Performance of a Hybrid Routing Protocol for Mobile Ad Hoc Networks

Asis Nasipuri, Ryan Burleson, Benjamin Hughes, and Johnny Roberts
Department of Electrical & Computer Engineering
University of North Carolina at Charlotte
Charlotte, NC 28223-0001

***Abstract*- Mobile ad hoc networks are characterized by multi-hop wireless links, absence of any fixed networking infrastructure, and a dynamic network topology. Routing protocols for such networks typically use exchanges of control packets, either at fixed intervals of time or in response to a requirement, to adapt to the changing network topology. Balancing the optimality of the routes used in an ad hoc network as well as the overhead incurred from transmissions of routing packets is a challenging task. In this paper, we propose a hybrid routing scheme that combines proactive route optimization to a reactive routing protocol, for reducing the average end-to-end delay in packet transmissions without exceeding the routing overhead. The proposed scheme uses a pre-emptive route discovery to replace an existing route by a shorter route when the route has been used for a given interval of time. The optimum time for making the pre-emptive search is obtained by studying the statistical distributions of the link and route lifetimes. The pre-emptive search is restricted within a limited distance from the old route by using a query-localization method. Performance evaluations of the proposed hybrid scheme in comparison with a purely on-demand routing protocol are presented.**

1 INTRODUCTION

A fundamental characteristic of mobile ad hoc networks is that the network conditions are highly dynamic. Frequent and random node movements make the quality of peer-to-peer wireless links in an ad hoc network change unpredictably. This is due to factors such as variation of the distance between two peers, interference from other users, multipath fading, and shadowing. There are frequent link breakages, which are caused when the signal-to-interference-and-noise ratio (SINR) at a receiver drops below the limit that guarantees an acceptable packet error rate. Node movements also cause the appearance of new links between nodes who move within range of each other. As a result of these phenomena, there is a continuous change in the network topology of an ad hoc network. Routing protocols for mobile ad hoc networks cope with this characteristic by dynamically maintaining routes between the nodes in the network. The central issue for designing these protocols is to track the changing network topology without incurring a large overhead of routing packets. Proactive routing protocols perform this task by periodically updating routing tables at every node. A less expensive technique is to perform this task on an "as needed" basis where nodes actively search for a route to a particular destination only when needed. In the general sense, there is a trade-off between the routing overhead and the responsiveness of the network to changing conditions.

In this paper, we propose a hybrid routing strategy that draws the advantages of both proactive and reactive mechanisms to improve the communication quality of the active routes in the network while maintaining a low routing overhead. The proposed protocol uses a pre-emptive local search for a better route to replace the existing one if the elapsed time since the route was first discovered exceeds a predetermined threshold. We perform simulations to show that the proposed hybrid routing protocol reduces the average number of hops as well as the average physical path distance of the active routes. Both of these parameters contribute to the end-to-end communication quality of a multi-hop route. The paper is organized as follows. In section 2 we review routing issues in mobile ad hoc networks. The proposed hybrid routing protocol is described in section 3. Results obtained from simulations on the link lifetime statistics as well as the performance of the hybrid routing protocol are presented in section 4. We conclude in section 5.

2 ROUTING IN MOBILE AD HOC NETWORKS

Based on the ways of adapting to the dynamics of the network, routing protocols for mobile ad hoc networks may be broadly classified into two categories - *proactive* or table-driven protocols, and *reactive* or on-demand protocols [8]. Proactive routing protocols [17, 12] attempt to maintain shortest-path routes by using periodic updates to track changes in the network topology. The main drawback of this technique is that there are routing updates even when they are not needed, such as when nodes have not moved or are not involved in communication. Since the wireless bandwidth is at a premium, it is also important that routing protocols for mobile ad hoc networks maintain a low routing overhead, which is measured in terms of the number of routing packets transmitted in the network. This provides the basic motivation for the on-demand routing protocols [3, 16, 15, 7, 11], which create and maintain routes only when required, thus saving on redundant routing overhead from periodic updates. Typically, these protocols react to a route failure by searching for a fresh route using a flood of query packets.

