Telecommun Syst
DOI 10.1007/s11235-011-9501-9

A mobility-based upper bound on route length in MANETs

M. Pascoe · J. Gomez · V. Rangel · M. Lopez-Guerrero · F. Mendoza

Abstract In mobile ad-hoc networks (MANETs) routes are usually found by means of discovery packets that are injected to the network by sender nodes. Once the intended destination is reached by a discovery packet, it replies back to the sender using the same route. 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 connectivity disruptions. Furthermore, the whole process of route discovery breaks down when, due to position changes, the route followed by a discovery packet is useless by the time it reaches the destination. In this paper the conditions leading to this effect are studied and it is shown that they impose a practical limit on how long a route can be. The paper introduces a model to compute an upper bound on route length in MANETs, which is derived from the combination of a route duration model and an access delay model for multi-hop routes. The model was validated by simulations with different network settings. From this model, it was found that the node transmission range, node mobility and total per-hop delays actually define the maximum feasible number of hops in a route. To the best of the authors' knowledge, this is a fundamental scaling problem of mobile ad-hoc networks that has not been analyzed before from a mobility-delay perspective.

Keywords MANETs · Mobility · Maximum route length · Network size

1 Introduction

A mobile ad-hoc network (MANET) consists of a collection of mobile nodes connected by wireless links. In these networks, nodes are free to move and organize without involving any infrastructure or centralized administration. Due to the limited transmission range of their wireless radio transceivers, there may be a need for intermediate relay nodes to establish a communication path between source-destination pairs. This is illustrated in Fig. 1 where we can observe that, due to the fact that each node has a limited transmission radius R, a route from a source node S to a destination node D requires several relaying nodes. In this scenario, 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 the route discovery and route maintenance procedures. In *proactive* routing, routes from one node to all the others in the network are discovered and maintained even when not needed. For *reactive* routing, nodes discover a route only when needed, ordinarily by flooding the entire network with control packets. Reactive protocols generally exhibit higher

M. Pascoe (✉) · M. Lopez-Guerrero
Department of Electrical Engineering, Metropolitan Autonomous University, Mexico City, Mexico
e-mail: mpascoe@xanum.uam.mx

M. Lopez-Guerrero
e-mail: milo@xanum.uam.mx

J. Gomez · V. Rangel · F. Mendoza
Department of Electrical Engineering, National Autonomous University of Mexico, Mexico City, Mexico

J. Gomez
e-mail: javierg@fi-b.unam.mx

V. Rangel
e-mail: victor@fi-b.unam.mx

F. Mendoza
e-mail: fortunato.mendoza@comunidad.unam.mx

Published online: 15 June 2011

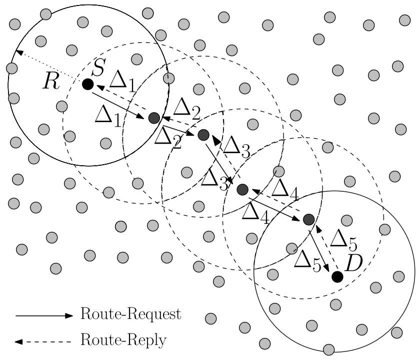

Fig. 1 Multi-hop routing in MANETs

latency compared to proactive protocols. However, they usually generate less signaling and are preferably used in many practical scenarios. Due to this reason in this paper we focus on reactive unicast routing protocols such as DSR [17] and AODV [29].

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 previously 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. The route discovery procedure goes through the following phases. When node S attempts to send data packets to node D, it disseminates control packets across the entire the network. This 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. It is worth mentioning that control and data packets experience queueing and processing delays, channel contention, transmission and propagation latencies at each relaying node. Let us consider a total per-hop delay composed of such delays. Denote these delays by Δ_i, where index i represents the i-th hop of the route. In spite of these delays and under some conditions (e.g., absence of transmission errors and full network connectivity), at least one route-request packet will reach node D at a later time. Let us denote the direction of the data flow from node S to node D by $S \to D$. When node D receives the route request, it sends a route-reply packet back to node S using the same route; but in the opposite direction, i.e., $D \to S$. *From the source perspective*, the route between S and D will be completely established only when node S receives the route-reply packet from node D. However, due to node mobility, this route may soon fail at some point, thus preventing the route-reply packet from reaching node S. This is a fundamental issue in the route discovery process for reactive routing protocols. This situation is illustrated in Fig. 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 one of the intermediate nodes changes its position, thus leading to connectivity loss and therefore a route failure, the reply may not be able to reach node S.

At this point, the operation of the routing protocol collapses because route segments fail before the end-to-end route can be discovered. This situation is exacerbated in a long route since the longer the time it takes to create it, the more likely one of its segments will fail before its discovery is completed. Based on this observation, we can assume the existence of an upper limit on route length for wireless ad-hoc networks with mobility.

In this paper we study the scaling of MANETs as a result of the interaction between delay and mobility. We show that the interplay of these factors results in a practical limit on the number of hops that can be connected in order to create a route. Up to the authors' best knowledge, this is a fundamental scaling problem in ad-hoc networks that has not been looked at before from this perspective. Previous studies related to scaling properties of ad-hoc networks have mostly analyzed the traffic carrying capacity (e.g., [11, 12, 15, 21, 22]). We argue that, for this capacity to be useful, routes must be valid for a time interval that allows a successful packet exchange between any source-destination pair, even if the end nodes are located at the farthest opposite boundaries of the network. To this end, we first depart from an access delay model for single-hop WLAN networks, found in [5], in order to compute a multi-hop delay. Second, we derive a route duration model that considers the delay involved during the route discovery process. By combining both models, we obtain a closed-form expression to compute the maximum length for routes in mobile ad-hoc networks and therefore, the maximum network size.

The rest of the paper is organized as follows. Section 2 summarizes some relevant works found in the literature. Section 3 presents the round trip time and route duration models. Section 4 presents an analysis to obtain the maximum length of routes in mobile ad-hoc networks. Section 5 presents the results obtained by simulation in order to validate the proposed model. Finally, Sect. 6 presents our conclusions.

2 Related work

In this section, we overview some works that can be found in the literature related to the scaling properties of ad-hoc networks from different perspectives.

