Modeling of Network Connectivity in Multi-Homed Hybrid Ad Hoc Networks

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Abstract. A Hybrid Ad Hoc Network consists of self-organized and self-configured mobile nodes, which make use of a fixed gateway to connect to the Internet. When there are two or more gateways to the fixed network, this is referred to with MultiHomed Hybrid Ad Hoc Network. In this scenario, different networks are formed, each one associated with a different gateway. A node can maintain its connectivity to the Internet when moving from a network to another by performing handover procedures and changing its gateway to the Internet. This scenario is quite interesting for its capacity of increasing the geographical extension of a single mobile network. The major contribution of this work is to provide a preliminary modeling of the node connectivity in this framework. We consider a typical architecture with gateways organized in a honey cell structure, where nodes move according to the RDMM (Random Direction Mobility Model), and present a three-state Markov model that describes the moving node behaviour: mobility without route changes, route change, and handover. Notwithstanding the simplicity of the underlying assumptions, the proposed model represents a valid basis for the analysis of the connectivity performance in this scenario, whose accuracy has been proved by means of extensive simulations.

Keywords: MANETs, hybrid ad hoc network, multi homed, Markov model, mobility modeling.

1 Introduction

Mobile Ad Hoc Networks (MANETs) are networks without infrastructures where mobile nodes are self-organized and self-configured making use of ad hoc routing protocols. These characteristics make these technologies good solutions for nodes that need to communicate with a host in a fixed infrastructure, but are away from it. Communication can be made through special nodes, called gateways, which are equipped with fixed network and MANET interfaces. When a MANET is connected to two or more gateways it is referred to with Multi-Homed Hybrid Ad Hoc Network. In this scenario, different MANETs are formed,

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each one associated with a different gateway. A node can maintain its connectivity to the Internet when moving from a network to another by performing handover procedures and changing its gateway to the Internet. This scenario is quite interesting for its capacity of increasing the geographical extension of a single mobile network, but at the same time it makes quite complex the management of node connectivity, especially if the active connections are to be kept alive during handover.

The contribution of this paper is a *preliminary modeling of the node connectivity in the scenario of Multi-Homed Hybrid Ad Hoc Networks*, considering both the events of nodes changing the route to the gateway and nodes performing handoff from a mobile network to another. Specifically, the objective is to highlight the effects of mobility on connection retainability. We consider a typical architecture with gateways organized in a honey cell structure, where nodes move according to the RDMM (Random Direction Mobility Model), and present a three-state Markov model that describes the moving node behaviour: mobility without route changes, route change, and handover. To the best of our knowledge the literature is missing this study, whereas several works deal with the modeling of single link lifetime.

Of particular relevance to our work are the studies in [1] and [2], where Samar and Wicker created a model to characterize the statistics for link dynamics in MANETs assuming the nodes maintain constant speed and direction. In [3], Wu, Sadjadpour and Garcia-Luna-Aceves improve this model with a two-state Markov chain, where nodes move according to the RDMM described in [4] and [5]. They also demonstrate how Samar and Wicker's work is a particular case that gives good approximation only when the ratio between the radio range and the node's speed is small. Preliminary works that extend the link lifetime analysis to model route retainability are [6] and [7]. They both rely on the Random WayPoint model (RWP) as mobility model to evaluate network connectivity, which shows some unrealistic movement behaviors. When studying our scenario of Multi-Homed Hybrid Ad Hoc Networks, we mainly exploit the results in [3] to evaluate the performance during route changes and handover.

The paper is organized as follows. Section 2 describes the considered scenario and the mobility model. In Section 3 we describe the proposed three-state Markov model, while Section 4 presents the simulation results. Conclusions are drawn in Section 5.

2 System Description

2.1 Routing and Gateway Discovery

The performance in a MANET is highly influenced by the type of the routing protocol implemented, which can roughly belong to either the proactive or reactive categories. In proactive routing protocols, every node keeps routing information about its neighbors so it can respond to a topology change as soon as it detects a link fault, but this leads to significant and sometimes prohibitive signalling overhead; to overcome this problem a reactive routing protocol can be used to discover routes only when they are needed; the price to paid is a longer time to set the route when the active one is failed.