However, there are certain drawbacks of the on-demand technique as well. Firstly, the network-wide flood of query packets is a bandwidth-expensive operation. Many optimizations to the basic on-demand mechanism has been proposed to solve this problem. For instance, DSR has the provision of using *non-propagating route requests* which only queries the neighbors of a source for a route to the destination [10]. This is used to avoid flooding the entire network when the source can obtain a route to the destination from one of its neighbors. AODV reduces the spread of query packets by the use of an *expanding ring search* [5]. Many other approaches to reduce the routing overhead caused by query-floods have also been studied. Notable amongst them are the *location based* approach [9] which uses GPS information for localizing a search, and the *spatial-locality based* query localization [4]. The use of directional antennas for limiting the extent of query floods has been explored in [14]. The common ground for all these approaches is the confinement of the spread of query packets within a subset of the nodes in the network amongst which the likelihood of finding the desired route is high. The subset of nodes is chosen on the basis of their proximity to the last route that was active between the two nodes in question.

An approach often used to obtain a better balance between the adaptibility to varying network conditions and the routing overhead is the use of hybrid routing protocols [7, 18, 11]. These protocols use different routing strategies in different regions or times in the same network. For instance, hybrid protocols may benefit from forming clusters of nodes within the same network and applying appropriately different routing schemes for communications within and outside the clusters. A hybrid routing protocol that adapts the frequency and size of the routing updates according to network conditions is presented in [1].

A second concern for on-demand routing is the latency in data packet delivery. Since the route discovery is only triggered by the need for sending a data packet for which the route is unknown, a source must wait for the the route discovery to be completed before sending it. Techniques such as multipath routing [13] and salvaging [10] reduce the data packet latency by using an alternate route when the existing one is broken. Here multiple alternate routes to the same destinations are maintained so that when the primary route breaks, alternate routes may be used without waiting for a fresh search to be completed. However, the basic mechanism used in on-demand routing introduces latency for achieving routing efficiency.

Another concern with on-demand routing, which is the focus of this paper, is that they usually discover a new route only when the existing one is broken. Hence if a route becomes sub-optimal, it will still be used until broken. We assume that the optimality of a route depends on the number of hops as well the physical length of the entire path in the route. To clarify this, we illustrate two examples of sub-optimal and the corresponding "better" quality routes in Figure 1. It may be noted that a purely on-demand routing protocol does not have any provisions for avoiding these conditions that may result in the usage of "poor" quality routes. A larger number of hops increase the end-to-end delay of data transmissions. Even if two routes have the same number of hops, the physically longer route may have poorer quality as a longer path length will result in a smaller signal strength which will generate higher packet error rates at the receiver. Hence, a route having a physically longer path may also result in longer delays due to a larger number of link-level packet retransmissions. Protocols such as Associativity-based-routing (ABR) and Signal Stability Routing (SSR) address the issue of route quality by selecting routes that meet certain criteria for stability [19] and signal power [6]. However, these protocols are also on-demand in nature, implying that the newer routes based on the quality criteria are determined only when an existing one breaks.

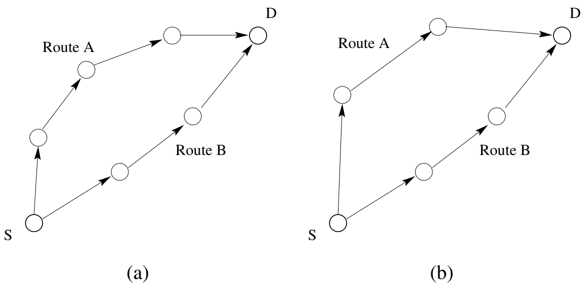


Figure 1: Examples for comparing the quality of alternate routes. In (a) route B is better as it has a fewer number of hops. In (b) both routes have three hops, but route B is shorter in path length, and will perform better than route A due to comparitively better signal strengths on all links.

