION

Mobile Multihop Network (MMN) is a wireless networking system consisting of a set of nodes that communicate through multihop connections, where some or all nodes are mobile. MMNs include Mobile Ad hoc Networks (MANETs), Mobile Wireless Sensor Networks (MWSNs), mesh networks, and Vehicle Ad hoc Networks (VANETs) [1]. Because of the possibility of ubiquitous communications, MMNs have for some time received increasing interest. MMNs enable users to maintain connectivity to a fixed network or exchange information with or without using existing infrastructure, such as a base station or an access point. This is achieved through multihop communications. Mobile multihop networks were envisioned for various usages such as disaster management, everyday Internet access, and military applications. Each of these use cases has different assumptions and protocol requirements [2].

In MMNs, nodes have limited transmission power, which limits the communication range of wireless radio transceivers. As a result, nodes that cannot communicate directly use one or more intermediate nodes as relays to forward traffic from the source node to the destination node. The number of intermediate nodes depends on different network characteristics, such as the network area size, the number of nodes in the network, the distance between the source and destination, the transmission range, and the type of movement of nodes (mobility) [3].

Node mobility in mobile multihop networks introduces frequent arbitrary changes in the network topology. Consequently, frequent disconnections (failures) arise in links and routes between node pairs. Thus, alternate routes must be found, which affects the network performance. The presence of mobility makes designing and implementation of

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MMNs in real life a challenge because traditional schemes cannot be applicable. It is a challenge to design mechanisms for topology control, routing protocol, quality-of-services (QoS) and resource management, service discovery, network operations and management, security services, and service offerings [1].

In MMNs, the link lifetime is the amount of time in which a node has an active link with its neighbor nodes to forward traffic to the destination node. The route lifetime is the period of time in which the route is available. This work introduces a closed-form analytical model that predicts the link and route lifetime in MMNs, especially MANETs, under the random waypoint mobility model, taking into account most network characteristics. In addition, bounds (maximum and minimum) of the route lifetime are analyzed under different network configurations.

Analyzing the dynamic behavior of the network routes can be performed using simulation or analytical studies. However, analytical analysis can provide insights on general problems and identify possible solutions under general network conditions. It provides the best insight into the effects of various parameters and their interactions [4]. In addition, analytical solutions are generally less costly and have higher applicability than simulation or empirical models because they are not tied to any specific simulation scenario. Having said this, analytical analysis of the route stability in mobile multihop networks with random mobility is a challenge. This is because there are many factors that affect the route stability, such as the dynamic topology, the number of nodes, the type of random mobility, the size of the network area, the shape of the network area, and the transmission range.

Substantial number of studies have been introduced to the body of work related to the theoretical analysis of the link and route stability in MMNs, especially MANETs [5]–[19] and VANETs [20]–[28]. The downside to most of these studies is that too often, they concentrate on the impact of mobility and do not pay attention to the effects of the network configurations, such as the number of nodes, the size of the network area, the shape of the network area, the speed of nodes, the number of hops of routes, the distance between nodes, and the transmission range. In most of these studies, these network parameters were mostly assigned fixed values or did not considered. The changes in these parameters though, have great impacts on the link and route dynamics. In addition, in most of previous studies, to simplify the analysis, most adopted random mobility models are approximated to the exponential distribution model or a simpler model, as explained in the next section.

To the best of our knowledge:

1) There is no closed-form analytical study for link and route stability in MANETs under any random mobility model.
2) There is no analytical study for link and route stability in MANETs under the random waypoint mobility model without simplification of mobility model.
3) There is no analytical study that investigates the bounds of link and route lifetime in MANETs under any random mobility model.
4) There is no analytical study that explores the effects of most network characteristics on link and route stability in MANETs under any random mobility model.

These constitute the motivation for this work, in which, for the first time, we develop a closed-form analytical model for the link and route lifetime for MANETs, where nodes move according to the random waypoint mobility model. The proposed model can capture the effects of different network parameters including the number of mobile nodes, the number of hops, the network area size, the transmission range, and the maximum and minimum speed of nodes. The proposed model is used to derive expressions for the bounds and the average of the link and route lifetime under different network configurations. The random waypoint mobility model was selected because it is one of the most commonly used mobility models in MANET studies. MANETs under the random waypoint mobility model is used for different applications such as [1], [2]:

- Army tactical MANETs: Soldiers communicate in foreign terrains, giving them superiority on the battlefield.
- MWSNs: Sensor nodes move randomly in an area to collect information related to a specific parameter, such as noise, temperature, humidity, pressure, etc.
- Ad hoc network of robots: Integrating Teams of Mobile Robots in a wireless ad hoc network to accomplish more complex tasks.
- Disaster rescue ad hoc network: At times of disasters (floods, storms, etc.) rescue workers can use ad hoc networks to communicate.

Although, the proposed model was developed for MANETs, it can be modified to analyze VANETs and MWSNs under any random mobility model.

The proposed analytical model for the expected and bounds of the route lifetime in MANETs can be used in different applications:

1) Predicting the link and route lifetime using the proposed model can help determine the timer setting of routing protocols [29], such as the Time-to-Live (TTL) interval of route caches in on-demand routing protocols.
2) Designing of better routing protocols to cope with link breakage caused by node mobility. Predicting the route lifetime can help avoid route failure by creating backup routes before the breaking of the current one, which can enhance the network performance [5], [30].
3) The route lifetime affects the packet delivery ratio, packet delay, and network throughput. Therefore, the model can help characterize the network performance.
4) The route lifetime is one of the most important metrics to meet the quality-of-service requirements [31]. Therefore, the proposed model for bounds of the route

lifetime can help analyze the network to meet a certain level of quality-of-service.

5) The analytical model of route lifetime bounds can be used in designing and planning of the mobile multi-hop networks. It can be used to estimate the network configurations that optimize network performance and reliability.

The rest of the paper is organized as follows: The related work is discussed in Section II. In Section III, basic concepts about mobile multihop networks are explained. In Section IV, the analytical model for the link and route lifetime is presented. To derive mathematical expressions for the link and route lifetime, we first need to derive expressions for three parameters; the two-hop apart distance between mobile nodes in multihop routes, the relative speed between two mobile nodes, and the path length of the intermediate node (router) in a two-hop route. Sections IV-A to IV-C show how to derive these three parameters. Section IV-D explains how to derive expressions for the link and route lifetime and their bounds. The proposed model is validated using extensive simulations in Section V. Finally, some conclusions are drawn in Section VI.

II. RELATED WORK

Many studies were proposed to analyze the link and route lifetime in mobile multihop networks, such as MANETs and VANETs. The authors in [6] used simple statistical analysis to characterize the statistics of link and route durations for different mobility models using simulation. They investigated possible distributions to approximate the Probability Density Function (PDF) of the link and route lifetime in MANETs. A connection availability model of two-hop ad hoc networks was presented in [7], where nodes move according to the random direction model. Analytical expressions were presented for the leaving rate and the returning rate in the intersection region. Although the authors adopted a random mobility model, they assumed that the node spatial density function is constant. The impact of human mobility on the link and route lifetime of mobile ad hoc networks was analyzed in [8]. In addition, a framework to model the link and route lifetime was developed. The model was developed using measurements for real user mobility, which limits the results this study.

Wu *et al.* [9] proposed theoretical analysis for the link lifetime in multihop mobile networks with the random walk mobility model. They indicated that the connection time for two nodes can be determined using the relative speed between the two nodes and the distance during which the link is connected. However, the authors supposed that the nodes are uniformly distributed in the network outside the transmission range. Also, they did not consider the minimum and maximum speed of nodes in the analysis.

In [10], authors studied the duration and availability probabilities of routing paths in MANETs. They focused on the effect of the random direction mobility model. They used the results to determine the optimal path in terms of route stability. To simplify the analysis, the authors assumed that the move and pause phases of mobile nodes are exponentially distributed. In [11], the authors derived an expression for the PDF of the route lifetime of 3-node routes for the random walk mobility model. An approximate PDF was derived for the route lifetime for routes formed by M intermediate nodes, using the minimum route lifetime of 3-node routes. The derived expressions for the PDF of the route lifetime is based on statistical analysis.

Namuduri *et al.* proposed an analytical model to estimate the path duration in a MANET using the random waypoint mobility model as a reference [12]. Some network parameters were considered in the analysis, such as the node density and transmission range. Nevertheless, to simplify the analysis, this work supposed that the distance between nodes, moving using the random waypoint mobility model, is exponentially distributed. In addition, the number of hops and maximum and minimum speed of nodes were not considered in the analysis.

Dung and An [13] proposed a mathematical model for supporting and evaluating the performance of multi-hop routes in mobile ad hoc networks under random waypoint mobility model. Authors presented mathematical analysis for the distribution of hop count of multihop routes. Nevertheless, to avoid the complexity of analyzing of the random waypoint mobility, authors assumed that nodes are distributed in the network according to the Poisson distribution.