When considering a Multi-Homed Hybrid Ad Hoc Network the type of the handoff trigger also influences the network performance [8]. In a proactive approach, nodes periodically receive advertisements from the reachable gateways and can choose every moment the most convenient one, which is usually done on the basis of the gateway distance in terms of the number of hops measure. Differently, in a reactive approach, nodes receive advertisements only when they require them so they need more time to handoff.

Routing and handoff strategies can be selected independently each other so that we may have four possible combinations. However, a good compromise in terms of reactivity and time of service interruption is to make use of a reactive routing protocol and a proactive gateway discovery. This is the scenario we consider in this work so that the computation of a new route is performed when the transmitting node identifies a route failure, whereas gateway handover is performed when the end-node receives advertisements from a gateway that is closer then the current one.

2.2 Network Architecture

We consider a network architecture like the one in Figure 1, with gateways organized in a honey cell structure of side L. We consider the number of nodes following a two-dimensional Poisson Process with intensity σ so that for a region D of area A the probability to have k nodes within is the following [1]:

$$Pr(k\, nodes\, in\, D) = \frac{(\sigma A)^k e^{-\sigma A}}{k!} \tag{1}$$

where σA represents the expected number of nodes in D.

We consider a generic node having an ongoing communication to a host in the Internet. A node can establish bidirectional links with every node if it is R meters far from it. Indeed, we consider every node to have the same transmission power, whereas we are not considering shadowing and multipath fading that change transmission range from a symmetrical shape to an asymmetrical one.

Mobility in the network is modelled by the random direction mobility model (RDMM); this model assumes that nodes movement is divided in temporal windows, called epochs, whose length is exponentially distributed with mean λ^{-1}, so that the cumulative distribution function (CDF) is the following [4]:

$$F(x) = P\{Epoch\, lenghts\ \leq\ x\} = 1 - e^{-\lambda x} \tag{2}$$

During each epoch a node has constant speed and direction, but these parameters change from one epoch to another; direction and speed are uniformly distributed respectively between 0 and 2π and between a minimum speed v_{min} and a maximum speed v_{max}. Since epoch times and nodes directions and velocities are mutually independent, we can consider their movement independent and identically distributed (i.i.d.) so we have a uniform distribution of node locations at

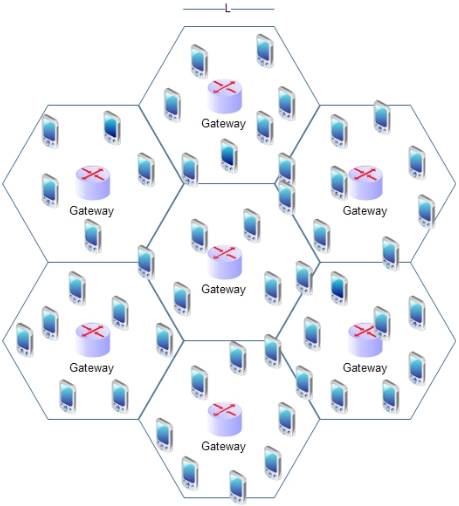

Fig. 1. Reference architecture for a Multi-Home Hybrid Ad Hoc Network

any point of time and the number of nodes distribution at the start and in every moment is still the same as described by (1).

2.3 Link Lifetime

To better understand the model we propose, we want to briefly summarize the results obtained from Wu, Sadjadpour and Garcia-Luna-Aceves in [3] for the link lifetime (LLT) T_L, which represents the duration of the link that can be used for data transfer.