One issue that has been analyzed is the traffic carrying capacity of wireless networks for unicast or multicast transmissions. For instance, in [15] the authors investigated the traffic carrying capacity at the physical layer for static wireless networks under different conditions. In [13] it was analyzed how mobility increases the traffic carrying capacity of ad-hoc wireless networks. In [21], the authors examined the capacity of wireless ad hoc networks at the MAC layer via both, simulations and analysis from basic principles. In [22], the authors studied the capacity of large-scale random wireless networks. In [11] and [12] it was studied how individual variable-range power control affects the physical and network connectivity, network capacity, and power savings of wireless multi-hop networks. Another subject that has been examined is how some scaling properties of ad-hoc networks affect the performance of routing protocols. Most of these studies were based on simulations, e.g., [4, 20] and [23], under different network conditions, such as the number of contending stations, network size and mobility patterns. However, none of these works considered the existence of an upper bound on network size in mobile ad-hoc networks.

As we argued before, a multi-hop route would be useful for data transfer between any source-destination pair, only if route duration is longer than the time required to exchange packets between the end points. The route duration in MANETs is an issue that has been widely studied in the literature. Available studies on route duration in MANETs fall into two different categories depending on whether the authors followed experimental or analytical methods. Under the experimental category, simulation has been the main method through which route duration properties of mobile ad-hoc networks have been investigated. Simulation-based studies consider several parameters, such as mobility and traffic patterns, number of hops, node density, transmission range and propagation model, among others, e.g., [1, 2] and [16]. Under the analytical category, the literature includes also several studies related to route duration. In general, analytical studies have a limited applicability since they only modeled route duration by considering a limited number of intermediate nodes, e.g., [7] and [14], or few mobility patterns, e.g., [33–36]. From these studies it can be concluded that route length directly affects the route duration time. However, to the best of our knowledge, available studies in the literature consider that the route discovery time is negligible compared to the route lifetime (e.g., [7, 14, 26, 28]). As we have mentioned above, this may not always be the case and, in this paper, we derive a route duration model that considers the delay involved during the route discovery procedure.

Another fundamental aspect for this paper is to find a way to determine the time required for exchanging packets between the end points of a multi-hop route, specially during the route discovery process. Let's summarize some studies related to the delay computation. The authors in [5] introduced a model to compute the average access delay (average service time) due to channel contention and transmission delays for single-hop WLAN networks. This model relies on the one introduced by Bianchi in [3], which provides a way to evaluate the saturation throughput of the IEEE 802.11 MAC protocol under the hypothesis of ideal channel conditions (i.e., absence of hidden stations and transmission errors). There are other works related to the modelling of the access delay on single or multi-hop wireless networks, which are based on Bianchi's work, e.g., [8, 10, 31]. Additionally, in the literature we can find other studies following different approaches in order to provide a model for throughput and access delay in WLANs, e.g., [6, 9, 18, 24, 25, 32]. In [19], the authors presented an analytical model to provide estimates for throughput and end-to-end packet delay in single hop and multi-hop IEEE 802.11 networks under different loading conditions. In our simulations we considered saturated conditions so that we decided to depart from the model found in [5] to compute the access delay in a hop and generalize it to the multi-hop case. This model component and the other ones are described in the following section.

3 Model components

In this section we introduce a model required for the derivation of an upper bound on route length. First, we extend a delay model for single-hop WLAN networks introduced in [5] in order to derive an access delay model for multi-hop routes. This model is necessary to compute the round trip time for a packet traversing a multi-hop route. Related details will be given below. Second, we deduce a route duration model in terms of the number of nodes involved in a multi-hop 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 Sect. 4.

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 between S and D, see Fig. 1. The round trip time depends on many factors including: the data transfer rate of the network links, queueing delays, number of intermediate nodes between source and destination nodes, the amount of traffic in the network and the MAC protocol.

First, let us consider a route formed by a source node (S), a variable number of intermediate nodes and a destination node (D). The number of intermediate nodes, which is represented by N, depends on many factors, such as the distance between source and destination nodes, node transmission range and node density. A packet transfer through this route would experience a delay on each hop, Δ_i, where index i represents the i-th hop of the route from S to D). This delay results from a sum of several latencies: the access delay (due to channel contention, transmission and propagation delays) plus queueing and processing delays on each hop of the route. For a packet exchange between the end points there would be another series of delays on the other direction, i.e. $D \rightarrow S$. By considering that propagation and processing delays are negligible, the total per-hop delay would be $\Delta_i = T_{\Delta_i} + T_{Q_i}$, where terms T_{Δ_i} and T_{Q_i} are the access delay and queueing delay on the i-th hop, respectively. Thus, the round trip time for packets traversing a multi-hop route would be

$$T_{RTT} = \sum_{i=1}^{N+1} \underset{S\rightarrow D}{\Delta_i} + \sum_{i=1}^{N+1} \underset{D\rightarrow S}{\Delta_i} = \sum_{i=1}^{N+1} (\underset{S\rightarrow D}{T_{\Delta_i}} + \underset{S\rightarrow D}{T_{Q_i}}) + \sum_{i=1}^{N+1} (\underset{D\rightarrow S}{T_{\Delta_i}} + \underset{D\rightarrow S}{T_{Q_i}}). \quad (1)$$

The access delay is given by $T_{\Delta_i} = T_{B_i} + T_{S_i}$. Terms T_{B_i} and T_{S_i} are the contention and transmission delays, respectively, which are both random variables. As mentioned before, these variables depend on many factors such as the amount of traffic experienced by each node in the network, the MAC protocol, the data transfer rate of the network links, the distance between source and destination nodes, the packet size, etc. Factor $(N + 1)$ counts the number of hops in a route formed by N intermediate nodes.