In [14], the authors proposed an analytical model to evaluate the distribution of link lifetime in a mobile ad hoc network under the random waypoint mobility model. They derived an expression for the PDF of the link lifetime. However, the drawbacks of this study are (1) the authors tested the proposed model using only two nodes (one stationary and another moving with constant speed), (2) the distance between nodes did not considered in the analysis, (3) analysis of route lifetime did not considered, (4) the analysis ignored effects of the node density and the network area size

The authors in [15] determined the distribution of the overall link duration by considering both interference and mobility of linked nodes. They approximated the link lifetime due to interference by an exponential distribution, and the overall link lifetime due to mobility and interference by a Rayleigh distribution. The authors considered only the smooth mobility model and assumed that the distance between nodes is identical Gaussian distribution with zero mean.

Yadav *et al.* [5] proposed an analytical study for link lifetime to find the stable routes in MANETs that was used to enhance the performance of the Ad hoc On-demand Multipath Distance Vector (AOMDV) routing protocol, which is a multipath routing protocol for MANETs. The authors used the instantaneous distance between nodes and their velocity to estimate the link lifetime. This study supposed that nodes move according to the random direction model. However, the distance between two relaying nodes was estimated using the received signal strength. In Addition, derived expression or the link lifetime is not accurate. This is because the authors did not consider the distance between the router and the source and destination in a two-hop route in computing the path length of a router.

In [16], a mathematical model was proposed to capture the effects of dynamic transmission range due to radio channel fading and relative distance of a node-pair resulting from random movements. Only link properties in multihop networks are investigated. In addition a simple mobility model, called smooth mobility model, is adopted.

The work in [17] considered the link quality issue of a single hop wireless sensor networks in case of Brownian motion using mathematical analysis. The relationship of link throughput with other real conditions such as movement specifications and packet sizes were delivered to reach optimal transmission performance. The authors did not consider analysis of multihop routes. In addition, the Brownian motion mobility was adopted to simplify the analysis. Statistical models were developed in [18] to accurately evaluate the distribution of the connection time of wireless links in mobile multihop networks in which nodes move randomly within constrained areas.

A multipath routing protocol for MANET was proposed in [19], which selects the most stable route instead of the first available one. An approximate technique for link lifetime estimation was used to select the most stable route from available routes to the destination. The protocol was implemented using AOMDV protocol. To simplify the analysis, this work assumed that mobility epoch of any node is exponentially distributed, which is not correct in most mobility patterns. An analytical model was proposed in [20] for the probability density function of the link lifetime. The authors assumed that the mobile nodes were equally spaced. This assumption is not reasonable because in random mobile multihop networks, the distance between nodes is a random variable.

In [21], Yan *et al.* studied the PDF of the link lifetime for each two nodes in VANETs under the following assumptions: (1) the PDF of the headway distance of inter-vehicles is lognormal, and (2) the vehicle speed is constant. Yet, empirical studies showed that vehicle arrival process can be approximated by Poisson distribution, while the Uniform distribution represents an excellent model for the vehicle speed [32], [33]. To maximize the expected path lifetime, a routing algorithm was proposed in [22] for cognitive-radio enabled VANETs (CRVANETs). A new protocol was proposed by Barghi *et al.* [23] that uses the features of vehicle movements to predict the vehicle behavior to choose the best route with the longest lifetime to connect a vehicle to the Internet.

An analytical model was presented in [24] to find the probability density function of link and path duration in vehicular ad hoc networks, assuming the distance headway to have lognormal distribution. The authors analyzed the impact of vehicle mobility and transmission range on the link duration PDF and mean path duration in VANETs. Authors in [25] proposed a sector-based protocol with the consideration of the localization between the intersections. In order to maintain QoS for each link, a path reliability is estimated before sending the data over that link.

In [26], the authors proposed a mathematical model for vehicle-to-vehicle wireless connectivity. They considered the effect of the message size, acceleration, the headway distance, the relative speed of vehicles, the association time, and the transmission range. The proposed model is approximated by assuming that the distribution of vehicles is based on the Poisson distribution. In [27], an analytical model was proposed for estimating the route duration in VANETs to be used for enhancing the routing of traffic. The authors in [27] assumed that the assistance is provided by the fixed infrastructure and every vehicle is equipped with the Global Positioning System (GPS). Nevertheless, GPS may not detect obstacles and needs resources. An analytical predication for the link failure probability was proposed in [28] using support vector regression. The proposed method allows vehicles to control the state of the link during the communications to improve the quality-of-service in vehicular ad hoc networks. This approach though, uses GPS that may not detect obstacles.

III. BACKGROUND

In MMNs, each node is supplied with an antenna that allows it to transmit and receive information from other nodes. The antenna can radiate and receive within a certain radius, which is called the transmission range (r). The radius is determined by the level of transmission power [2]. When a node $N1$ transmits to another node $N2$, all nodes that lie within transmission range of $N1$ can hear its transmission, and these nodes are called neighbor nodes. The area covered by the transmission range of a node is called the capture area of the node. The higher the transmission power, the larger the size of the capture area and the number of neighbor nodes, but potentially also, the higher the amount of interference that may be experienced from neighbor nodes [1]. Figure 1 shows a mobile multihop network with 15 nodes, where nodes $N2$ to $N4$ are neighbors of node $N1$.

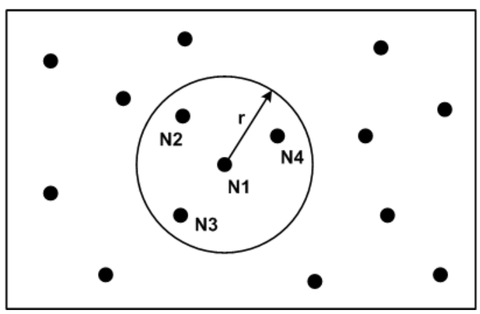

FIGURE 1. Transmission range and neighbor nodes of N1.

In mobile multihop networks, a node can send a message to another node beyond its transmission range by using other nodes as relay points. This mode of communication is known as wireless multihop. Figure 2 shows a multihop route between nodes $N1$ and $N5$, where nodes $N2$ to $N4$ are used as relays. In addition, nodes in MMNs are free to

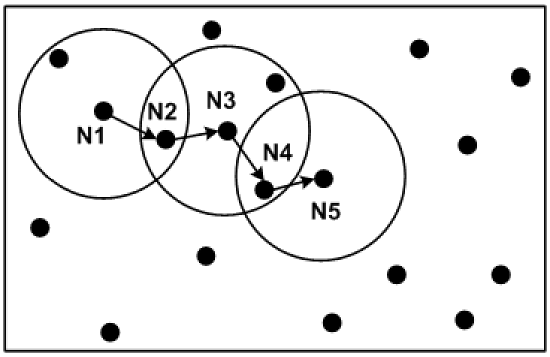

FIGURE 2. Multihop route between a source and a destination.

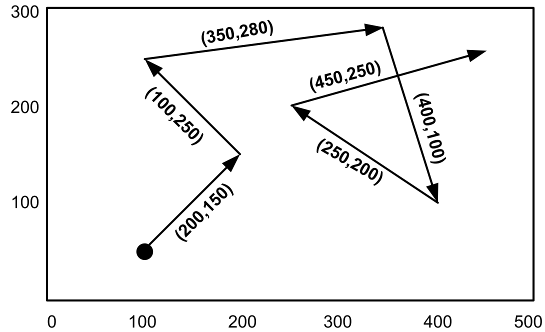

FIGURE 3. Movement of a mobile node using the RWP mobility model.

move. Hence, the network topology often changes rapidly and unpredictably. The dynamic nature of the network topology results in frequent route breaks. Therefore, nodes need to periodically collect connectivity information from other nodes. One implication of this is that the message overhead needed to collect topology information will increase. Mobility is a crucial factor affecting the design and analysis of MMNs [1].

Mobility models characterize the movements of mobile users with respect to their location, speed, and direction over a period of time. A mobility model attempts to mimic the movement of real mobile nodes that change the speed and direction with time [9]. Many mobility models are designed to recreate the real world scenarios for better application to MMNs. In random mobility models such as random waypoint, random direction, random walk, freeway, and Manhattan mobility models, the nodes move randomly, and can be classified further based on the statistical properties of randomness [8]. The mobility patterns are a key issue in mobile multihop networks, which influence the performance characteristics of the network. The effects of the random mobility patterns of mobile nodes on the performance of the network were extensively analyzed in the literature [34].

The random characteristics of mobile nodes in MMNs may consist of a stochastic process, and each node's movement may consist of a sequence of random length intervals, called mobility epoch, during which a node moves in a constant direction at a constant speed. The speed and direction of a mobile node may vary from an epoch to another in accordance with mobility criteria [35].

The Random Waypoint (RWP) mobility model is one of the most commonly used mobility models for MMNs, especially MANETs [36]. In the RWP mobility model, a node chooses a uniform random destination anywhere in the network area, then moves towards the destination point with a speed chosen randomly from a minimum speed ($Vmin$) to a maximum speed ($Vmax$). When the node reaches the destination, it may stop for a duration defined by the "pause time" parameter. Then, it chooses and moves towards a new destination in a similar manner. Each node repeats this behavior for the length of simulation time [34]. Figure 3 shows the movement of a mobile node in a rectangle area of size 500×300 m^2 using the RWP mobility model, where the numbers between brackets represent coordinates (X, Y) of the new destination of the mobile node.