They consider a link to be up if two nodes (e.g. a and b) are within range of each other during a communication session, so that:

$$T_L = min(T_a, T_b) \tag{3}$$

T_a and T_b are defined as Single-Node Link Lifetime (S-LLT) which measures the duration of time for a node to stay inside the communication circle of another node; since the nodes are random located, they have the same distribution and it is possible to calculate the complementary cumulative distribution function for T_L:

$$F_L(t) = F_S^2(t) \tag{4}$$

where $F_S(t)$ is the S-LLT complementary cumulative distribution function. To calculate it, the characteristic function $U_{T_S}(\theta)$ is computed as:

$$U_{T_S}(\theta) = \frac{U_1(\theta)}{1 - U_0(\theta)P_S} \tag{5}$$

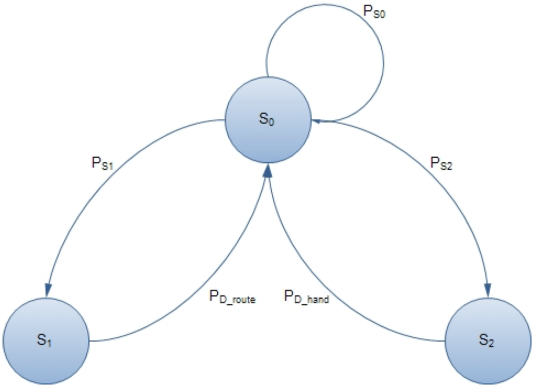

Fig. 2. The proposed three-state Markov chain

where P_S is the residence probability (i.e., the probability a node will be inside the communication circle at the end of a time epoch), $U_1(\theta)$ represents the characteristic functions of $p_{S_1}(t)$ (i.e., the probability of a node moving out of the communication circle at time t), and $U_0(\theta)$ is the characteristic function of $p_{S_0}(t)$ (i.e., the probability of a node being inside the communication circle at time t). We refer to [3] for a complete analysis of the model.

3 Proposed Model

To model the node behaviour in a Multi-Homed Hybrid Ad Hoc Network we introduce the time-continuous three-state Markov chain shown in Figure 2. S_0 represents the desired state of a node with a working stable route to the Internet gateway. It remains in this state for K epochs of the RDMM until either one of the links that connects it to the destination breaks or it finds a closer gateway and decides to handoff. S_1 describes a node looking for a new route to reach the same gateway after a link failure. S_2 represents a node trying to register to a new gateway because a shorter route to the Internet has been found. The transition probabilities from S_0 to the other states ($P_{S_0}(t)$, $P_{S_1}(t)$ and $P_{S_2}(t)$) are influenced by the two possible events that can occur in the network: a node losing its route to the Internet and a node changing its gateway for a closer one. We describe these events by computing the route and the handoff lifetimes.

In subsection A we obtain an estimation of the average number of hops to the gateway. It is then used in subsection B to present the computation of the proposed Markov model transition probabilities.

3.1 Number of Hops to the Gateway

The number of hops to the gateway is a variable that depends on the distance from the destination and on the distribution of the nodes. Herein, we are interested in estimating the expected number of hops N for a generic node in the considered scenario. We can easily observe that N can be expressed as

$$N = \frac{mean\, distance\, from\, the\, gateway}{mean\, distance\, covered\, by\, a\, single\, hop} \tag{6}$$

To calculate the mean distance d_g between a node and the gateway we approximate the hexagonal cell with a circle with the same area. Then the radius L_{eq} of the approximating circle is:

$$L_{eq} = \sqrt{\frac{3\sqrt{3}}{2\pi}}L \approx 0.91L \tag{7}$$

and since the mobile nodes are spread over the area of the cell uniformly, we can calculate d_g, which is equal to $\frac{2}{3}L_{eq}$.

To estimate the distance covered by a single hop in the gateway direction, d_c, we assume that the shortest route is always selected among the possible ones, as it is done by most of the available ad hoc routing algorithms. In this scenario, on average, each hop is the one that allows for the longest run in the direction of the gateway. The next hop node will be located in the semicircle of the node coverage area in the direction of the gateway. To determine d_c, we divide this semicircle in circular segments with parallel bases, so that the difference of two consecutive circular segments has a constant area A. This area is chosen so that the highest probability is reached for only one node within. With reference to Figure 3, A_1, A_2 and A_3 are the differences of the considered circular segments, whose area is equal to A.