Equation (1) can be simplified by presuming that the wireless links on both directions, i.e., $S \rightarrow D$ and $D \rightarrow S$, remain symmetrical during a period of time longer than the round trip time, i.e., the total delays on the forwarding links would be equal to the ones on their corresponding backward links, therefore,

$$T_{RTT} = 2\sum_{i=1}^{N+1} \Delta_i = 2\sum_{i=1}^{N+1} (T_{\Delta_i} + T_{Q_i}). \quad (2)$$

Now, (2) can be further simplified by assuming that transmitted packets experience practically the same average total delay on each hop of the route, $\overline{\Delta}$. Finally, by taking expected values, from (2) we can obtain the average round trip time for a multi-hop route, $\overline{T}_{RTT}$, as follows

$$\overline{T}_{RTT} = 2(N + 1)\overline{\Delta}, \quad (3)$$

where factor $2(N + 1)$ corresponds to the number of hops in a route formed by N intermediate nodes, counted in both directions. Term $\overline{\Delta}$ is the average total per-hop delay, given by $\overline{\Delta} = \overline{T}_{\Delta} + \overline{T}_Q$. Terms $\overline{T}_{\Delta}$ and $\overline{T}_Q$ correspond to the average access delay and the average queueing delay on each hop, respectively. In order to obtain the average per-hop access delay $\overline{T}_{\Delta}$, we propose to use a single-hop access delay model found in [5]. Additionally, we present a method to determine the average queueing delay $\overline{T}_Q$. These model components will be discussed below.

3.1.1 *Average per-hop access delay model*

As mentioned above, we propose to use a model introduced by the authors in [5], in order to compute the average per-hop access delay, $\overline{T}_{\Delta}$, due to channel contention and transmission delays. A packet transmitted by a node will experience this delay in the presence of c contending nodes in a saturated situation (i.e., as soon as a node is able to transmit a packet, another packet is generated). In this paper we focus on IEEE 802.11 MAC 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 a single-hop route is given by [5]:

$$\overline{T}_{\Delta} = \overline{T}_B + \overline{T}_S, \quad (4)$$

where term $\overline{T}_B$ is the average contention time and is given by $\overline{T}_B = \frac{\alpha(W_{\min}\beta-1)}{2q} + \frac{1-q}{q}\overline{T}_C$. 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 $\overline{T}_C = T_{DIFS} + T_{RTS} + T_\sigma$. The terms T_{DIFS} and T_{SIFS} 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 transmission times required by RTS, CTS, H (headers), P (payload or data) and ACK packets, respectively. T_σ is the slot time during which the channel is idle. The slot time is set equal to the time needed to detect the transmission of a packet by any station. It depends on the physical layer, and it takes into account the propagation delay, the time needed to switch from the receiving to the transmitting state and the time to detect the state of the channel at the MAC layer. Additionally, $\alpha = (1 - P_T)T_\sigma + P_T P_S \overline{T}_S + P_T(1 - P_S)\overline{T}_C$ and $\beta = \frac{q-2^m(1-q)^{m+1}}{1-2(1-q)}$, 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 [5] and [3]. The authors in [5] 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.,

$$p \approx \frac{2W_{\min}(c-1)}{(W_{\min}+1)^2 + 2W_{\min}(c-1)}. \tag{5}$$

In (1)–(4), the average per-hop processing times and signal propagation delays are neglected, because these variables are several orders of magnitude lower than the access delay. In contrast, in many cases, queueing delays contribute significantly to total delay. In the next section, we detail how we can compute the average queueing delay for a multi-hop route.

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*, 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 average 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:

$$\overline{T}_Q = \overline{B} \cdot \overline{T}_\Delta + \overline{T}_R, \tag{6}$$

where term $\overline{T}_R$ 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.

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 (6) in (3), we obtain that the average round trip time for multi-hop routes is given by:

$$\overline{T}_{RTT} = 2(N+1)\overline{\Delta}, \tag{7}$$

where $\overline{\Delta} = \overline{T}_\Delta + \overline{T}_Q$ or equivalently $\overline{\Delta} = \overline{T}_\Delta + \overline{B} \cdot \overline{T}_\Delta + \overline{T}_R$.

3.2 Route duration model

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 the last two concepts share the same time origin (i.e., the instant in which the source node sends the initial route request), see Fig. 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:

$$T_{RD} = \begin{cases} T_F - T_D; & T_F \geq T_D \\ 0; & T_F < T_D. \end{cases} \tag{8}$$

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 be impossible to discover

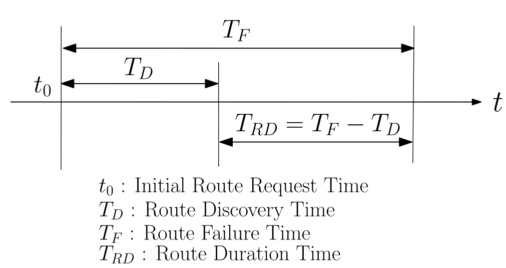

Fig. 2 Time diagram for route discovery, route failure and route duration times

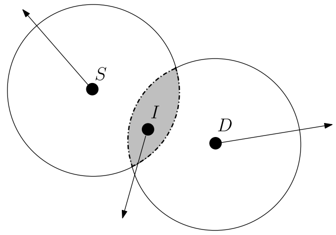

Fig. 3 Route formed by 3 mobile nodes. Nodes' movement is illustrated by *arrows*

it. This definition also assumes that a route can be considered as discovered when the source node acquires the routing information. Once this information is received, even if a route failure occurs, the route maintenance procedure can be started to locally repair any broken link.

As illustrated in Fig. 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 relay 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. 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. 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.

In [28], we 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 [28], we performed an exhaustive data analysis of routes with 3 mobile nodes, as the one shown in Fig. 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:

$$f_T(t) = \sum_{j=1}^{2} \alpha_j e^{-(\frac{t-\beta_j}{\gamma_j})^2} u(t), \tag{9}$$

where parameters α_j, β_j, γ_j, for $j = 1, 2$, can be found by fitting the analyzed data to the previous model. The term $u(t)$ is the unit step function. The expression shown in (9) 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 4a roughly illustrates the PDF given by (9). 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 (9). Finally, in [28], 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 are given in [28].

The route duration model that we set forth in this paper extends the one presented in [28] 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. As we argued above, the route discovery time cannot be ignored when obtaining maximum route length.