IV. PROPOSED ANALYTICAL MODEL

This section introduces the proposed analytical model for the link and route lifetime in mobile multihop networks. Mathematical expressions for the link and route lifetime are derived. To do this, we first need to derive expressions for three parameters; the two-hop apart distance between mobile nodes in multihop routes, the relative speed between two mobile nodes, and the path length of the intermediate node (router) in a two-hop route. In Sections IV-A, IV-B, and IV-B, these three parameters and their probability density functions are derived. In Section IV-D, these parameters are used to derive a mathematical model for the link stability of one-hop route, which is then generalized to obtain a closed-form mathematical model for multihop routes.

To develop the analytical model for the link and route lifetime in MMNs, we assumed that all nodes use the same transmission power, and have the same transmission range. Also, All nodes move under the RWP mobility model in a network with the size equal to $W \times W$. The speed of nodes is chosen randomly from the range $[Vmin, Vmax]$, and the pause time is set to zero to increase the mobility of nodes.

A. DISTANCE BETWEEN NODES

In multihop networks, if the destination is not in the transmission range of the source, the packets are routed through h hops through neighbor nodes. Figure 4 shows a two-hop communication route between the source node $N1$ and the destination node $N4$. To establish a connection between $N1$ and $N4$, traffic must go through one of the nodes ($N2$ or $N3$) located in the intersection area between the area covered by the transmission range of $N4$ and $N1$ (shaded area), simply called the intersection area. As shown in Figure 4, node $N1$ uses node $N3$ as a router to forward its packets to node $N4$. Node $N3$ is the active router, whereas node $N2$ is a backup router. When the active router fails, one of the backup routers is used to forward packets. Failure of the active nodes usually is

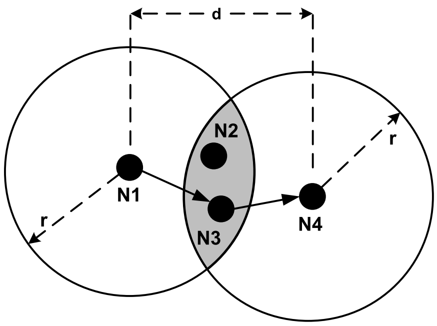

FIGURE 4. Two-hop communication route between two nodes.

due to power consumption, hardware failure, or mobility (the active router leaves the intersection area).

The failure of the active router to route traffic due to moving outside the intersection area depends on the speed and direction of the node, and the size of the intersection area. The size of the intersection area A_i can be computed as [36]:

$$A_i = r^2\left(2ArcCos\left(\frac{d}{2\text{r}}\right) - d\cdot\sqrt{1-\frac{d}{4\text{r}}}\right)$$

The size of the intersection area depends on two parameters; the transmission range r and the distance between two-hop apart nodes d. According to [36], the distance d depends on the number of nodes in the network, the speed of nodes, the mobility pattern, and the size of the network area. As proved in [36], if the network area is a square with size $W \times W$, the probability density function of the distance between any two nodes in the network $f_d(\delta)$ can be expressed as

$$\begin{aligned} f_d(\delta) &= \frac{6\delta^3}{W^8} - \frac{6\delta^4}{5W^{10}} + \frac{6\delta^5}{125W^{12}} + \frac{96\sqrt{\delta}^3}{5W^5}\frac{1584\sqrt{\delta}^5}{125W^7} \\ &\quad + \frac{36\pi}{25W^2} + \frac{192d^2\sqrt{\delta}^3}{175W^9} - \frac{36\pi\delta}{5W^4} - \frac{48d\sqrt{\delta}^3}{5W^7} + \frac{9\pi\delta^2}{2W^6} \end{aligned}$$

where $\delta < \sqrt{2}\,W$. By definition, the Cumulative Distribution Function (CDF) of the distance d can be expressed as

$$\begin{aligned} F_d(\delta) = \int f_d(\delta)\,d\delta &= \frac{3\delta^3}{2W^8} - \frac{6\delta^{10}}{25W^{10}} + \frac{\delta^{12}}{125W^{12}} \\ &\quad + \frac{36\pi\delta^2}{25W^2} - \frac{18\pi\delta^4}{5W^4} + \frac{3\pi\delta^6}{2W^6} + \frac{192\delta^5}{5W^5} \\ &\quad - \frac{96\delta^7}{35W^7} - \frac{3168\delta^7}{875W^7} + \frac{128\delta^9}{525W^9} \end{aligned}$$

As explained in [37], to minimize the number of hops, packets are forwarded to the node with the maximum distance toward the destination. Therefore, if there are k neighbor nodes toward the destination for a router node (e.g. $N3$ in Figure 4), the two-hop apart distance is the maximum distance dx of a set of k random variables, where their PDF and CDF are $f_d(\delta)$ and $F_d(\delta)$, respectively. In [38], the authors derived expressions for the PDF and CDF of the maximum and minimum of a set of continuous random variables. Using these expressions, the CDF of the maximum distance dx can be expressed as [38]

$$\begin{aligned} F_{dx}(\delta) &= P(dx \le \delta) = P\left(\underset{1\le i\le k}{\text{MAX}}\, dx_i \le \delta\right) \\ &= \prod_{i=1}^{k} P(d \le \delta) = [P(d \le \delta)]^k = [F_d(\delta)]^k \end{aligned}$$

By definition, the PDF of dx is the differentiation of its CDF.

$$f_{dx}(\delta) = \frac{dF_{dx}(\delta)}{d\delta} = k\cdot f_d(\delta)\cdot(F_d(\delta))^{k-1}$$

Because the distance between two-hop apart nodes varies between r and $2r$, its expected value can be computed as follows:

$$\begin{aligned} E(d) &= \int_r^{2r} \delta\cdot f_{dx}(\delta)\,d\delta \\ &= \int_r^{2r} \delta\cdot k\cdot f_d(\delta)\cdot(F_d(\delta))^{k-1}\,d\delta \end{aligned} \tag{1}$$

Figure 5 shows the expected distance between two-hop apart nodes that move according to the RWP mobility model in a square area, plotted against different values of the transmission range and the number of neighbor nodes toward the destination. It is clear that increasing k or r increases the expected distance between two-hop apart nodes.

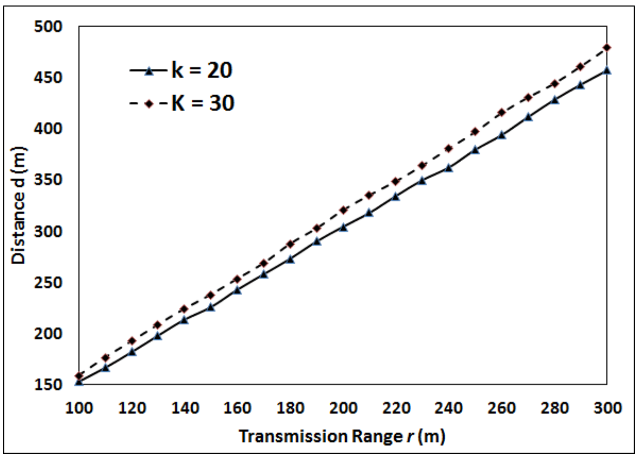

FIGURE 5. The expected distance between two-hop apart nodes versus the transmission range and the number of neighbors.

B. BOUNDS OF NODES' SPEED

The link and route stability rely on the relative speed of nodes. We need to derive its PDF and CDF. Consider nodes X and Y moving in the network with speeds V_X and V_Y, respectively, as shown in Figure 6. Let the incident angle between the relative speed of node X and Y is ρ_{XY}. The incident angle changes between 0 and π. The relative speed V_{XY} between X and Y can be evaluated as:

$$V_{XY} = \sqrt{V_X^2 + V_Y^2 - 2V_XV_Ycos(\rho_{XY})} \tag{2}$$

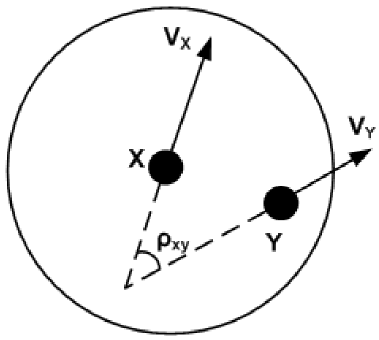

FIGURE 6. Relative movement of two nodes.