Each area has a barycentre indicated with b_i as shown by the red dot in Figure 3. So since we are interested in the longest run, we weight each barycentre with the probability p_i to have a node in the area A_i and none in the areas A_j with $j = 1 \cdots i - 1$:

$$p_i = Pr(1\, node\, in\, A_i,\ 0\, nodes\, in\, A_1, \ldots, A_{i-1}) \tag{8}$$

so that d_c can be finally computed as:

$$d_c = \sum_{i=1}^{M} b_i p_i \Bigg/ \sum_{i=1}^{M} p_i \tag{9}$$

However, even if this path is the shortest one, it is unlikely that all the hops are aligned in the gateway direction. In most cases, the next hop is in a different direction, creating an angle α with respect to the direction between source node and gateway (Figure 3).

The receiver node has coordinates d_c and x_c, calculated considering the barycentre of half equivalent circular segment with barycentre d_c (the grey area in Figure 3).

The angle α can then be calculated as:

$$\alpha = \frac{\pi}{2} - tan^{-1}\left(\frac{d_c}{x_c}\right) \tag{10}$$

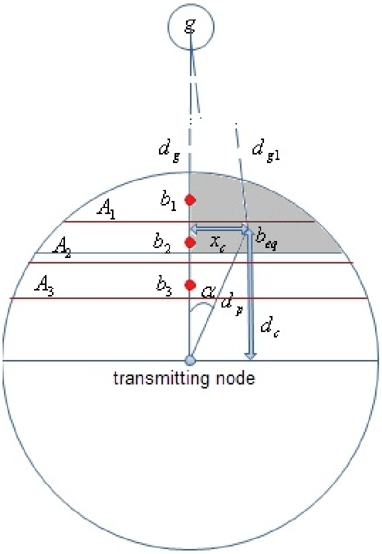

Fig. 3. Distance progress in the gateway direction

The distance covered by a single hop d_p in Figure 3 is:

$$d_p = \frac{d_c}{cos\alpha} \tag{11}$$

The distance to the gateway is:

$$d_{g_i} = \sqrt{d^2_{g_{i-1}} + d^2_p - 2d_{g_{i-1}} d_p cos\alpha} \tag{12}$$

where i indexes the hops to the gateway, with $i = 1 \cdots N$ and d_{g_0} equals to d_g. This distance is not the same in every hop, since it depends on the distance to the gateway in the previous hop. We can finally say that the average distance covered by a single hop can be calculated as:

$$\frac{(d_g - d_{g_1}) + \cdots + (d_{g_{N-1}} - d_{g_N})}{N} = \frac{d_g - d_{g_N}}{N} \tag{13}$$

Unluckily, to compute exactly this formula we need a priori knowledge of the number of hops N; a good approximation can be obtained if we consider the minimum number of hops to reach the gateway from the generic node at distance d_g:

$$N_{min} = \left\lfloor \frac{d_g}{R} \right\rfloor \tag{14}$$

Finally the number of hops is:

$$N = \frac{d_g}{\frac{d_g - d_{g_{N_{min}}}}{N_{min}}} \tag{15}$$

3.2 Route and Handoff Lifetime

We are interested in computing the probability for a route to stay alive. To this we define T_R as the route lifetime, i.e., a random variable representing the time the route remains up before one link within breaks. Since the nodes movement are i.i.d. in the considered RDMM, also the links between each pair of nodes that set the route will be i.i.d.; we can evaluate the route lifetime complementary cumulative distribution function (CCDF) $F_R(t) = P(T_R \geq t)$ starting from the single-node link lifetime distribution $F_S(t)$ described in Section 2.C:

$$F_R(t) = F_L(t)^{N-1} F_S(t) \tag{16}$$

where N specifies the expected number of links between the source and the gateway; only $N-1$ links can be described with the LLT distribution since they have two mobile nodes involved in the communication, while in the last link (mobile node - gateway) there is only one mobile device, since the gateway position is fixed, so we use the S-LLT.

