Longevity of Routes in Mobile Ad hoc Networks*

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Abstract

An ad hoc network is a collection of mobile nodes where communication takes place through the wireless medium and in the absence of any fixed infrastructure. Direct communication is only possible between neighboring nodes and hence multi hop communication becomes necessary for distant nodes. It is essential that a routing protocol is used by a source node to discover a route to the destination node so that it can successfully transmit its message via the intermediate nodes. The lifetime *of a particular route is dependent on the speed and direction of movement of all the nodes involved in the route. In this paper, we investigate the expected lifetime of a route so that the route discovery protocol can be invoked at the right time without disrupting the communication. We argue that if the movement pattern of the nodes is absolutely deterministic then the lifetime of a route can be determined exactly. On the other hand, a chaotic mobility pattern will bring in uncertainty to the lifetime of the route. We calculate the expected lifetime for different mobility models.*

1 Introduction

Cellular wireless networks completely depend on fixed base stations which are all connected to the wired backbone. The deployment of such a network is not practical in times of utmost emergency due to both time and economical constraints. Instead, mobile multi-hop radio networks, also called *ad hoc* or *peer-to-peer* networks, play a critical role in setting up a network on the fly in situations such as law enforcement operations, battle field communications, disaster recovery situations, and so on. In such situations, all the nodes in the network including the base stations are potentially mobile, and the communication must be supported untethered between any two nodes.

Static or single hop protocols (as in cellular networks) are not suitable for multi-hop mobile wireless networks since these protocols assume rare topology changes. Due to the mobility of the hosts and the limitations of the wireless channels, the problem of routing becomes more involved. Some form of routing is generally necessary in any multi-hop wireless network to route messages from a source to a destination. The efficiency of such a routing algorithm is very vital since the throughput of the system heavily depends on it. Frequent route changes due to mobility of the nodes would increase the signalling overhead which is required to establish a route. Once the route is established, a *route maintenance* protocol is used to provide feedback about the links of the route and to allow the route to be modified in case of any disruption due to movement of one or more nodes along the route. It also aims to maintain a route as long as possible because there is usually a high cost associated with every route repair.

It is clear from the earlier discussion that the mobility of the nodes affects the duration of routes. It is desired to keep the routes as long as possible so that not only the network sustains its stability, but also the overhead cost (signaling, computation, etc) associated with route discovery and maintenance is reduced. One of the well known solutions to this problem is the *mobility prediction* of the nodes. Various mobility prediction schemes have been proposed for ad hoc networks [1, 2, 5, 6, 7, 8, 9, 11, 12, 13], most of which are simulation-based. Many researchers have addressed the mobility characterization issues in wireless *cellular* networks, where one of the two nodes, the base station (BS) is stationary [14]. Refs. [7, 8] have extended the concept of cellular mobility in ad hoc networking application, where any two nodes are mobile. Associativity-based routing [13] selects a route based on associativity states of nodes. The objective is to select routes that have *long-*

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lived links according to the associativity of the nodes involved. Signal stability-based adaptive routing [2] selects a route based on both the signal strength between nodes and a node's location stability. The routes containing strongly connected nodes are preferred over the weakly connected nodes. The work presented in [1, 9] predicts status of links quantitatively. The *proximity model* proposed in [8] quantifies the future proximity of adjacent nodes. In [11, 12], the mobility prediction scheme enhances the performance of the unicast and the multicast routing protocols by using global positioning system (GPS) location information. Location-aided routing protocol [5] also uses location information obtained from GPS. The performance of on-demand multicast routing protocol is improved by the use of mobility and link connectivity prediction [6] in which the routes are selected based on the longest duration of their existence. These works take into account the random mobility of the network nodes to compute the future availability of a currently available route.

The expected lifetime of a route can be calculated once the route is provided by any routing protocol. For instance, one of the most popular routing algorithms is Dynamic Source Routing (DSR) [3, 4] which is an on-demand routing algorithm. DSR assumes that the path obtained is the shortest since it takes into consideration the first packet to arrive at the destination node. The route reply packet is sent to the source which contains the complete route information from source to destination. This might take considerable amount of time and might disrupt a real-time session. If an alternative route can be computed before an existing route breaks, then the session can be transfered to the alternate route without any delay. This can be made applicable to any multi-hop routing algorithms.