With the random waypoint mobility, the speed of nodes is randomly chosen from the predefined range [$Vmin$, $Vmax$]. Therefore, the average speed of nodes can be expressed as [9]

$$V_e = \frac{V_{max} - V_{min}}{\ln(V_{max}) - \ln(V_{min})}$$

To simplify the analysis, we consider that each node in the network moves with speed V_e. Therefore, from Equation 2, the relative speed V_r between two nodes can be expressed as follows:

$$V_{XY} = V_r = \sqrt{V_e^2 + V_e^2 - 2V_eV_e\cos(\rho)} = 2V_eSin\left(\frac{\rho}{2}\right)$$

Assuming that ρ is uniformly distributed in the range $[0, \pi]$, the probability density function of ρ can be described as follows:

$$f_\rho(\rho) = \frac{1}{\pi}$$

The probability that ρ is less than or equal to a value of β is given by

$$F_\rho(\beta) = P(\rho \leq \beta) = \int_0^\beta f_\rho(\rho)\, d\rho = \frac{\beta}{\pi} \tag{3}$$

The cumulative distribution function of V_r is expressed as

$$\begin{aligned} F_{Vr}(v) &= P(Vr \leq v) = P\left(2V_aSin\left(\frac{\rho}{2}\right) \leq v\right) \\ &= P\left(\rho \leq 2ArcSin\left(\frac{v}{2V_e}\right)\right) \end{aligned} \tag{4}$$

From Equations 3 and 4, the cumulative distribution function of V_r is expressed as

$$F_{Vr}(v) = \frac{2}{\pi}ArcSin\left(\frac{v}{2V_e}\right)$$

where $0 \leq v \leq 2V_e$. By definition, the PDF of $V_r(f_{Vr}(v))$ is derived by differentiation of $F_{Vr}(v)$ as

$$f_{Vr}(v) = \frac{dF_{Vr}(v)}{dv} = \frac{2}{\pi\sqrt{4V_e^2 - v^2}} \tag{5}$$

The expected relative speed between two nodes is derived as

$$\begin{aligned} E(Vr) &= \int_0^{2V_e} v \cdot f_{Vr}(v)\, dv \\ &= \int_0^{2V_e} v \cdot \frac{2}{\pi\sqrt{4V_e^2 - v^2}} dv = \frac{4V_e}{\pi} \end{aligned}$$

Figure 7 shows the PDF of the relative speed $f_{Vr}(v)$ for $Vmax = 20$ and 30 m/s. As shown in Figure 7, the PDF increases by increasing the relative speed V_r. The maximum probability is reached when $V_r = 2V_e$. In addition, increasing $Vmax$ decreases the PDF of Vr. This is due to increasing V_e which reduces $f_{Vr}(v)$.

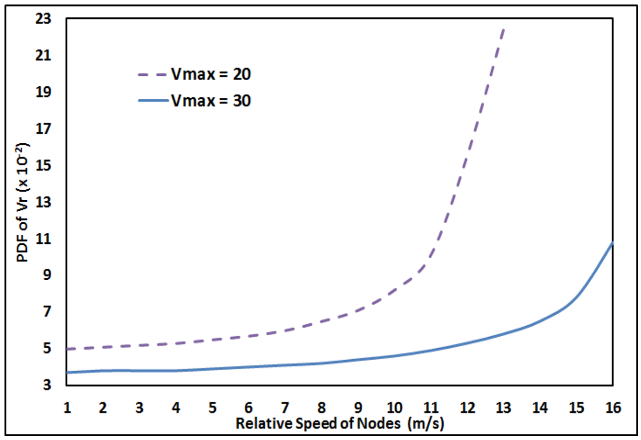

FIGURE 7. PDF of the relative speed V_r.

Suppose that there are n nodes in the intersection area between two nodes A and B. As explained above, one of these n nodes forward the traffic and others are considered as backup routers. If the intermediate node failed due to any reason, one of the backup routers is used to forward the traffic. Depending on their moving direction, the relative speed of nodes in the intersection area with A or B differs from node to node. We need to find nodes with the expected minimum and maximum relative speed. Therefore, we need to derive expressions for the PDF and CDF of the minimum and maximum relative speed of nodes in the intersection area, which is used to analyze the bounds of the link lifetime, as explained in Section IV-D.

We consider that the relative speed between each node in the intersection area with nodes A and B is a random variable. Thus, there are n random variables for the relative speed of nodes, where their PDF and CDF are $f_{Vr}(v)$ and $F_{Vr}(v)$, respectively. CDFs ($F_{Vm}(v)$ and $F_{Vx}(v)$) and PDFs ($f_{Vm}(v)$ and $f_{Vx}(v)$) of the minimum relative speed (Vm) and maximum relative speed (Vx) are expressed as follows [38]:

$$\begin{aligned} F_{Vm}(v) &= P\left(\underset{1\leq i\leq n}{\text{MIN}}\, Vm_i \geq v\right) = \prod_{i=1}^{n} P(Vr \geq v) \\ &= [P(Vr \geq v)]^n = [1 - P(Vr \leq v)]^n \\ &= [1 - F_{Vr}(v)]^n \\ f_{Vm}(v) &= \frac{dF_{Vm}(v)}{dv} = n \cdot [1 - F_{Vr}(v)]^{n-1} \cdot f_{Vr}(v) \end{aligned} \tag{6}$$

$$F_{Vx}(v) = P\left(\underset{1\le i\le n}{\text{MAX}} Vx_i \le v\right) = \prod_{i=1}^{n} P(Vr \le v) = [P(Vr \le v)]^n = [F_{Vr}(v)]^n$$

$$f_{Vx}(v) = \frac{dF_{Vx}(v)}{dv} = n \cdot [F_{Vr}(v)]^{n-1} \cdot f_{Vr}(v) \quad (7)$$

The expected values for maximum and minimum relative speed, $E(Vx)$ and $E(Vm)$, respectively, are computed numerically using the following:

$$E(Vm) = \int_0^{2V_e} v \cdot f_{Vm}(v) \quad (8)$$

$$E(Vx) = \int_0^{2V_e} v \cdot f_{Vx}(v) \quad (9)$$

Figure 8 shows the expected minimum and maximum relative speed versus the increasing number of neighbor nodes n in the intersection area. n is varied between 2 and 10, whereas $Vmax$ is set to 10 or 20 m/s. As shown in Figure 8, increasing n by 1 increased $E(Vx)$ by 1.8% on average, and decreased $E(Vm)$ by 2.3% on average. This is because increasing n increases the probability to find a node with more maximum relative speed or less minimum relative speed. In addition, as can be seen from Figure 8, increasing the maximum speed of nodes increased the expected minimum and maximum relative speed. However, compared to n, changing $Vmax$ has more significant effects on the expected minimum and maximum relative speed.

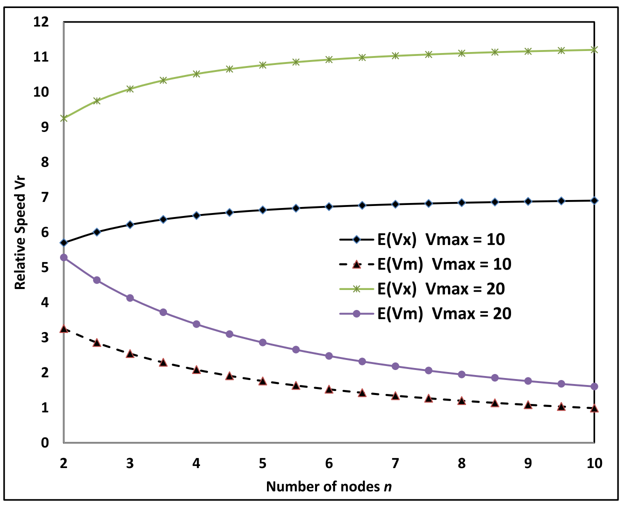

FIGURE 8. Bounds of the relative speed versus different number of neighbor nodes.

C. PATH LENGTH

As explained above and shown in Figure 9, if two-hop apart nodes $N1$ and $N2$ try to communicate, they must use an intermediate node, such as $N3$, located in the intersection area between $N1$ and $N2$ to forward traffic between them. The link stability between $N1$ and $N2$ depends on the time T needed by the intermediate node $N3$ to pass through the intersection area. Compared to the network area size, the size of the intersection area is small. Therefore, we presume that the intermediate node does not change its direction inside the intersection area. As a result, the time to pass the intersection area T can be computed as

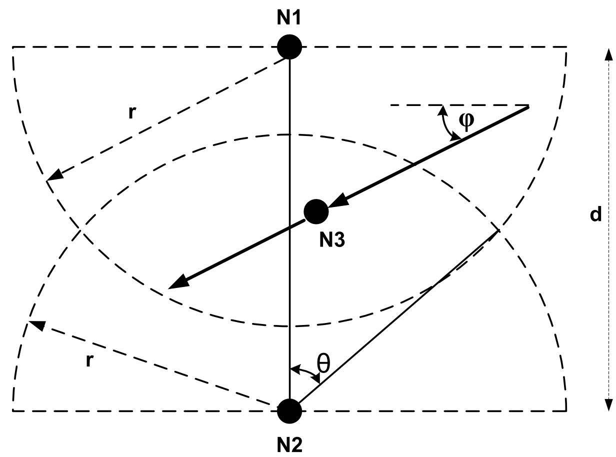

FIGURE 9. Entry angle in the intersection area.