We also define T_H as the handoff lifetime, i.e. the time a node will stay near its gateway without handoff to another one; we can calculate the complementary distribution function $F_H(t) = P(T_H \geq t)$ as:

$$F_H(t) = F_G(t) \tag{17}$$

where we define $F_G(t)$ as the single-node gateway lifetime. It can be evaluated starting from the single-node link lifetime, considering a communication circle with a radius of L_{eq} instead of R. This model represents a single node moving away from the gateway, which does not change its position, and becoming closer to another gateway.

It is now possible to calculate at any time t_1 the transition probabilities:

$$\begin{aligned} P_{s_0}(t_1) &= F_R(t_1) F_H(t_1) \\ P_{s_1}(t_1) &= F_H(t_1)(1 - F_R(t_1)) \\ P_{s_2}(t_1) &= (1 - F_H(t_1)) \end{aligned} \tag{18}$$

where the probability $P_{s_0}(t_1)$ to stay in the state S_0 after time t_1 is obtained by simply considering routes and gateway unchanged; the probability $P_{s_2}(t_1)$ to handover before time t_1 is calculated taking into account only the handoff lifetime as a result of the particular handoff trigger chosen, since the handoff is only based on the nearest gateway regardless whether the route is active or not. $P_{s_1}(t_1)$ represents the probability of a route lifetime lesser than t_1 considering the node is still register to the same gateway and it is calculated as the complement of the other two probabilities and shows how it depends from $F_H(t_1)$ since if a node decides to handoff it will also look for a new route.

These probabilities are then what we needed to design a variety of applications; the knowledge of the probability to change state can be used to adapt the bit rate in order to reduce packet loss or to meet deadlines.

Table 1. Time Components

Signalling Message	Transmission Time per hop	Processing and Queuing Time per node
Router Solicitation	T_{r_sol}	T_{pq_sol}
Router Advertisement	T_{r_adv}	T_{pq_adv}
Binding Update	T_{r_upd}	T_{pq_upd}
Binding Acknowledge	T_{r_ack}	T_{pq_ack}
Link Error	T_{r_err}	T_{pq_err}
Route Request	T_{r_req}	T_{pq_req}
Route Reply	T_{r_rep}	T_{pq_rep}

Table 2. Parameters Definition

Propagation Time / hop (Wireless Network)	T_{p_wir}
Propagation Time / hop (Infrastructure Network)	T_{p_inf}
Link Recovery Reactive Protocols	T_{lr}
Number of wireless hop	N_{wir}
Number of wired hop (Infrastructure network)	N_{inf}

3.3 Route and Handoff Delay

Many factors influence the time a node needs to change its route or its affiliation from one agent to another.

In this section we show the parameters that influence these delays, leaving to another time the exact calculation of the transition probabilities, since these will become easier to derive once defined more precisely the usage scenario.

In Table 1 we show the different time components associated with the processing and transmission of handover and route change signalling messages, while Table 2 presents some parameters definition.

The handover delay for the proactive approach can be expressed as follow:

$$\begin{aligned} D_{hand} = N_{wir}(T_{r\_sol} + T_{pq\_sol} + T_{r\_adv} + T_{pq\_adv}) + \\ N_{inf}(T_{r\_upd} + T_{pq\_upd} + T_{r\_ack} + T_{pq\_ack}) + \\ 2N_{wir}T_{p\_wir} + 2N_{inf}T_{p\_inf} \end{aligned} \tag{19}$$

while the delay for a route change can be derived from:

$$\begin{aligned} D_{route} = T_{lr} + \frac{N_{wir}}{2}(T_{r\_err} + T_{pq\_err}) + \\ \frac{N_{wir}}{2}(T_{r\_req} + T_{pq\_req}) + \frac{N_{wir}}{2}(T_{r\_rep} + T_{pq\_rep}) + \\ N_{wir}T_{p\_wir} \end{aligned} \tag{20}$$

Table 3. Simulation parameters

Parameter	Value
Number of gateways	7
L	1000 m
σ	$\frac{1}{\pi L} nodes/m^2$
Average number of nodes	5789
λ	4

The signalling message transmission delay T_r depends on the transmitted packet length and the transmission speed, while the process and queuing delay t_{pq} is a random variable characterized by the traffic load in the network and the queue length at each node.