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. 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 intuitively clear that the average route discovery time is proportional to the route length. If we assume that each hop experiences the same average total per-hop delay $\overline{\Delta}$ 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 (7) , i.e.,

$$\overline{T}_D = 2(N+1)\overline{\Delta}. \tag{10}$$

The derivation of the route duration model, presented in this paper, differs from other route duration models found in the literature because it considers the total per-hop delays in the computation. In Fig. 4b, we show a route formed by 3 intermediate nodes. It illustrates how route discovery and route duration are affected by these delays. The *clocks* shown in Fig. 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 $2\overline{\Delta}$ 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 (9). Each time shift t_n corresponds to the cumulative average access delay experienced by a packet up to the n-th intermediate node during the route discovery process. These time shifts can be computed as $t_n = n\overline{\Delta}$, for $n = 1, 2, \ldots, N$, see Fig. 4b. Time shifts applied to (9) yields the PDF associated to the new route duration model:

$$f_{T_n}(t) = \sum_{j=1}^{2} \alpha_j e^{-(\frac{(t-t_n)-\beta_j}{\gamma_j})^2} u(t-t_n), \tag{11}$$

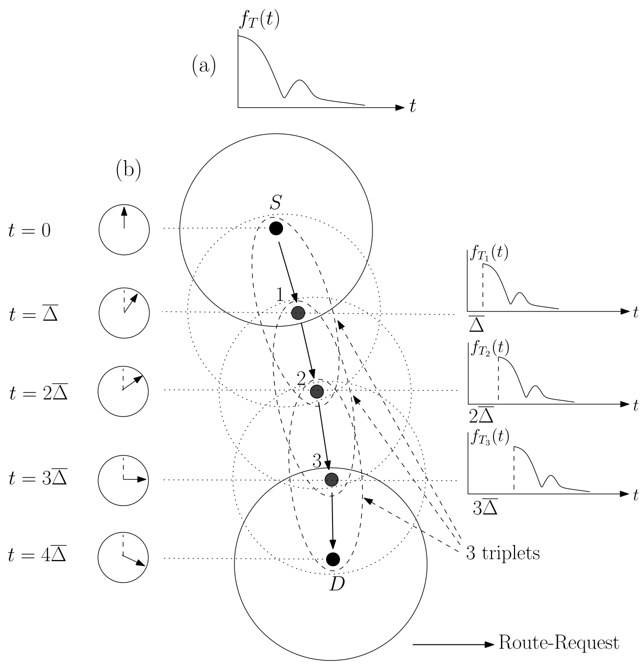

Fig. 4 (**a**) The PDF given by (9). (**b**) Impact of total per-hop delays on route discovery and on route duration

where parameters α_j, β_j, γ_j, for $j = 1, 2$, can be found by the same method, as used before for (9). Term T_n, for $n = 1, 2, \ldots, N$, is a random variable that represents the time that a specific intermediate node remains within its overlapping region, $T_n \geq 0$.

Now, we obtain a closed-form expression that allows us to compute the average route failure time ($\overline{T}_F$). 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 $T_n \leq t$. 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 $T_n > t$ would be given by the complementary cumulative distribution function (CCDF), i.e.,

$$C_{T_n}(t) = P(T_n > t) = 1 - F_{T_n}(t). \tag{12}$$

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 $T_F \leq t$ will be given by:

$$P(T_F \leq t) = 1 - \prod_{n=1}^{N} P(T_n > t), \tag{13}$$

or

$$P(T_F \leq t) = 1 - \prod_{n=1}^{N} C_{T_n}(t) = F_{T_F}(t), \tag{14}$$

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 [27]:

$$\overline{T}_F = \int_0^{\infty} (1 - F_{T_F}(\tau))d\tau. \tag{15}$$

If we replace (14) in (15), we obtain:

$$\overline{T}_F = \int_0^{\infty} \prod_{n=1}^{N} C_{T_n}(\tau)d\tau. \tag{16}$$

Apparently, the integral shown in (16) can only be solved by numerical methods for different values of N. When solving (16) 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, $\overline{T}_F$, could thus be expressed as:

$$\overline{T}_F = \frac{\kappa}{Nv} + \lambda(N+1) \tag{17}$$

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

Finally, if we replace (10) and (17) in (8), we can compute the average route duration time by means of:

$$\overline{T}_{RD} = \begin{cases} \frac{\kappa}{Nv} + (\lambda - 2\overline{\Delta})(N+1); & \overline{T}_F \geq \overline{T}_D \\ 0; & \overline{T}_F < \overline{T}_D \end{cases}. \tag{18}$$

4 Maximum route length

As mentioned before, a route would be useful if, and only if, route failure time is longer than the time interval required to discover the route. In Sect. 3, we mentioned that route duration decreases with route length and that the round trip time increases with route length. The routes should therefore

[1] Some statistical parameters related to the goodness of fit obtained for (18) are: *SSE* $\approx 10^{-4}$ and *R-square* ≈ 0.99. Similar values were obtained when fitting (9). 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* and the *total sum of squares*.

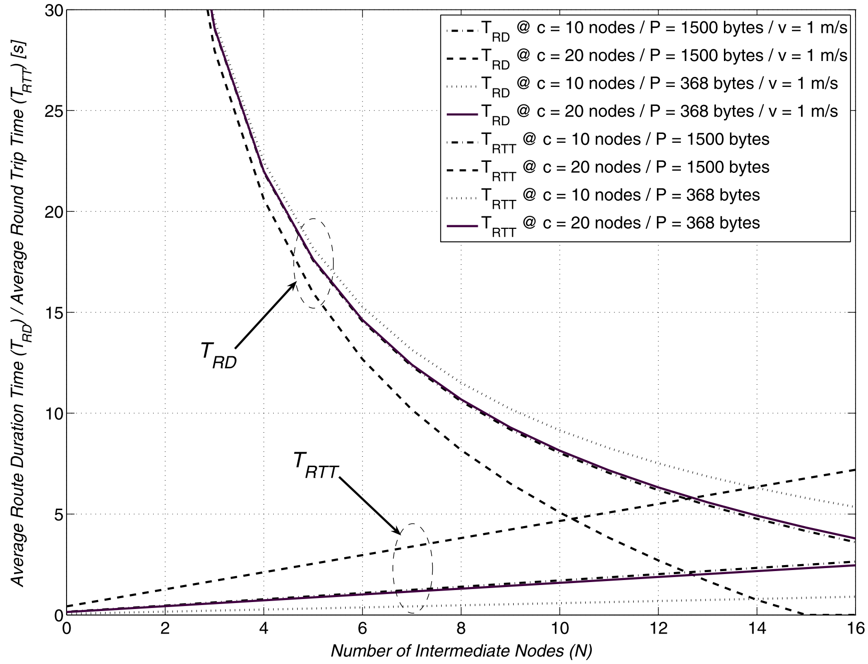

Fig. 5 Average route duration and average round trip time versus number of intermediate nodes in MANETs

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:

$$\overline{T}_{RD} \geq \overline{T}_{RTT}. \tag{19}$$

If we replace (18) and (7) in (19), we obtain:

$$\frac{\kappa}{Nv} + (\lambda - 2\overline{\Delta})(N+1) \geq 2(N+1)\overline{\Delta}. \tag{20}$$

In order to compute the *maximum route length* from (20), 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 $\overline{T}_R = 0$, thus leading to $\overline{\Delta} = \overline{T}_\Delta$. It is evident that, when the buffers are not empty, the 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. 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 [30]). In these computations, we consider a node transmission range of $R = 250$ [m] and the speed of movement is $v = 1$ [m/s].