$$T = \frac{L}{V_r}$$

where L is the length of the path that the intermediate node ($N3$) passes through in the intersection area, and V_r is the relative speed between node $N3$ and node $N1$ or $N2$. L depends on the distance between two-hop apart nodes d, the transmission range r, and the entry angle φ of the intermediate node to the intersection area shown in Figure 9. As explained in [7], the path length L can be computed by the following:

$$L(\varphi) = \begin{cases} 2r - d\cos(\varphi) & 0 \le \varphi < \theta \\ \sqrt{4r^2 - d^2} sin(\varphi) & \theta \le \varphi \le \frac{\pi}{2} \end{cases} \quad (10)$$

where $\theta = ArcCos\left(\frac{d}{2r}\right)$

The CDF of L can be expressed as:

$$F_L(l) = P(L \le l)$$

According to Equation 10, the distribution of $F_L(l)$ can be decomposed into two cases:

Case 1: $\mathbf{0 \le \varphi < \theta}$

$$F_L(l) = P(L \le l) = P(2r - d\cos(\varphi) \le l) = P\left(\varphi \le ArcCos\left(\frac{2r - l}{d}\right)\right) \quad (11)$$

Because of horizontal and vertical symmetry, entry angle φ is uniformly distributed in the range $[0, \pi/2]$. Similar to ρ, the probability density function $f_\varphi(\mu)$ and cumulative distribution function $F_\varphi(\mu)$ of φ can be expressed as follows:

$$f_\varphi(\mu) = \frac{2}{\pi}$$

$$F_\varphi(\mu) = P(\varphi \le \mu) = \frac{2\mu}{\pi} \quad (12)$$

By plugging Equation 12 into Equation 11, CDF of L is derived as

$$F_L(l) = P(L \le l) = \frac{2}{\pi} ArcCos\left(\frac{2r-l}{d}\right)$$

By definition, the PDF of the path length is expressed as

$$f_L(l) = \frac{dF_L(l)}{dl} = \frac{2}{\pi\sqrt{d^2 - (2r\text{-}l)^2}}$$

where $2r - d < l < \frac{4r^2-d^2}{2r}$

Case 2: $\boldsymbol{\theta} \le \boldsymbol{\varphi} < \boldsymbol{\pi}$

$$F_L(l) = P(L \le l) = P\left(\sqrt{4r^2-d^2}\sin(\varphi) \le l\right)$$
$$= P\left(\varphi \le ArcSin\left(\frac{l}{\sqrt{4r^2-d^2}}\right)\right)$$

From Equation 12, we get

$$F_L(l) = \frac{2}{\pi} ArcSin\left(\frac{l}{\sqrt{4r^2-d^2}}\right)$$

As a result, for this case, the PDF of the path length is given by

$$f_L(l) = \frac{dF_L(l)}{dl} = \frac{2}{\pi\sqrt{4r^2-l^2-d^2}}$$

where $\frac{4r^2-d^2}{2r} \le l < \sqrt{4r^2-d^2}$

Therefore, the CDF and PDF of L are as follows:

$$f_L(l) = \begin{cases} \frac{2}{\pi\sqrt{d^2-(l-2r)^2}} L_{min} < l < L_{th} \\ \frac{2}{\pi\sqrt{4r^2-l^2-d^2}} L_{th} \le l < L_{max} \end{cases} \quad (13)$$

$$F_L(l) = \begin{cases} \frac{2}{\pi} ArcCos\left(\frac{2r-l}{d}\right) L_{min} < l < L_{th} \\ \frac{2}{\pi} ArcSin\left(\frac{l}{\sqrt{4r^2-d^2}}\right) L_{th} \le l < L_{max} \end{cases} \quad (14)$$

where $L_{min} = 2r - d$, $L_{max} = \sqrt{4r^2-d^2}$, and $L_{th} = \frac{4r^2-d^2}{2r}$. The expected value of the distance L is computed as

$$E(L) = \int_{L_{min}}^{L_{max}} l \cdot f_L(l)\,dl$$
$$= \int_{L_{min}}^{L_{th}} \frac{2l}{\pi\sqrt{d^2-(l-2r)^2}} dl$$
$$+ \int_{L_{th}}^{L_{max}} \frac{2l}{\pi\sqrt{4r^2-l^2-d^2}} dl$$
$$= \frac{4r}{\pi} \cdot ArcTan\left(\frac{d}{\sqrt{4r^2-d^2}}\right) - \frac{d}{2\pi r}\sqrt{4r^2-d^2}$$

Figure 10 shows the PDF of the path length L, where $r = 250$ or 300 m, and $d = 350$ or 500 m. As shown in Figure 10, the path length has the lowest probability around L_{th}. Decreasing or increasing L over L_{th} increases the pdf. In addition, Figure 10 shows that increasing the transmission range increases the probability of $L > L_{th}$, and decreases the probability of $L < L_{th}$. This is due to increasing of the size of the intersection area because of increasing transmission range, which reduces the probability of small path length and increases the probability of large path length.

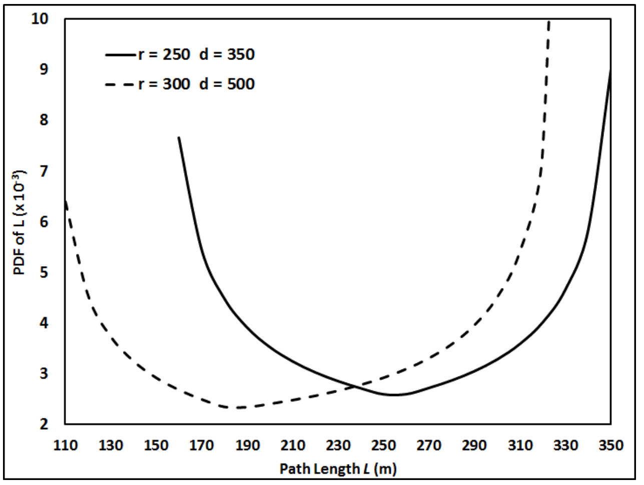

FIGURE 10. PDF of the path length L.

Figure 11 depicts the expected path length versus the transmission range, where the side length of the network area $W = 1000$ or 2000 m. It is apparent from this figure that the higher the transmission range the higher the expected path length. In addition, it shows that decreasing the size of the network area increases the expected path length. This is because increasing the transmission range or decreasing the network area size increases the size of the intersection area, which increases $E(L)$.

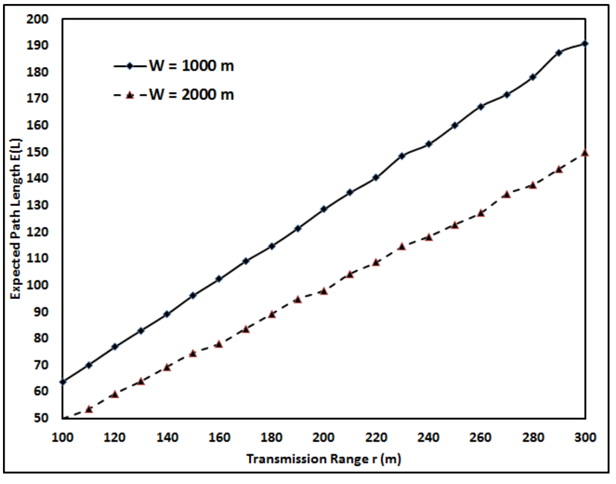

FIGURE 11. Expected path length versus the transmission range.

If there are n nodes in the intersection area, one of these nodes has the minimum path length (L_m), and another one has the maximum path length (L_x). If L_i is a path length of a node i. We can consider the path lengths L_i to L_n as a set of random variables with probability density function $f_L(l)$. Therefore, the PDF and CDF of the minimum and maximum value of the random variable L can be derived as

$$F_{Lm}(l) = P\left(\underset{1\le i\le n}{\text{MIN}}\, Lm_i \ge l\right) = \prod_{i=1}^{n} P(L\ge l) = [P(L\ge l)]^n = [1-P(L\le l)]^n = [1-F_L(l)]^n$$

$$f_{Lm}(l) = \frac{dF_{Lm}(l)}{dl} = n\cdot f_L(l)\cdot[1-F_L(l)]^{n-1}$$

$$F_{Lx}(l) = P\left(\underset{1\le i\le n}{\text{MAX}}\, Lx_i \ge l\right) = \prod_{i=1}^{n} P(L\le l) = [P(L\le l)]^n = [F_L(l)]^n$$

$$f_{Lx}(l) = \frac{dF_{Lx}(l)}{dl} = n\cdot f_L(l)\cdot[F_L(l)]^{n-1}$$

By plugging Equations 13 and 14 into the last equations, we get

$$f_{Lm}(l) = \begin{cases} f^1_{Lm}(l) & L_{min} < l < L_{th} \\ f^2_{Lm}(l) & L_{th} \le l < L_{max} \end{cases} \tag{15}$$

where

$$f^1_{Lm}(l) = \frac{2n}{\pi\sqrt{d^2-(l-2r)^2}}\left[1-\frac{2}{\pi}ArcCos\left(\frac{2r-l}{d}\right)\right]^{n-1}$$

$$f^2_{Lm}(l) = \frac{2n}{\pi\sqrt{4r^2-l^2-d^2}} \times \left[1-\frac{2}{\pi}ArcSin\left(\frac{l}{\sqrt{4r^2-d^2}}\right)\right]^{n-1}$$

$$f_{Lx}(l) = \begin{cases} f^1_{Lx}(l) L_{min} < l < L_{th} \\ f^2_{Lx}(l) L_{th} \le l < L_{max} \end{cases} \tag{16}$$

where

$$f^1_{Lx}(l) = \frac{2n}{\pi\sqrt{d^2-(l-2r)^2}}\left[\frac{2}{\pi}ArcCos\left(\frac{2r-l}{d}\right)\right]^{n-1}$$

$$f^2_{Lx}(l) = \frac{2n}{\pi\sqrt{4r^2-l^2-d^2}}\left[\frac{2}{\pi}ArcSin\left(\frac{l}{\sqrt{4r^2-d^2}}\right)\right]^{n-1}$$

In Figure 12, the expected minimum and maximum path length are plotted versus the increasing value of the transmission range. As shown in Figure 12, increasing the transmission range from 100 m to 300 m increased the minimum and maximum path length by 215% and 197%, respectively. This shows the great impact of transmission range on the bounds and the expected value of the path length.