The number of wireless hops N_{wir} is a random variable depending on the particular mobile nodes distribution, and in our scenario, with a Poisson distribution, its mean is represented by (15) calculated in Section 4.B.

The propagation time T_p, both in the wireless and in the wired network, depends on the hop distance, while T_{lr} represents the time a node needs to recognize a link fault and depends on the particular routing protocol implemented.

4 Simulation Results

To evaluate the reliability of the proposed model, we have performed simulations with different scenarios using the Matlab environment. The simulation parameters are shown in Table 3: the gateways are arranged as shown in Figure 1, where nodes are placed randomly. The number of nodes is not fixed but it is decided by (1), where node density σ has been chosen so that in every moment there is at least one route from each node to a gateway. The nodes move according to the RDMM with epoch lifetime controlled by parameter λ.

We have considered different scenarios changing the transmission radius and the speed of the nodes. Two different profiles have been chosen for the transmission radius: $100m$ and $200m$. The minimum velocity has been chosen equals to $0m/sec$, while we have set the maximum velocity to: $1m/sec$, $10m/sec$ and $20m/sec$, i.e., from walker to car speed. For each scenario, five simulations were run, with statistics recorded for $3600sec$ for the handoff lifetime and for $180sec$ for the route lifetime.

We assume to have a perfect MAC and routing layer and that the hidden and exposed terminal problems do not affect the communications, so that the simulations only show the behaviour of node mobility. This is done because we want

Table 4. Number of hops

R (m)	N		percentage error
	Simulated	Theoretical	
100	9.07	9.02	0.55 %
150	5.39	5.23	3 %
200	4	3.8	5 %

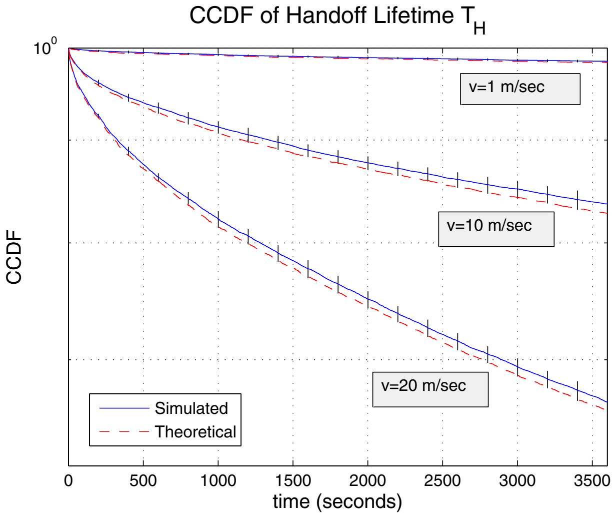

Fig. 4. Handoff lifetime T_H. For the simulation results the curves show the 99% confidence interval.

to analyze how mobility affects connectivity regardless of how the connections were established.

Table 4 describes the number of hops calculated with (15) and the simulated one, for three different values of the radio transmission range R. It is worth to note that even if our formula is only a first approximation, the results are quite accurate and with an error always lower than 5%. The differences are due to the fact that our formula consider only N_{min} hops to compute the mean distance covered by a single hop. This implies that the mean distance covered by a single hop is slightly higher than the real one (simulated) and consequently we have a slightly lower number of hops with our formula.

Figures 4 and 5 show the validity of our model for different combinations of the transmission radius and maximum velocity. This can be seen from Figure 4 where the 99% confidence interval is shown along with the simulation curves (blue lines). In Figure 5 the confidence interval is not shown for readability issues.