From Fig. 5, we can infer that there is one intersection point on each pair of curves (T_{RD} and 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 (20) and solve the resulting equation for N, we obtain the maximum value $N_{\max}$, given by:

$$N_{\max} = \left\lfloor \frac{1}{2}\left[-1 + \sqrt{1 + \frac{4\kappa}{v(4\overline{\Delta} - \lambda)}}\right]\right\rfloor, \tag{21}$$

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

In Fig. 6 we can observe a set of four curves displaying the maximum number of intermediate nodes, computed from (21), versus speed of movement. By comparing these curves, we can infer that the maximum number of intermediate nodes is inversely proportional to the packet size and node speed.

As mentioned above, by limiting the maximum route length to a hop-count under $N_{\max}$, given by (21), 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.,

$$D_{\max} = (N_{\max} + 1)\overline{d}. \tag{22}$$

According to (21), factor $(N_{\max} + 1)$ corresponds to the maximum feasible number of hops in a route (maximum route length).

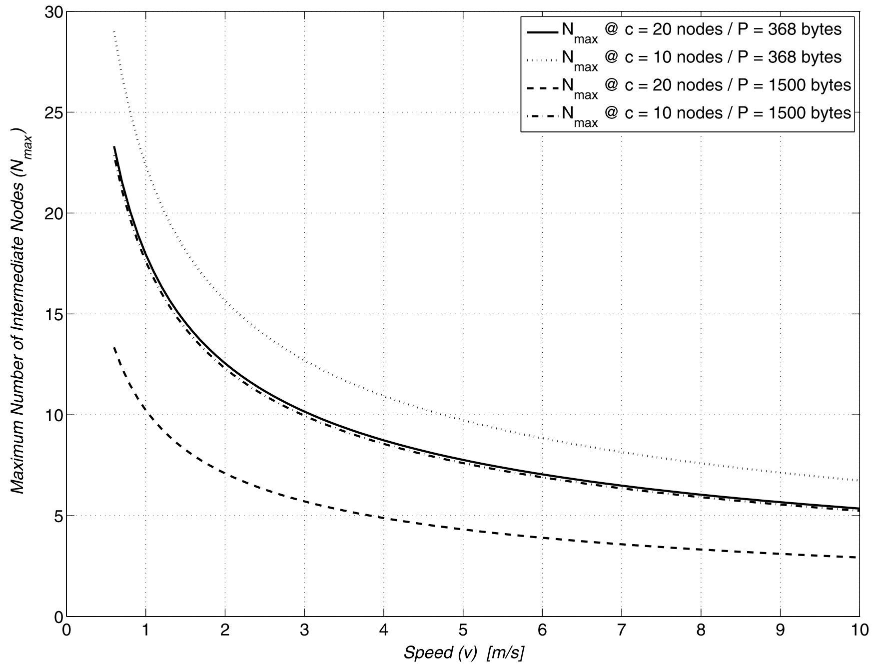

Fig. 6 Maximum number of intermediate nodes versus speed of movement in MANETs

A simple method to obtain the mean distance between two adjacent nodes $\overline{d}$, used in (22), is to analyze a route with one intermediate node only, as the one shown in Fig. 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 $\overline{d}_{SD} = (R + 2R)/2 = 1.5R$. Finally, the mean distance between either S–I or I–D corresponds to $\overline{d} = \overline{d}_{SD}/2 = 0.75R$. Other methods to find $\overline{d}$ would be to compute the average length of a MST (Minimum Spanning Tree) or by extensive network simulations.

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 paper. First, we conducted a series of simulations to measure 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.

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 $X = 2000$ [m] and $Y = 2000$ [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 according to [30]). 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 a transmission range of $R = 250$ [m]. We used saturated conditions, in which upon a successful packet transmission, a node generates another packet to be transmitted. 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 selected 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

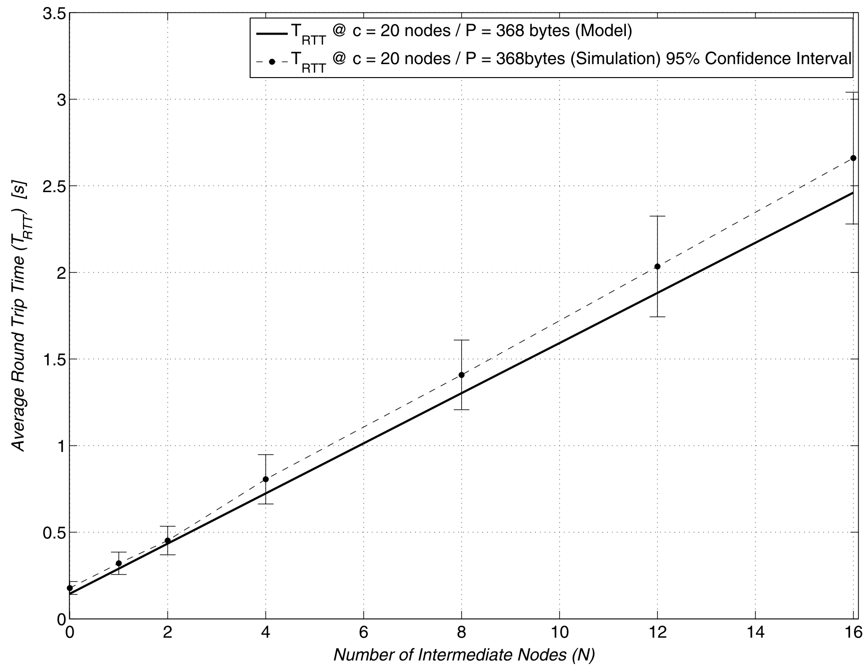

Fig. 7 Average round trip time for a wireless network with approximately 20 contending stations per sensing range

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, the delays experienced by a packet at each intermediate node will be longer than the scenario presented here. As mentioned above, 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 proposed model. We used the results provided by these simulations to generate the curve presented in Fig. 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. 7 includes 95% confidence intervals for the average round trip time obtained by the simulations.