In this paper, we argue that a prior knowledge about the possible disruption of routes is important and that the route rediscovery protocol should be invoked at the right time. An early route reconfiguration would mean more overhead. On the other hand, if the route re-configuration is delayed, then the route might break before a new route is found which would incur delay in the communication. We claim that the expected lifetime of routes will be different for different mobility models and we study the predictability of the lifetime of the routes. We consider four mobility models-deterministic, partially deterministic, Brownian motion and Brownian motion with drift. Although these models do not capture the complete mobility space, yet they capture some of the common scenarios which are completely predictable to completely unpredictable. For the individual mobility models, we analyze the expected lifetime or the probability that a link would be alive after a certain time. For the purpose of analysis, we only consider two neighboring nodes (within each other's transmission range) and their corresponding link. This can be extended for all the node pairs in route and the link with the lowest expected lifetime will dictate the lifetime of the entire route.

The rest of the paper is organized as follows. In Section 2, we motivate the need for prior knowledge of route disruption. In Section 3, we present our approach of finding the expected route lifetime from the knowledge of individual links. Section 4 discusses the four mobility models along with the analysis for the expected lifetime. Conclusions are drawn in the last section.

2 The Need for Prior Knowledge

It is not necessary that a route exists till the communicating session between the corresponding nodes is complete. This may simply happen if one or more nodes along the route move or a node fails in the unlikely event. In either case, a new route has to be found for the session to continue. If it is somehow possible to predict how long a particular route is going to last, then we can perform a route discovery sometime before the route is broken. The prediction of the lifetime of a route is possible since the destination node knows the location and the velocity of all the nodes along the route. It is also possible that a node gets a detailed information about the expected lifetime of individual hops along the route. The problem arises because of the fact that we are not able to accurately predict the lifetime of a route after it has been discovered because of the mobility of the nodes. It is possible to accurately predict the exact lifetime of a route if the mobility pattern of the nodes are completely deterministic. However, this is highly improbable.

The mobility model plays an essential role especially in routing in mobile ad hoc networks. The mobility model should include both the speed and the direction of movement of the mobile node. The expected lifetime of a route highly depends on the mobility pattern of the nodes. For example, if the nodes move in a deterministic manner (eg. in a straight line with a constant speed) or all the changes in direction and velocity are known in advance, then it is possible to determine the exact time at which two nodes will move out of each other's range, i.e, $d(x, y) \geq tx_{range}$. On the other hand, if there is no information available about the movement pattern or if the nodes are moving randomly in all directions, then it becomes difficult to predict the lifetime of a route. In that case, we can only make an estimate based on the average speed and the analysis becomes probabilistic. If the movement pattern is somewhat in between, i.e., there is a probability distribution function for the node going in different directions. The probability distribution function will have the highest value in the direction of motion, thus decreasing value on either side. Thus we see, how the lifetime of a route can be predicted from the mobility model of the nodes. Once the lifetime of a route from source to destination is successfully predicted, the alternative routes can be constructed prior to the end of the path lifetime in a timely manner.

3 Expected Lifetime

We assume that the route for which the expected lifetime is to be calculated is given by some routing protocol, DSR for example. We assume that the path is $v_1 \rightarrow v_n$, where v_1 and v_n are respectively the source and destination nodes. We also assume that all the nodes are able to record the information about their position (most likely from a GPS system) and velocity. During a route discovery procedure, this spatio-temporal information is passed on the neighbors who in turn pass on the information with its own information appended. In this manner, the location and velocity of all the nodes involved in a route are known to the source and destination nodes.

The idea behind computing the expected lifetime of a link is to determine the time at which the two nodes move out of each other's range. To find the expected lifetime of a route, we must consider all the hops (links) in the routes separately because a break in any of the hops will break the route. The condition for the existence of a link between two nodes x and y is

$$d(x,y) \leq tx_{range},$$

where $d(x,y)$ is the distance between x and y, and tx_{range} is their transmission range. For a route from v_1 to v_n, having $(n-1)$ hops, we can represent each hop by $v_i v_{i+1}$ for $1 \leq i \leq n-1$. Since there is a link $v_i v_{i+1}$ between v_i and v_{i+1}, we can say that $d(v_i, v_{i+1}) \leq tx_{range}$ for $1 \leq i \leq n-1$. But due to the mobility of the nodes, the inequality will not hold true after some period of time. The time for which the two nodes will be communicating will depend on their speeds and *relative* direction of motion. Let $E[t_i]$ be the expected time that a link will exist between v_i and v_{i+1}, which is the ith hop in the route. Therefore, the expected time for the entire route $E[t]$ can be found by taking the *minimum* of the expected lifetimes for all the hops. Thus,

$$E[t] = \min\{E[t]; 1 \leq i \leq n-1\}.$$

4 Longevity under Various Mobility Models

We consider four mobility models and study their effect on the longevity of routes.