D. BOUNDS OF LINK AND ROUTE LIFETIME

As explained above, for two-hop apart nodes, one of the nodes in the intersection area is used as a router to forward traffic. The link lifetime T is the duration of time that the router spends in the intersection area. The link lifetime is evaluated as $T = L/V_r$, where L is the path length in the intersection area, and V_r is the relative speed of nodes. L and V_r are statistically independent random variables [9]. Therefore, as explained in [39], their joint PDF can be expressed as

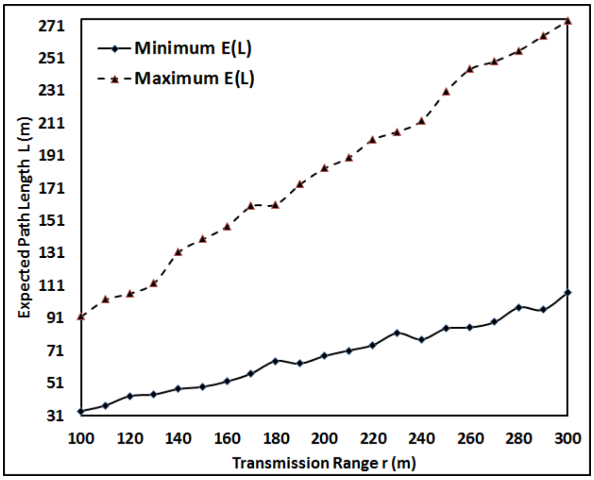

FIGURE 12. Expected minimum and maximum path length versus the transmission range.

$$f_T(t) = \int_{-\infty}^{\infty} |J|\cdot f_L(t\cdot v)\cdot f_{V_r}(v)\,dv$$

where $|J|$ is the Jacobian transformation, which equals to $|J| = |dl/dt| = v$. By substitution into the last equation, we obtain

$$f_T(t) = \int_0^{2V_e} v\cdot f_L(t\cdot v)\cdot f_{V_r}(v)\,dv$$

By plugging Equations 5 and 13 into the last equation, we obtain

$$f_T(t) = \begin{cases} f^1_T(t) t_{min} < t < t_{th} \\ f^2_T(t) t_{th} \le t < t_{min} \end{cases}$$

where

$$f^1_T(t) = \int_0^{2V_e} \frac{2}{\pi\sqrt{d^2-(t\cdot v-2r)^2}}\frac{2}{\pi\sqrt{4V_e^2-v^2}}dv = \frac{2}{\pi^2 t}ln\left(1+\frac{4tV_e\sqrt{4r^2-d^2}}{4V_e^2t^2+d^2-4r^2}\right)$$

$$f^2_T(t) = \int_0^{2V_e} \frac{2}{\pi\sqrt{4r^2-t^2v^2-d^2}}\frac{2}{\pi\sqrt{4V_e^2-v^2}}dv = \frac{2\sqrt{(d+2r)}}{t\sqrt{d-2r}\sqrt{d^2-(2r-2V_e\cdot t)^2}} + \frac{2(d+2r)}{2\sqrt{V_e t}\sqrt{d^2-(2r-2V_e\cdot t)^2}}$$

$$t_{min} = \frac{\sqrt{4r^2-d^2}}{E(Vx)}$$

$$t_{th} = \frac{4r^2-d^2}{2r\cdot E(Vr)}$$

$$t_{max} = \frac{2r-d}{E(Vm)}$$

The CDF of T and the expected link lifetime can be computed as

$$F_T(t) = \int_{t_{min}}^{t_{max}} f_T(t)\,dt = \int_{t_{min}}^{t_{max}} \left(f_T^1(t) + f_T^2(t)\right) dt$$
$$E(T) = \int_{t_{min}}^{t_{max}} t \cdot f_T(t)\,dt = \int_{t_{min}}^{t_{max}} t \cdot \left(f_T^1(t) + f_T^2(t)\right) dt$$

Next, the expected route lifetime is derived. Suppose that there is a multihop route between a source node N_s and a destination nodes N_d, where the route consists of h hops, the number of links that forward the traffic between N_s and N_d is h. If one of the h links between N_s and N_d fails, the connection between N_s and N_d is terminated. Therefore, the routing protocol at the source has to build a new connection between the source and destination by searching for new good links. From h links, the link with the minimum lifetime is the first link to break in the route. Therefore, the expected route lifetime is the expected minimum link lifetime $E(T_h)$ from h links.

To compute $E(T_h)$, we need to derive $f_{T_h}(t)$, which is the PDF of the minimum link lifetime. $f_{T_h}(t)$ represents the PDF of the minimum of h random variables, which can be derived as follows [38]:

$$\begin{aligned} F_{T_h}(t) &= P\left(\underset{1\le i\le h}{\text{MIN}}\, T_{h_i} > t\right) \\ &= \prod_{i=1}^{h} P(T > t) = [P(T > t)]^h \\ &= [1 - P(T \le t)]^h = [1 - F_T(t)]^h \end{aligned} \quad (17)$$

$$f_{T_h}(t) = \frac{dF_{T_h}(t)}{dt} = h \cdot f_T(t) \cdot [1 - F_T(t)]^{h-1} \quad (18)$$

Therefore, the expected route lifetime is expressed as

$$E(T_h) = \int_{t_{min}}^{t_{max}} t \cdot f_{T_h}(t)\,dt \quad (19)$$

For a network configuration, if the number of hops h is known, Equations 18 and 19 are used to compute the expected route lifetime $E(T_h)$. The number of hops depends on the network area size, the number of nodes, the transmission range, and the mobility model. If N nodes move in a square area with side length W according to the RWP mobility model, the expected number of hops is analytically evaluated using our algorithm introduced in [36], [37].

Finally, expressions for the minimum and maximum expected route lifetime are derived. The PDF of the minimum link lifetime $f_{T_m}(t)$ represents the probability that the node with the minimum path length has the maximum relative speed. $f_{T_m}(t)$ is expressed as

$$f_{T_m}(t) = \int_0^{2V_e} v \cdot f_{L_m}(t \cdot v) \cdot f_{Vx}(v)\,dv \quad (20)$$

As explained above, $f_{L_m}(l)$ is the PDF of the minimum path length of the nodes located in the intersection area. By substituting from Equations 7 and 15 into Equation 20, we get

$$f_{T_m}(t) = \begin{cases} f_{T_m}^1(t) & t_{min} < t < t_{th} \\ f_{T_m}^2(t) & t_{th} \le t < t_{min} \end{cases}$$

where

$$\begin{aligned} f_{T_m}^1(t) &= \int_0^{2V_e} v \cdot f_{L_m}(t \cdot v) \cdot f_{Vx}(v)\,dv \\ &= \int_0^{2V_e} \left[\begin{array}{l} \dfrac{2n \cdot v}{\pi\sqrt{d^2 - (t \cdot v - 2r)^2}} \\ \cdot \left[1 - \frac{2}{\pi} ArcCos\left(\dfrac{2r - t \cdot v}{d}\right)\right]^{n-1} \\ \cdot \dfrac{2n \cdot v}{\pi\sqrt{4V_e^2 - v^2}} \left[\dfrac{2}{\pi} ArcSin\left(\dfrac{v}{2V_e}\right)\right]^n \end{array} \right] dv \end{aligned}$$

$$\begin{aligned} f_{T_m}^2(t) &= \int_0^{2V_e} v \cdot f_{L_m}(t \cdot v) \cdot f_{Vx}(v)\,dv \\ &= \int_0^{2V_e} \left[\begin{array}{l} \dfrac{2n \cdot v}{\pi\sqrt{4r^2 - (t \cdot v)^2 - d^2}} \\ \cdot \left[1 - \dfrac{2}{\pi} ArcSin\left(\dfrac{t \cdot v}{\sqrt{4r^2 - d^2}}\right)\right]^{n-1} \\ \cdot \dfrac{2n \cdot v}{\pi\sqrt{4V_e^2 - v^2}} \left[\dfrac{2}{\pi} ArcSin\left(\dfrac{v}{2V_e}\right)\right]^n \end{array} \right] dv \end{aligned}$$