In this paper, we propose a new hybrid routing protocol and explore its potential in improving the quality of routes in comparison to a pure on-demand protocol. The proposed protocol advocates the use of a localized route discovery for a better alternative route between two communicating end systems *even when the existing route between them is alive*. The time to make this pre-emptive localized route discovery is based on the elapsed time since the route was first discovered. According to our scheme, an exisiting route will be replaced by a "better" route, if one such exists, when a route has been alive for a sufficient amount of time. If the existing route breaks before this time, a new route discovery is executed according to the standard method used by a pure on-demand protocol. This obviously involves more frequent route maintenance operations and may generate a higher routing overhead than a pure on-demand protocol. To keep the overhead small, we propose the pre-emptive route discovery to be localized within a certain maximum distance of the existing route by using a technique similar to that in [4]. In comparison with other hybrid routing protocols [7, 18, 1], the idea presented in this paper is much simpler to implement. Moreover, our protocol focuses on the path optimality issue, which deserves special attention in mobile ad hoc networks.

3 HYBRID ROUTING FOR PATH OPTIMALITY

The proposed routing protocol is based on the principle that routes obtained by using an on-demand protocol are optimal only at the time when they are discovered. With changes in network topology caused by node movements after a route discovery, other shorter and better (in terms of a lower end-to-end delay) routes may become available. Hence a routing protocol that searches for better alternatives for routing before the existing route is broken, can improve the quality of communication by replacing the existing route by the alternate route.

To keep the discussion straightforward, we assume that source routing is used. However, the mechanism proposed in this paper is applicable to other on-demand protocols as well. Consider that a source **S** has a sequence of data packets to transmit to a destination **D**. Initially, **S** performs a route discovery by broadcasting a query packet that reaches all nodes in the network. **D** responds to the first query packet that it receives by returning a route reply packet to **S** on the same path that was followed by the query packet, traced backwards. The route reply packet carries this path **P** back to the source, where it is cached for use of transmitting data packets to **D**. When **S** receives the route reply packet, it also starts a timer which counts down from a pre-defined parameter *T*.

Thereafter, **S** commences transmission of data packets to **D**, and continues till completion unless interrupted by one of the following events: (a) the route breaks and the node that detects the failed link (from a MAC layer timeout before receiving an acknowledgement) sends an error packet back to **S**, and (b) the timer at **S** expires. For the first case, **S** also stops further transmission of data packets to **D** and deletes the routing table entry for **D**. Both of these events prompt **S** to start a search for an alternate route to **D** which is localized within a certain maximum distance *k* from the original route **P** [4]. This is performed by sending a query packet that carries the old path **P** and a counter that is incremented every time it is received by a node which is not in **P**. The counter is reset to zero when the query packet is received by any node in **P**, and the query packet is dropped when the counter exceeds a threshold *k*. If the localized search does not fetch a reply packet from **D** within a certain period of time, then **S** starts a global route discovery. **S** replaces the old routing table entry for **D** by the newly discovered route.

Since pre-emption increases the frequency of local route discoveries, the localized search in the hybrid protocol is expected to have a higher probability of success over that in the purely on-demand protocol, as the probability of finding a route in a restricted zone confined near the earlier route decreases with time. This reduces the frequency of occurances of global route discoveries. Hence, it may be possible to minimize the routing overhead by a suitable choice of *T*. A little thought reveals that this will depend on a number of factors such as the dependence of the probability of success of the localized search on *T*, the cost of an unsuccessful local search (which depends on the routing load generated by a flood), and the dynamics of the network. However, we like to remind the reader that the main motivation of the proposed hybrid protocol is to improve the quality of the routes used in the network by reducing the average number of hops and the total path length. We evaluate the effect on routing overhead at the end of the paper. For the purpose of this work, we set $T = \alpha L_n$ for all nodes, where L_n is the estimated lifetime of the route being used by **S** for transmitting data packets to **D**, consisting of n hops, and α is a parameter.