4.1 Deterministic

In this model, the movement of all the nodes are completely defined, so it is possible to calculate the exact time at which two nodes will move away from each other's transmission range. The instantaneous position of a node can be represented by a vector in the two-dimensional plane. Let us consider two nodes n_1 and n_2 with position vectors $\vec{p}_1$ and $\vec{p}_2$ respectively, at time t as shown in Figure 1. If $d(t) = |\vec{p}_1 - \vec{p}_2|$ is the mutual separation of the two nodes at time t, then for the two nodes to communicate with each other $d(t) \leq tx_{range}$. Now let us consider the positions of the two nodes at time $t + \delta t$. If their movement vector within the time interval was $\vec{v}_1$ and $\vec{v}_2$, their current positions at time $t + \delta t$ would be $(\vec{p}_1 + \vec{v}_1)$ and $(\vec{p}_2 + \vec{v}_2)$ respectively. Their mutual separation would be $d(t + \delta t) = (\vec{p}_1 + \vec{v}_1) - (\vec{p}_2 + \vec{v}_2)$. If we continue in a similar fashion and calculate their mutual separation after time $(t + k\delta t)$, where k is an integer, then

$$d(t + k\delta t) = (\vec{p}_1 + k\vec{v}_1) - (\vec{p}_2 + k\vec{v}_2).$$

This is due to the assumption that the nodes move with a steady velocity. The link between the two nodes will break if $d(t + k\delta t) \geq tx_{range}$. So, by knowing the initial positions and the velocities of the nodes, we can calculate the value of k for which $d(t + k\delta t) \geq tx_{range}$. The corresponding time for which the link would be active is $k\delta t$. Thus, the expected lifetime of a link is

$$E[T] = k\delta t.$$

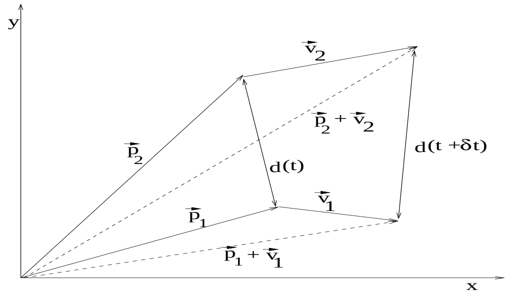

Figure 1. Deterministic motion of nodes

4.2 Partially deterministic

In this model, the direction of movement of all the nodes are known with a certain probability. We assume that there is a probability distribution function for the direction of motion. For the sake of demonstration, we consider the probability distribution function as shown in Figure 2, where the probability that a node deviates by an angle θ from its mean path is proportional to $\cos\theta$. So the probability that a node changes its direction between θ and $(\theta + \delta\theta)$, where $\delta\theta \rightarrow 0$, is given by $\frac{1}{2}\cos\theta\delta\theta$. The factor of $\frac{1}{2}$ comes because it can go to either side, left or right, with equal probability. The expected life of a link can be calculated in the same manner as the previous model, but with the uncertainty factor of $\frac{1}{2}\cos\theta\delta\theta$.

It can be noted that any other probability model could have worked as well, the direction would simply result in a different term for the deviation. This model is motivated from the fact that nodes have a general direction of motion. A node moving in a particular direction tends to move in that direction, may be with slight deviations. It is hardly the case that a node after traversing in a particular direction will travel in the opposite direction. If we follow the same approach as in the previous case then the expected lifetime would be

$$E\left[T\right] = \left(\tfrac{1}{2}\cos\theta_i\delta\theta\right)^k k\delta t.$$

where θ_i is the deviation from the forward direction at the ith time epoch.

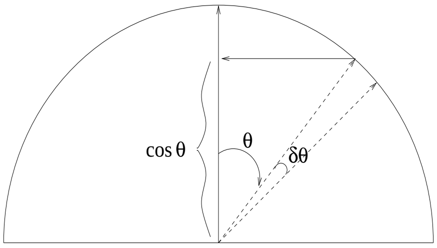

Figure 2. Probabilistic direction of motion

4.3 Brownian motion

In this model, the direction of movement is a continuous random variable uniformly distributed between 0 and 2π. Also, the velocity at any given time is random. The motion is shown in Figure 3, where a node undergoes random movements for 8 time epochs. It can be seen that the distances moved in each time epochs are random and the direction of movement is also random. It is rather difficult to analyze the link condition between two nodes when both the nodes involved are moving in random directions with different speeds. The link condition of a node in a *cellular* architecture is always analyzed with respect to the *static* base station. But in ad hoc networks, all nodes are mobile and the mobility of a node has to be analyzed by fixing the reference frame of one with respect to another. This is because the link between two nodes is dependent on the *relative* movement of the nodes [7]. For every movement of a node, the reference frame of the other node is translated an equal distance in the opposite direction. Effectively, the mobility vector of a node can be obtained as the difference of the mobility vectors of the two nodes.