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 mentioned in the previous section, the simulation settings consisted of a square network with the following dimensions $X = 2000$ [m] and $Y = 2000$ [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 a transmission range of $R = 250$ [m].

Briefly, the implementation of the RWP mobility model is as follows: when 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: $P_I = \frac{A_{or}(h)}{A_{sc}}$, where: $A_{or}(h) = 2R^2 \arccos(\frac{R-h}{R}) - 2(R-h)\sqrt{R^2 - (R-h)^2}$ is the area of the overlapping region and $A_{sc} = XY$ is the area

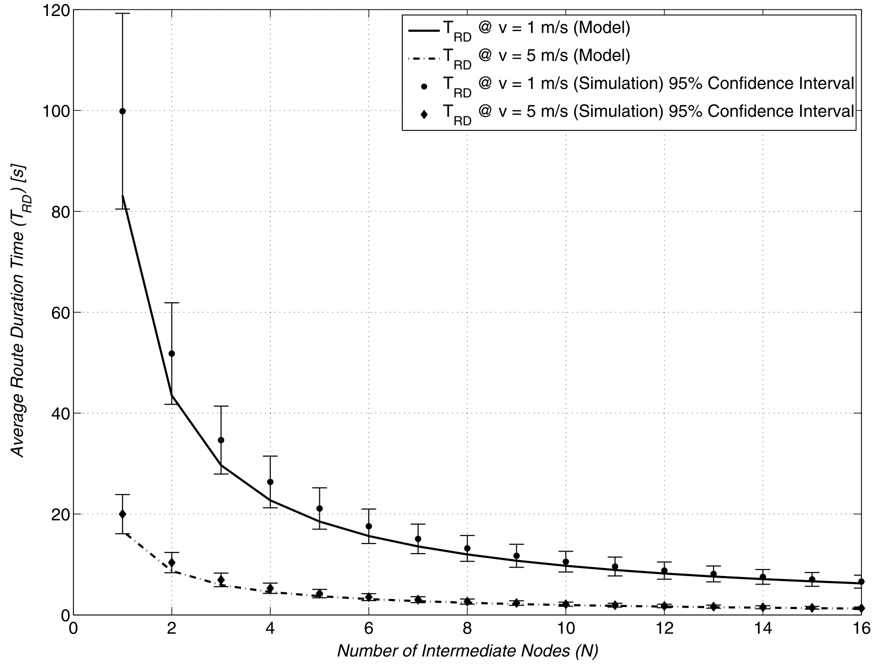

Fig. 8 Average route duration time for a MANET where nodes move at speeds of 1 and 5 [m/s]

of the scenario. If we consider our network settings, we have that $P_I < 1\%$.

From the mobile-node group, we selected 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. 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. It is worth mentioning that the choice of a specific routing algorithm does not affect the validity of our findings, as long as it is a reactive protocol and discovers routes with the same average hop count between the same end points.

Route duration simulation results were obtained for $v = 1$ [m/s], although they can be scaled to a different speed (s) by simply multiplying the values obtained for 1 [m/s] by factor (v/s). We used the results provided by these simulations to generate the curves presented in Fig. 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. 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. 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 used saturated conditions. 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. 9, we show the impact of the presence of 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 (18). It is evident that they closely match within a satisfactory margin of error. This figure also includes 95% confidence intervals for the average route duration time obtained by the simulations.

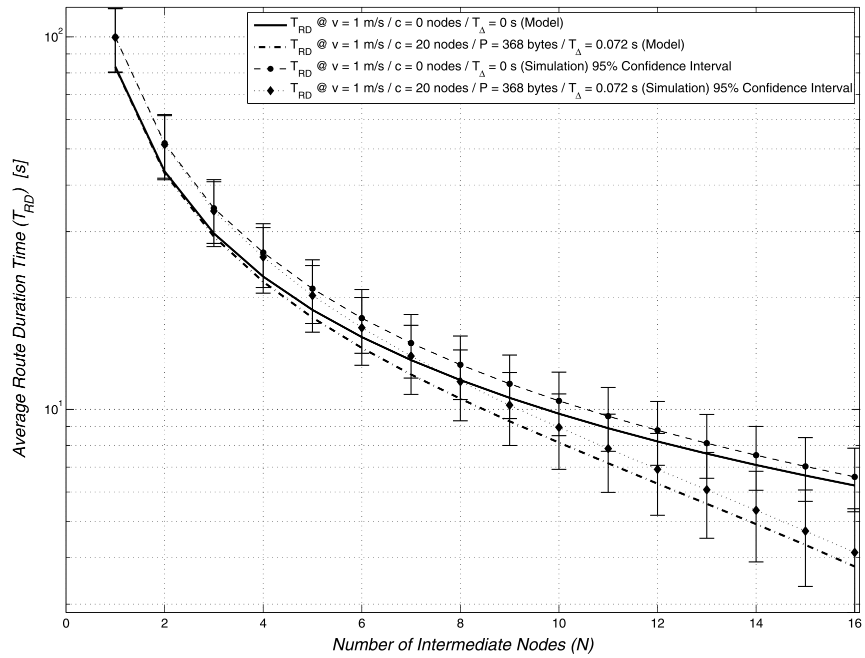

Fig. 9 Average route duration time for a MANET with and without the presence of background traffic

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 used saturated conditions, in which upon a successful packet transmission, a node generates another packet to be transmitted.

Once we generated the background traffic, we performed the following experiment. From the mobile-node group, we selected 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 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. 10. In this figure, we can make a comparison between the simulation results and the maximum route length, computed by means of (21). Figure 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. 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 proposed model 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.