The cumulative distribution function and the expected value of the minimum link lifetime $F_{T_m}(t)$ is expressed as

$$F_{T_m}(t) = \int_{t_{min}}^{t_{max}} f_{T_m}(t)\,dt$$
$$E(T_m) = \int_{t_{min}}^{t_{max}} t \cdot f_{T_m}(t)\,dt$$

The PDF of the minimum link lifetime in one intersection area $f_{T_m}(t)$ is used to derive expressions for the minimum route lifetime. As explained above, if the route length is h hops, the PDF of the minimum route lifetime $f_{T_M}(t)$ represents the probability of the minimum link lifetime of h links, which can be computed as follows:

$$\begin{aligned} F_{T_M}(t) &= [P(T_M \ge t)]^h = \left[1 - F_{T_m}(t)\right]^h \\ f_{T_M}(t) &= h \cdot f_{T_M}(t) \cdot \left[1 - F_{T_m}(t)\right]^h \end{aligned} \quad (21)$$

As a result, the expected minimum route lifetime $E(T_M)$ is derived as

$$E(T_M) = \int_{t_{min}}^{t_{max}} t \cdot f_{T_M}(t)\,dt \quad (22)$$

In a similar way, The PDF, CDF and expected value of the maximum route lifetime; $f_{T_X}(t)$, $F_{T_X}(t)$ and $E(T_X)$, respectively, are derived as

$$f_{T_x}(t) = \int_0^{2V_e} v \cdot f_{L_x}(t \cdot v) \cdot f_{Vm}(v)\,dv$$
$$F_{T_x}(t) = \int_{t_{min}}^{t_{max}} f_{T_x}(t)\,dt$$
$$\begin{aligned} F_{T_X}(t) &= [P(T_X \ge t)]^h = \left[1 - F_{T_x}(t)\right]^h \\ f_{T_X}(t) &= h \cdot f_{T_x}(t) \cdot \left[1 - F_{T_x}(t)\right]^{h-1} \end{aligned} \quad (23)$$
$$E(T_X) = \int_{t_{min}}^{t_{max}} t \cdot f_{T_X}(t)\,dt \quad (24)$$

V. VALIDATION AND PERFORMANCE EVALUATION

In this section, the proposed analytical model is validated by comparing the analytical and simulation results. Simulation experiments are performed using ns-3 [40]. Important simulation parameters are shown in Table 1. For all simulation scenarios, all nodes move according to the random waypoint mobility model, where the speed of nodes is chosen randomly from *Vmin* to *Vmax* m/s. For all mobility scenarios, nodes start to move at the start of the simulation and do not stop until the end of the simulation. The source-destination pairs are chosen randomly over the network where Constant Bit Rate (CBR) traffic sources are used. The number of CBR sources is equal to the number of nodes, where the destinations are randomly chosen. Identical mobility scenarios and traffic patterns are used across simulation scenarios to achieve a fair comparison. The simulation time is set at 1100s. Results of the first 100s are discarded in order to be sure that the network has reached the steady state. All simulation results are obtained with 95% confidence interval and a relative error less than 5%.

TABLE 1. Simulation parameters.

Simulation Parameter	Value
Simulation time	1100 s
Start Measuring Time	100 s
Number of nodes	20–120
Network area side length	800–1200 m
Radio Type	802.11 a/g
Data Rate	8 Mb/s
Transmission Range	100–300 m
Mobility Model	Random waypoint
Node Speed	1–20 m/s
Pause Time	0 s
Routing Protocol	Ad hoc On-demand Distance Vector
Traffic Type	CBR
Packet Size	512 bytes

To validate the proposed model, many network simulation scenarios were conducted. First, the PDF of the link lifetime is investigated. The transmission range is set at 200 or 220 m, where $Vmax = 20$ m/s, $Vmin = 1$ m/s, $W = 1000$ m, and $N = 100$. Figure 13 shows the simulation results (labelled "Sim.") and analytical results (labelled "Ana.") for this scenario. As can be seen from the figure, the probability increases with increasing the link lifetime, and then it starts to decrease. This conversion point with the highest probability is at $T = t_{th}$. Since $T = L/V$, small T results from small L and/or larger V. As shown in Figures 7 and 10, the probability of small L and the probability of large V are high. Therefore, the probability of small T is high. On the other hand, the probability of large L is high, whereas the probability of small V is very low. As a result, the probability of large T is low.

Next, the analytical and simulation results of the PDF of the route lifetime are compared. The transmission range is set at 100 or 150 m, where $Vmax = 20$ m/s, $Vmin = 1$ m/s, $W = 1000$ m, and $N = 100$. Figure 14 shows the results of this scenario. As shown in Figures 13 and 14, for $t < t_{th}$, increasing the transmission range decreases the probability of the route lifetime. On the contrary, for $t > t_{th}$, increasing the transmission range increases the probability of the route lifetime. This is because increasing the transmission range increases the intersection area size. As a result, as shown in Figure 10, the probability of small path length decreases,

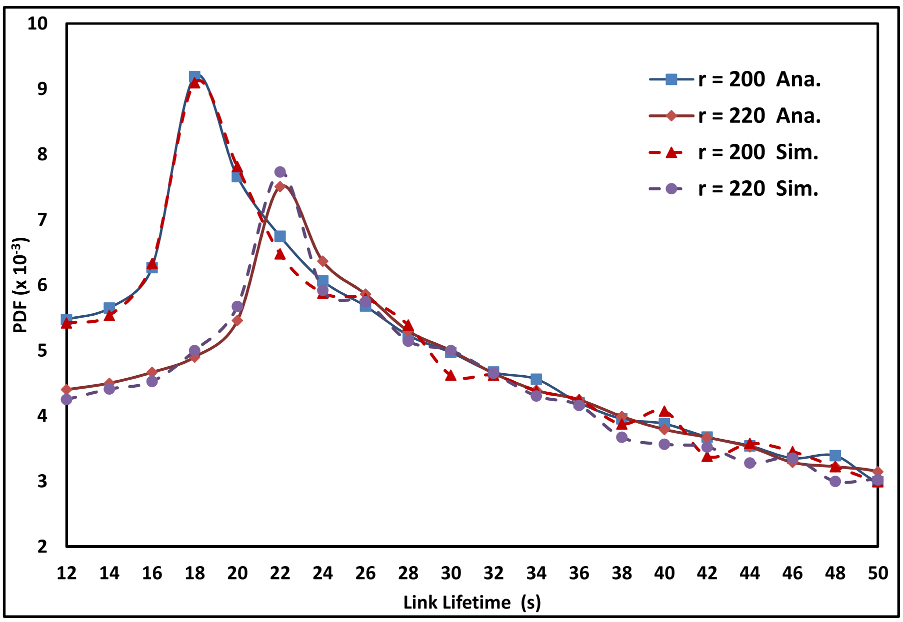

FIGURE 13. PDF of the link lifetime.

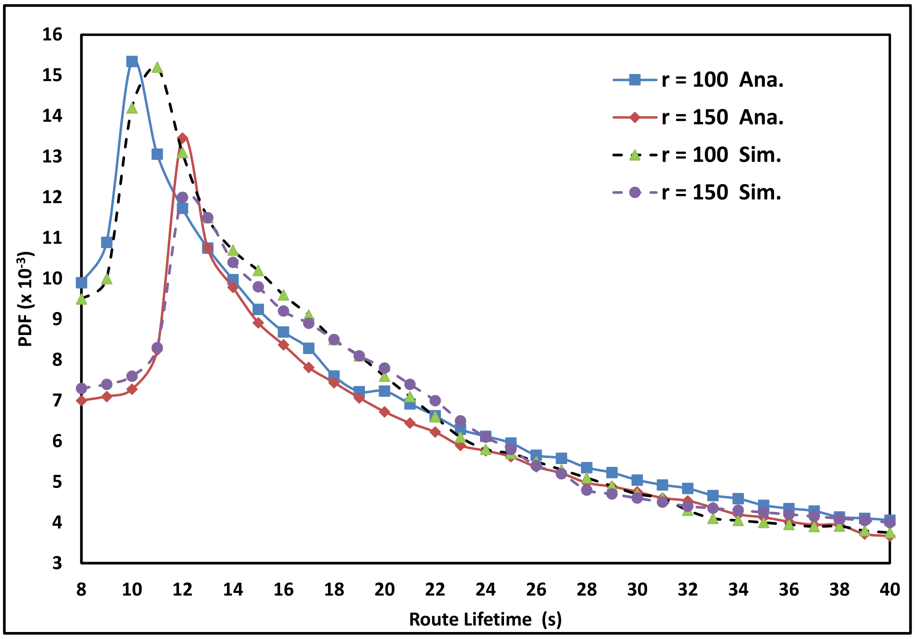

FIGURE 14. PDF of the route lifetime.