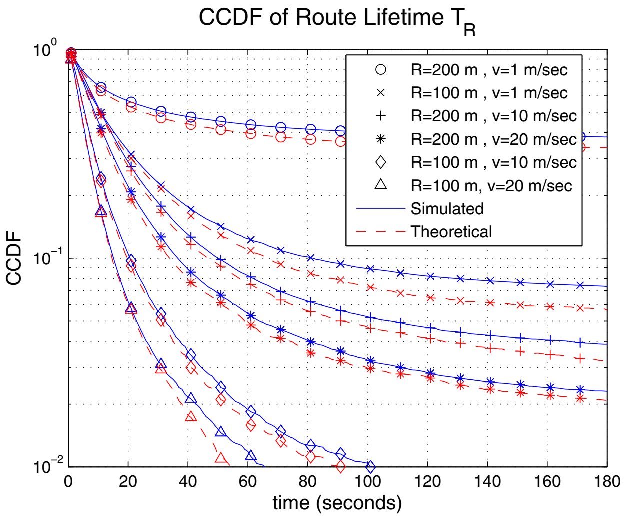

Fig. 5. Route lifetime T_R

These clearly show how the dynamics of a network are highly influenced by the route lifetime. For a given time, in fact, the probability to lose a route is much higher than the probability to handoff.

The route lifetime is characterized by a dependency from the R/v ratio. As expected, decreasing this ratio brings to a quick decrease in the $F_R(t)$ probability, which means frequent changes in the network topology. This is because this ratio represents the maximum time interval a node needs to pass through the trasmission radius of another node; decreasing this ratio means reducing the available time for two nodes to communicate. Moreover, for every link that makes up the route, two mobile nodes are involved in the communication so this further reduces the route lifetime.

Differently, the handoff lifetime does not depend on the transmission radius since the decision for a node to handoff is only affected by the distance from the gateways. Moreover, during handover, only a node is moving since the gateways don't change their position. Accordingly, since we consider a fixed cell size L, the only parameter that influences the handoff lifetime is the velocity of the node.

4.1 Use Case

We consider the scenario of a mobile node connected to a streaming server on the Internet, running a video application with a low frame rate: the mobile node can freely move in an architecture like the one in Figure 1, using a reactive protocol, such as AODV, to discovery the route while connection with the gateways follows a proactive approach.

Video streaming applications are one of the most challenging among the multimedia services, first of all due to time constraints. Being able to know when a route is going to break or a handover to occur can be really useful to help an application to modify its bit rate and achieve deadlines.

We want to show the possible benefits of an application that makes use of our model; we don't examine problems of collisions and interference for both the applications, so that the only difference is the knowledge of the network connectivity due to the mobility.

We can assume to know the maximum bit rate the network can support for the considered application. In a normal video streaming application, after the communication is established, the source starts to send packets with a constant bit rate, using the maximum link capacity. When the connection is interrupted, a certain number of packets will be lost as the source does not notice immediately the fault and will continue to send data until it receives an error notification. These packets can be retransmitted when the connection is established again or otherwise they are considered lost packet and the result is a worse quality video.

In a mobile network, like the one we are considering, this approach is hazardous because the connections are likely to be interrupted; as we have demonstrated, the network topology becomes more dynamic and the routes are more instable as the velocity increase.

If the application knows that a connection is going to break with a certain probability at the time t, it can adapt its transmission in different ways. One possibility should be to reduce the frames coding rate when the probability for the streaming video to stop is above a certain threshold. In this way, we lower the quality video, but we accomplish a better recovery capability. Another possibility should be to send important data, for example I-frames, when the probability to stay connected is high to be sure to respect a deadline.

5 Conclusions

In this paper, we have proposed a three-state Markov model to study the dynamics of a Multi-Homed Hybrid Ad Hoc Network. It provides the probability for a node to remain in the stable working connection to the Internet for the next desired interval. This can be useful when implementing application rate-control algorithms, which would modify the source and channel rates according to the node state.

Simulations have shown the model represents a valid basis for the analysis of the connectivity performance.

Even if our formula for the number of hops is only a first approximation, the results are quite accurate and with an error always lower than 5%. The estimated transition probabilities fall within the 99% confidence interval with less than 1% errors.

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