4 PERFORMANCE EVALUATIONS

In this section we present results from computer simulations for evaluating the viability of the proposed hybrid routing protocol. We first describe the simulation model that is used in this work. The evaluation of the average lifetime of independent links and routes consisting of n independent hops is presented next. Finally we present results demonstrating the performance of the proposed hybrid routing protocol.

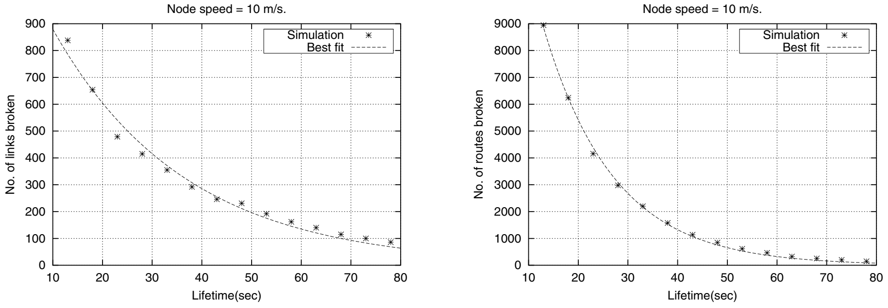
4.1 Simulation Model

The simulation model used in this paper is simplistic in the sense that it simulates only the node movements and not actual packet transmissions and network protocols as in the case of an event–driven network simulator. We use a program that simulates node movements according to a chosen mobility model, and *predicts* the corresponding events based on the appearance and breakage of links between the nodes in the network. The program considers a pair of nodes to have a link between them as long as they are within radio range of each other. In reality, a wireless link can break even when the receiver is within range of the transmitter, due to multipath fading and shadowing effects, interference from other users, or node failures. However, the model used in this work assumes that the existance of a wireless link depends only on the distance between the two nodes, which technically determines the *average* received power at the receiver. We assume that a route discovery is performed whenever the route between two communicating nodes is broken. In the absence of details such as packet transmission, radio interference, successful reception, and processing of events at the individual nodes, this translates to the assumption that all packet transmissions are perfect and instantaneous as long as the sending and receiving nodes are within range of each other. We also assume that node movements are slow compared to the rate of arrival of data packets, so that a route discovery is triggered whenever one of the links in the existing route between the nodes is broken. Based on the network topology at that time, a shortest path algorithm is applied to determine the likely route obtained from a route discovery for the given pair of nodes in the network. For simplicity, we assume that the restricted search zone for a localized search is large enough so that the shortest path between the source-destination pair always lies in it. A source continues to use a route until replaced by another one which is obtained from a fresh route discovery. Under these assumptions, this simple simulation model allows us to evaluate two parameters which are the central objectives of our work: *the average number of hops* and *the total physical path length* between two selected communicating nodes in the network.

We consider a 1000 m × 1000 m square area in which nodes move randomly and independent of one another. We use a mobility model in which node movements are linear during short intervals of t seconds. After every t second interval, the direction of motion of the node is varied by a random amount, which is uniformly distributed in $[-\theta, \theta]$, where θ is a parameter. All nodes move with the same speed. This is similar to the random waypoint model [2] with continuous motion.

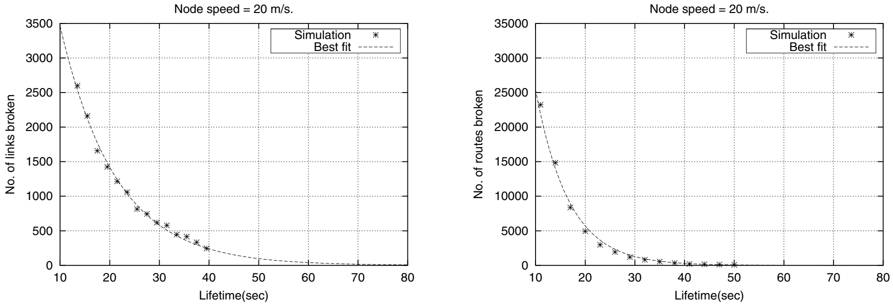
4.2 Link Lifetime Statistics

Using the above network and simulation model, we first estimate the distribution of the lifetime of wireless links in