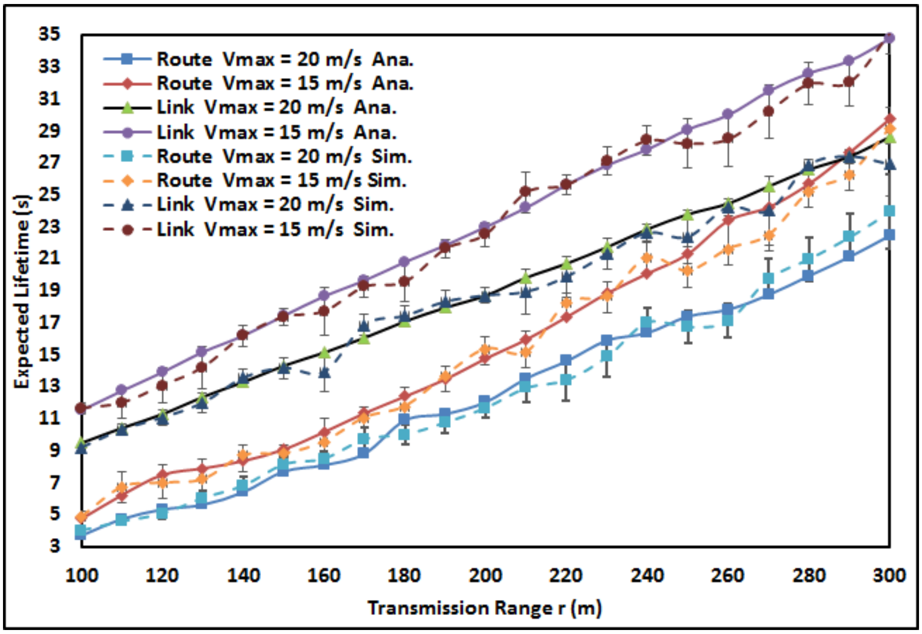

FIGURE 15. Expected link and route lifetime.

which decreases the probability of small link and route lifetime. On the other hand, as shown in Figure 10, increasing the size of the intersection area increases the probability of large path length, which increases the probability of large link and route lifetime.

In the next simulation experiment, we measured the expected link and route lifetime. This experiment investigates the effect of varying the transmission range and the maximum speed on the expected link and route lifetime. Figure 15 shows the analytical and simulation results of this experiment. In Figure 15, the expected link and route lifetime are plotted versus increasing values of the transmission range; from 100 to 300 m. Two cases were considered. In the first case, we considered $Vmax = 20$ m/s, labelled as "Route $Vmax = 20$ m/s" and "Link $Vmax = 20$ m/s", for the expected route and link lifetime, respectively. In the second case we considered $Vmax = 15$ m/s.

From Figure 15, we can notice the significant effect of the transmission range and maximum speed on the expected route and link lifetime. The higher the transmission range the higher the expected link and route lifetime. Increasing the transmission range increases the size of the intersection area, which increases the expected path length that consequently increases the link lifetime. Moreover, the growth of the transmission range reduces the expected number of hops between any source and destination, which increases the route lifetime. Figure 15 shows that the higher the maximum speed of nodes the lower the expected link and route lifetime due to increasing the expected speed of nodes. The vertical bars shown in Figure 15 are the error bars for 95% confidence interval. As can be seen in Figure 15, analytical results are within the confidence interval of the simulation results. This reveals the accuracy of analytical results compared to simulation results. The average relative error in analytical results of the route lifetime is relatively larger than that of the link lifetime. This is because of dependency and accumulation of errors for consecutive hops. In the next scenario, we study the effects of the network area size and the number of nodes N on the expected route lifetime. The number of nodes in the network varies between 20 and 120 nodes. The side length of the network area size is set at $W = 800$ or 1200 m, whereas the transmission range of any node is fixed at 150 m, $Vmax =$ 20 m/s, and $Vmin = 1$ m/s. Figure 16 depicts analytical and simulation results of this scenario. The vertical bars shown in Figure 16 are the error bars for 95% confidence interval. As shown in this figure, the analytical results are within the confidence interval of the simulation results. This indicates that the proposed analysis provides precise predictions for the route lifetime. From the results shown in Figure 16, we can observe that increasing the network area size has more significant effects on the expected route lifetime than increasing the number of nodes. For this scenario, for a fixed number of nodes, increasing the side length of the network area from 800 to 1200 m decreased the route lifetime by 21.5% on average. On the other hand, raising the number of nodes in the network from 20 to 120 increased the route lifetime by 11.3% on average. Increasing the size of the network area increases the number of hops and the distance between two-hop apart nodes, which both have negative effects on the link and route lifetime. However, as explained in [35], increasing the number of nodes in the network increases the number of neighbor nodes, which modestly decreases the number of hops, which in turn modestly increases the route lifetime.

In the last validation experiment, the upper and lower bounds of the expected route lifetime are investigated. In this experiment, the transmission range is varied from 100 to 300 m, where other parameters are set as follows; $W = 1000$ m, $N = 100$, $Vmin = 1$ m/s, and $Vmax =$ 20 m/s. For different transmission ranges, the minimum and maximum route lifetime are measured. In simulations, the minimum or maximum route lifetime is measured for each route and are averaged over all routes. The simulation and analytical results are shown in Figure 17. It can be seen from Figure 17 that increasing the transmission range from 100 to 300 m increased the minimum and maximum route lifetime by 63.6% and 87.1%, respectively. As explained in Section IV-B and IV-C, increasing the transmission range has a significant effect on increasing the expected minimum and maximum path length. However, it doesn't have much effect on the expected minimum and maximum speed. As a result, increasing the transmission range increases the expected minimum and maximum route lifetime.

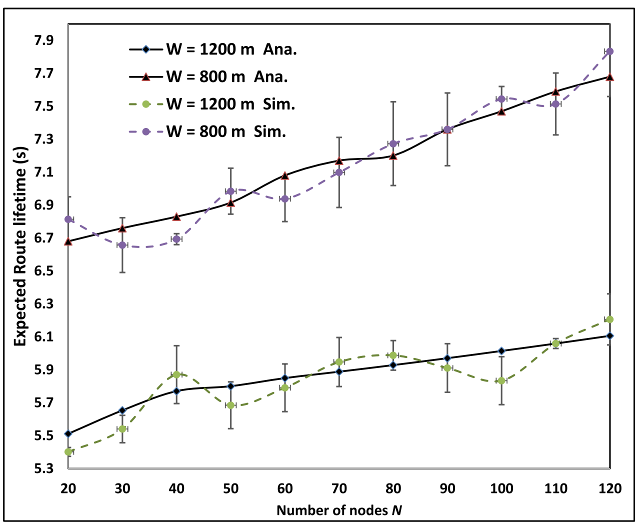

FIGURE 16. Expected route lifetime versus the number of nodes.

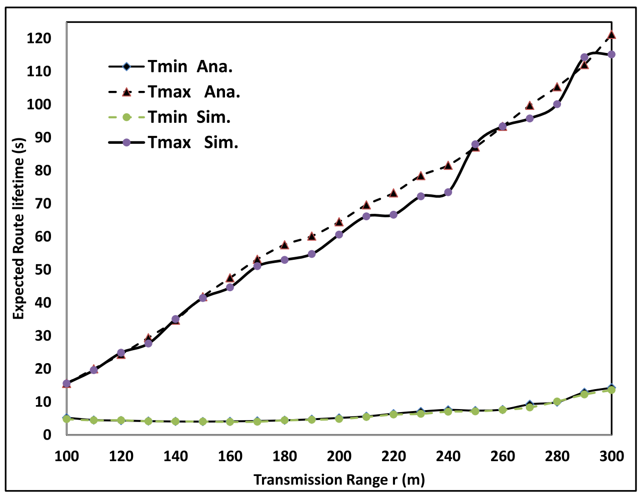

FIGURE 17. Bounds of the route lifetime.

VI. CONCLUSION AND FUTURE WORK

In this work, we introduced a closed-from analytical model to investigate the behavior of the link and route lifetime in mobile multihop networks with the random waypoint mobility model. The proposed model captures the effects of most network characteristics including the distance between nodes, the number of nodes in the network, the size of the network area, the maximum and minimum speed of nodes, and the transmission range. First, we derived expressions for the expected value of the distance between two-hop apart nodes. Then, we developed expressions for the probability density function, average, and expected minimum and maximum relative speed of nodes. After that, the probability density functions of the expected, minimum, and maximum path length were developed. Finally, the derived expressions were used to express the probability density function, average, and the expected minimum and maximum link and route lifetime. The analytical results were validated using extensive simulations using ns-3. The results showed that the transmission range, network area size, and speed of nodes have more significant effects on the route lifetime compared to the node density. In addition, in practice, to increase the network or route lifetime, we should increase the transmission range. However, this increases the interference from neighbor nodes that reduces the network throughput. Therefore, our next project will examine how we can optimize the transmission range to maximize the route lifetime and minimize the interference. In addition, the proposed model will be implemented with a routing protocol to analyze and choose routes based on their stability.

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