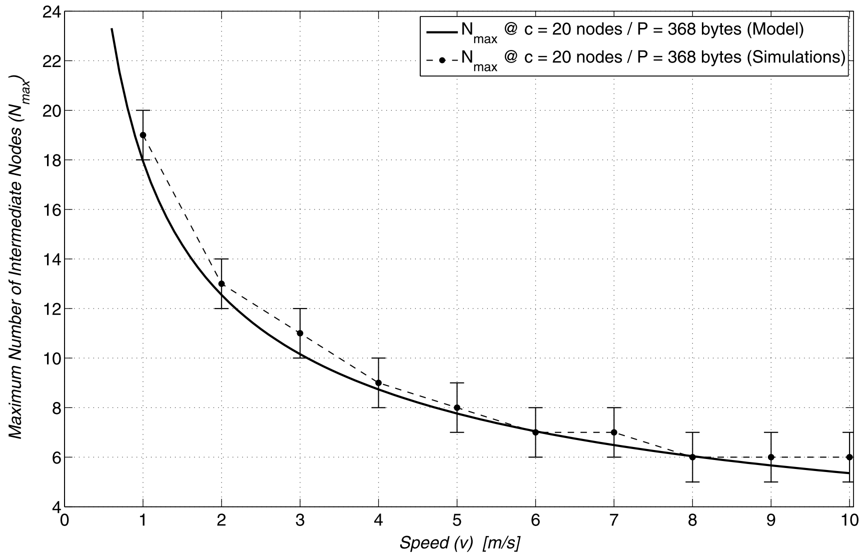

Fig. 10 Maximum number of intermediate nodes for a wireless network with approximately 20 contending nodes per sensing range and a packet size of 368 bytes

6 Conclusions

In this paper, we introduced a model to determine the upper bound on route length of wireless ad-hoc networks. The upper bound on route length is found by determining the maximum feasible number of intermediate nodes, $N_{\max}$, in any route of the network. First, we approached this problem 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, we set forth a new route duration model for routes formed by N intermediate nodes that takes the average route discovery time into account. Based on this model, we provided an approximation to compute the average route failure time and, therefore, the average route duration time. From both models, we obtained a closed-form expression to compute the maximum feasible number of intermediate nodes (*maximum route length*) that guarantees a reliable communication path for any source-destination pair. 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 the packet size and speed of nodes. 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 wireless ad-hoc networks. We conclude that node transmission range, node mobility and total per-hop delays actually define the maximum route length, measured by the number of intermediate nodes, and therefore also define the maximum size of the network.

Acknowledgements This work was supported in part by research funds from CONACyT grants 105117 and 105279, by DGAPA - PAPIIT grants IN108910 and IN106609, Texas A&M University-CONACyT grant 2010-049 and PAPIME PE 103807.

References

1. Bai, F., Sadagopan, N., & Helmy, A. (2003). The IMPORTANT framework for analyzing the impact of mobility on performance of routing protocols for ad-hoc networks. *Ad-Hoc Networks Journal*, *1*(4), 383–403.
2. Bai, F., Sadagopan, N., Krishnamachari, B., & Helmy, A. (2004). Modelling path duration distributions in MANETs and their impact on reactive routing protocols. *IEEE Journal on Selected Areas in Communications*, *22*(7), 1357–1373.
3. Bianchi, G. (2000). Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE Journal on Selected Areas in Communications*, *3*(18), 535–547.
4. Broch, J., Maltz, D., Johnson, D., & Hu, Y. (1998). A performance comparison of multi-hop wireless ad hoc network routing protocols. In *Proceedings of the fourth annual ACM/IEEE international conference on mobile computing and networking (MobiCom'98)*, October (pp. 85–97).
5. Carvalho, M., & Garcia-Luna-Aceves, J. J. (2003). Delay analysis of IEEE 802.11 in single-hop networks. In *Proceedings of the 11th IEEE international conference on network protocols* (pp. 146–155).
6. Chang, & Misra (2006). IEEE 802.11b throughput with link interference. In *Proceedings of infocom 2006*.
7. Cho, S., & Hayes, J. P. (2005). Impact of mobility on connection stability in ad-hoc networks. In *Proceedings of IEEE communication society, WCNC 2005*, New Orleans (USA) (Vol. *3*, pp. 1650–1656).
8. Barowski et al. (2005). Towards the performance analysis of IEEE 802.11 in multi-hop ad-hoc networks. In *Proceedings of WCNC 2005*.
9. Yun et al. (2005). Analyzing the channel access delay of IEEE 802.11 DCF. In *Proceedings of Globecom 2005*.
10. Zanella et al. (2005). Statistical characterization of the service in saturated IEEE 802.11 networks. *IEEE Communication Letters*, *9*(3).
11. Gomez, J., & Campbell, A. T. (2004). A case for variable-range transmission power control in wireless multihop networks. In *Proceedings of IEEE INFOCOM 2004* (pp. 1425–1436).