(a) Single link

(b) 2-hop route



(c) Single link

(d) 2-hop route

Figure 2: Distribution of the lifetime of wireless links and 2-hop paths in an ad hoc network of 100 nodes. The solid lines represent exponential functions of the form $\frac{A}{\lambda}\exp(-t/\lambda)$, with $\lambda = 26.7$ in (a), $\lambda = 12.7$ in (b), $\lambda = 11.2$ in (c), and $\lambda = 6.6$ in (d).

the network. This was done by running the simulator for 5000 seconds and tracking the times for which all the peer-to-peer links in the network were alive. The results for a 100 node network, with a radio range of 200 m at two different node speeds, are shown in Figure 2. An update time interval of $t = 1$ second and peak angular deviation of $\theta = 45^o$ were used for all simulations. It is interesting to note that an exponential curve of the form $f(x) = \frac{A}{\lambda}e^{-x/\lambda}$ fits the data very well, indicating that the link and route lifetimes may both be approximated by exponential probability density functions (pdfs). Moreover, the average lifetime of the 2-hop routes estimated from Figure 2(b) and (d) are approximately half of those of the corresponding pair-wise links in the network (estimated from Figure 2(a) and (c), respectively). The average lifetime of a link in the network depends on the speed of movement of the nodes, radio transmission range, and the physical dimensions of the network area.

The above observations allow us to model the lifetime of wireless links in an ad hoc network by independent and identically distributed (*iid*) exponential random variables. Noting that a route consisting of n independent links will break when *any one* of the n links break, the lifetime of the route can be represented by a random variable L_n, expressed as

$$L_n = \min(X_1, X_2, \cdots, X_n) \qquad (1)$$

where $X_i,\ i = 1,\ 2, \cdots,\ n$, are *iid* exponential random variables, representing the lifetime of the i^{th} link in a route. Thus L_n is also exponential, with $E[L_n] = L/n$, where $L = E[X_i]$ is the average lifetime of a wireless link. All of these agree with our observations, as presented in Figure 2. Note that these observations support the assumptions made in [13] where the performance of multipath routing protocols were analyzed.

We determine the average link lifetime L off-line, and make it available to all the nodes in the network. A source may therefore determine the timeout T by setting

$$T = \alpha L/n \qquad (2)$$

where n is number of hops in the route that it has been using. Note that these parameters may be specific for a given set of mobility and network parameters such as node speed, radio range, and network area.

4.3 Performance of the Hybrid Routing Protocol

We now present simulation results evaluating the performance of the proposed routing protocol. In our simulations we evaluate the performance of the hybrid routing protocol with different values of α and compare it with the shortest existing route between the source and the destination. Note that with increasing values of α, there will be fewer pre-emptive searches using the hybrid protocol. Consequently, using a very large value of α is equivalent to using a purely on-demand routing protocol which uses localized searches in the first attempt to replace a broken route. We consider a 100-node network where all nodes are moving with the same speed of 10 m/s with the parameter $\theta = 45^o$. For each simulation run of 2000 seconds, we select a random pair of source and destination nodes and continuously monitor the shortest path route between them and also the *predicted* route that would be obtained by applying the hybrid routing protocol for the prevalent network topology. For each set of parameters, 20 separate runs were performed to derive the following parameters: (i) the average ratio of the number of hops used in the routes obtained by the hybrid protocol to that of the shortest path route between the two nodes, (ii) the average ratio of the total physical path length of the routes obtained using the hybrid routing protocol to that of the shortest path route between the two nodes. In addition to these averages, the maximum values of these two ratios from the 20 simulation runs were obtained. These are plotted in Figures 3 and 4. Results show that, on the average, a purely on-demand routing protocol (large value of α) has about 10-15% higher number of hops in comparison to the shortest path that exist between the source and destination nodes. The hybrid protocol, on the other hand, can generate routes that are within 5% of the smallest number hops between the two nodes. We note that the improvement is not very significant. Also, this is obtained for values of α smaller than one, i.e. for cases where a pre-emptive search is execeuted at intervals smaller than the average predicted life of the used route. Quantitatively similar results are also observed on the average physical path length between two communicating nodes on the shortest path and the routes used by the hybrid or purely on-demand protocols (see Figure 4).