Let T denote the first time a node crosses tx_range. We will compute $P\{tx\_range < T\}$ by considering $P\{X(t) \geq tx\_range\}$, where $X(t)$ is the Brownian process and conditioning on whether or not $T \leq t$. This gives

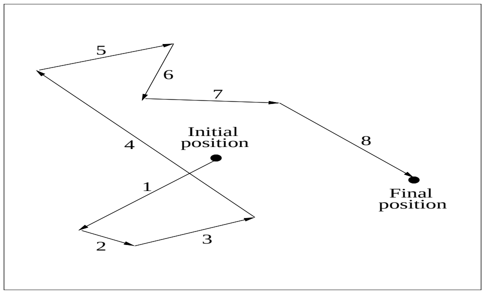

Figure 3. Brownian motion of nodes

$$\begin{aligned} P\{X(t) \geq tx_{range}\} = {} & P\{X(t) \geq tx_{range} | T < t\}P\{T < t\} \\ & + P\{X(t) \geq tx_{range} | T \geq t\}P\{T \geq t\} \end{aligned}$$

By using symmetry and simplifying algebraically, we find that $P\{T \geq t\} = 2P\{X(t) \geq tx_{range}\}$. We also know from the properties of Brownian motion that $X(t)$ is normal with mean 0 and variance t, its density function is given by $f(x) = \frac{1}{\sqrt{2\pi t}} e^{-x^2/2t}$. Therefore,

$$P\{T \geq t\} = \frac{2}{\sqrt{2\pi t}} \int_{tx_{range}}^{\infty} e^{-x^2/2t} dx.$$

From the above expression, we can find out the probability with which a node will move out from the transmission range of another. Since we have assumed a reference frame with respect with another node, the velocity vector of a node as seen by the other's reference frame will be double the actual velocity. The expected lifetime can be shown to be [10]

$$E\left[T\right] = \infty.$$

It follows that T, though finite with probability 1, has an infinite expectation. That is, with probability 1, the Brownian motion process eventually crosses tx_{range}, but its mean time is infinite.

4.4 Brownian motion with drift

This model is more observed in real life where the nodes move randomly as in the previous case but the probability cloud has a general direction of movement. An example would be a convoy which is moving in a particular direction and the individuals are moving in random directions within the convoy. The motion can be defined as

$$X(t) = B(t) + \mu t,$$

where $B(t)$ is the standard Brownian motion. Thus a Brownian motion with drift is a process that tends to drift off at a rate μ. It can be shown that

$$E\left[X(t)\right] \to \mu t, \text{ and } Var(X(t)) \to t.$$

If we consider all the nodes in the system having the same drift velocity and direction, then the problem boils down to the ordinary Brownian motion as discussed before. This is because of the fact that all nodes will have zero *relative* drift velocity with respect to each other. If the nodes do not move with the same drift velocity and direction, then a correction term containing the relative drift motion vector needs to be added to the previous analysis. The correction term would be $\vec{\mu_1} - \vec{\mu_2}$, where $\vec{\mu_1}$ and $\vec{\mu_2}$ are the drift velocities of the two nodes. Since, the expected lifetime was infinity for Brownian motion, addition of a finite term does not change the expected lifetime in this case.

5 Conclusions

In this paper, we argue that prior knowledge of the lifetime of a route in an ad hoc network is crucial because of the delay involved in any route discovery protocol. Also, by knowing the the expected disruption time of a route, a new route may be discovered before a link fails along a route. We claim that the lifetime of a particular route is dependent on the speed and direction of movement of all the nodes involved in the route. Thus, the mobility models play an important role in the lifetime of a route. We analyzed the expected lifetime of a route by considering two neighboring nodes (within each other's transmission range) and their corresponding link. This can be extended for all the node pairs in route and the link with the least expected lifetime will dictate the lifetime of the entire route. The expected lifetime for a link was calculated for four different mobility models. We are currently in the process of validating our analytical model by exhaustive simulation where a number of nodes are randomly distributed over a region and are undergoing motions according to different mobility models. We also need to decide when to invoke the route discovery protocol before the route disrupts.

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