12. Gomez, J., & Campbell, A. T. (2007). Using variable-range transmission power control in wireless ad-hoc networks. *IEEE Transactions on Mobile Computing*, *6*(1).
13. Grossglauser, M., & Tse, D. (2002). Mobility increases the capacity of ad-hoc wireless networks. *IEEE/ACM Transactions on Networking*, *10*, 477–486.
14. Gruber, I., & Li, H. (2002). Link expiration times in mobile ad-hoc networks. In *Proceedings of the 27th annual IEEE conference on local computer networks (LCN '02)*, Tampa, Florida, November 2002 (pp. 743–750).
15. Gupta, P., & Kumar, P. R. (2000). The capacity of wireless networks. *IEEE Transactions Information Theory*, *46*(2), 388–404.
16. Han, Y., La, R., Makowski, A., Armand, M., & Lee, S. (2006). Distribution of path durations in mobile ad-hoc networks: Palm's theorem to the rescue. *Computer Networks*, *50*(20), 1887–1900.
17. Johnson, D. B., & Maltz, D. A. (1999). The dynamic source routing protocol for mobile ad hoc networks. *draft-ietf-manet-dsr-02.txt*.
18. Khalaf, R., & Rubin, I. (2004). Enhancing the delay-throughput performance of IEEE 802.11 based networks through direct transmissions. In *Proceedings of IEEE VTC 2004-Fall*.
19. Khalaf, R., & Rubin, I. (2006). Throughput and delay analysis in single hop and multihop IEEE 802.11 networks. In *3rd international conference on broadband communications, networks and systems, BROADNETS*, October 2006 (pp. 1–9).
20. Layuan, L., Chunlin, L., & Peiyan, Y. (2007). Performance evaluation and simulations of routing protocols in ad hoc networks. *Computer Communications*, *30*(8).
21. Li, J. et al. (2001). Capacity of ad-hoc wireless networks. In *Proceedings of the 7th annual ACM/IEEE international conference on mobile computing and networking (MobiCom '01)* (pp. 61–69), July 2001.
22. Li, X., Tang, S., & Ophier, F. (2007). Multicast capacity for large scale wireless ad-hoc networks. In *Proceedings of the 13th annual ACM/IEEE international conference on mobile computing and networking (MobiCom '07)*, September 2007 (pp. 266–277).
23. Mbarushimana, C., Shahrabi, A., & Larijani, H. (2007). *The effect of routing protocol dynamics on TCP performance in mobile ad hoc networks*. *Lecture notes in computer science* (Vol. *4658*, pp. 20–29).
24. Medepalli, & Tobagi (2005). Throughput analysis of IEEE 802.11 wireless LAN using an average cycle time approach. In *Proceedings of Globecom 2005*.
25. Medepalli, & Tobagi (2006). Towards performance modeling of IEEE 802.11 based wireless networks: a unified framework and its applications. In *Proceedings of IEEE Infocom 2006*.
26. Nasipuri, A., Castaneda, R., & Das, S. R. (2001). Performance of multipath routing for on-demand protocols in ad-hoc networks. *Mobile Networks and Applications (MONET) Journal*, *6*(4), 339–349.
27. Papoulis, A. (2002). *Probability, random variables and stochastic processes*. New York: McGraw-Hill.
28. Pascoe, M., Gomez, J., Rangel, V., & Lopez-Guerrero, M. (2010). Route duration modeling for mobile ad-hoc networks. *ACM Wireless Networks Journal (WiNet)*, *16*(3), 743–757.
29. Perkins, C. E., Royer, E. M., & Das, S. R. (1999). Ad hoc on-demand distance vector (AODV) routing. *draft-ietf-manet-aodv-03.txt*.
30. Rangel, V., Edwards, R. M., Tzerefos, P., & Schunke, K. (2002). Delivery of low rate isochronous streams over the digital video broadcasting/digital audio-visual council cable television protocol. *IEEE Transactions on Broadcasting*, *48*(4), 307–316.
31. Sharma, G., Ganesh, A., & Key, P. (2006). Performance analysis of contention based medium access control protocols. In *Proceedings of IEEE INFOCOM 2006*.
32. Tickoo, & Srikdar (2004). Queuing analysis and delay mitigation in IEEE 802.11 random access MAC based wireless networks. In *Proceedings of infocom 2004*.
33. Tseng, Y. C., Li, Y. F., & Chang, Y. C. (2003). On route lifetime in multihop mobile ad-hoc networks. *IEEE Trans. on Mobile Computing*, *2*(4), 366–376.
34. Turgut, D., Das, S. K., & Chatterjee, M. (2001). Longevity of routes in mobile ad-hoc networks. In *Proceedings of IEEE vehicular technology conference VTC 2001*, Rhodes, Greece (Vol. *4*, pp. 2833–2837).
35. Wu, X., Sadjadpour, H. R., & Garcia-Luna-Aceves, J. J. (2007). Link lifetime as a function of node mobility in MANETs with restricted mobility: modeling and applications. In *Proceedings of the 5th international symposium on modeling and optimization in mobile, ad hoc and wireless networks and workshops, 2007. WiOpt 2007* (pp. 1–10), April 2007.
36. Yu, D., Li, H., & Gruber, I. (2003). Path availability in ad-hoc networks. In *Telecommunications, ICT 10th international conference* (Vol. *1*, pp. 383–387), March 2003.

M. Pascoe received his B.Sc. in Mechanical-Electrical Engineering in 1997 and the M.Sc. and the Ph.D. with honors in Electrical Engineering in 2005 and 2010, respectively, all from the National Autonomous University of Mexico (UNAM). His areas of academic and research interest include routing protocols, location systems and modeling of node mobility in wireless ad-hoc networks. Currently, he is a visiting scholar with the Metropolitan Autonomous University (Mexico City).

J. Gomez received the B.S. degree with honors in Electrical Engineering in 1993 from the National Autonomous University of Mexico (UNAM) and the M.S. and Ph.D. degrees in Electrical Engineering in 1996 and 2002, respectively, from Columbia University and its COMET Group. During his Ph.D. studies at Columbia University, he collaborated and worked on several occasions at the IBM T.J. Watson Research Center, Hawthorne, New York. His research interests cover routing, QoS, and MAC design for wireless ad hoc, sensor, and mesh networks. Since 2002, he has been an Associate Professor with the National Autonomous University of Mexico. Javier Gomez is member of the SNI (level I) since 2004.

V. Rangel received the B.Eng. (Hons.) degree in Computer Engineering in the Engineering School from the National Autonomous University of Mexico (UNAM) in 1996, the M.Sc. in Telematics from the University of Sheffield, UK in 1998, and the Ph.D. in performance analysis and traffic scheduling in broadband networks in 2002, from the University of Sheffield. Since 2002, he has been with the School of Engineering, UNAM, where he is currently a Research-Professor in wireless networks. His research focuses on fixed, mesh and mobile broadband wireless access networks, QoS over IP, traffic shaping and scheduling.

M. Lopez-Guerrero received his B.Sc. in Mechanical-Electrical Engineering in 1995 and the M.Sc. in Electrical Engineering in 1998, both from the National Autonomous University of Mexico. He received his Ph.D. in Electrical Engineering from the University of Ottawa in 2004. He is an Associate Professor with the Metropolitan Autonomous University (Mexico City). His areas of academic interest are medium access control, traffic control and traffic modeling. He is a member of the IEEE.

F. Mendoza Fortunate Mendoza received his B.Sc. in Telecommunications Engineering in 2000 from the "Universidad del Valle de Mexico" (UVM) and the M.Sc. in Electrical Engineering in 2010 from the National Autonomous University of Mexico (UNAM). His research interests include RFID and wireless technologies. Currently, he is conducting research for the Institute of Science and Technology (ICyTDF) in Mexico City.