Even though the number of hops and the physical path length of the routes in a purely on-demand routing protocol are found to exceed the shortest path route by only 15%, it is important to note that occasionally the difference may be as high as 50-60%. However, as shown in Figures 3 and 4, the same figures for the routes obtained using the hybrid routing protocol rarely exceed 20% when $\alpha < 1.0$. This indicates that pre-emptive routing at a time approximately equal to the lifetime of the route being used, may be highly beneficial for keeping the worst case communication quality of the routes within acceptable limits.

Finally, we evaluate the routing overhead of the hybrid routing protocol. Since the employed simulation model cannot evaluate routing loads, we use an analytical procedure to estimate this for the proposed hybrid protocol as well as a purely on-demand routing protocol. Our analysis, whose details are given in the Appendix, are based on the following assumptions:

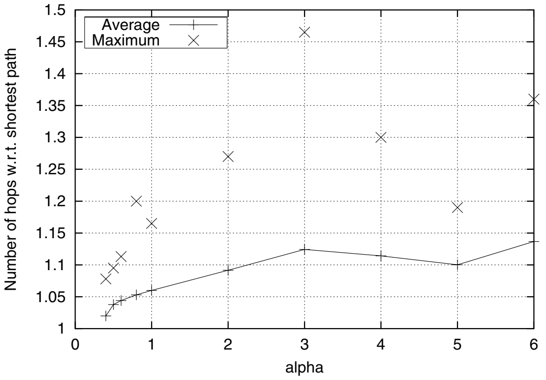


Figure 3: Number of hops of the routes used in the hybrid routing protocol in comparison to the shortest existing route between two nodes in a mobile ad hoc network of 100 nodes.

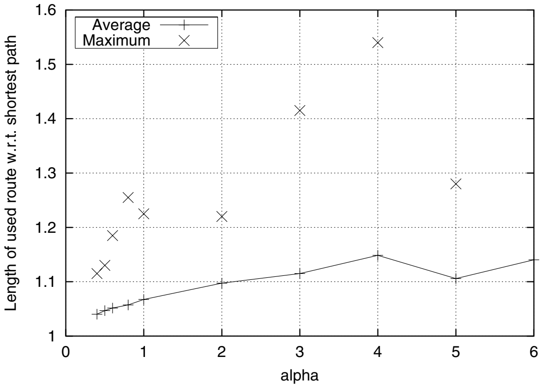


Figure 4: Average physical length of the routes used in the hybrid routing protocol in comparison to the shortest existing route between two nodes in a mobile ad hoc network of 100 nodes.

1. Route lifetimes follow exponential pdfs as discussed in the previous section, with an average lifetime λ which is known in advance. Since the average path lengths in our simulations appeared to be in the range of 2 to 4 hops, we assume $\lambda = L/3$, where $L = 26.7$ seconds is the average lifetime of the wireless links in the network with a node speed of 10 m/s and $\theta = 45^o$.

2. For all routes, there is a threshold of time β such that a search that is localized within a maximum distance of k nodes from all nodes in the route at any time $t < \beta$, will be able to find an alternate route between the same source-destination pair with probability one. Such a local route discovery made at a time $t > \beta$ from when a route was first discovered, will not be successful, requiring an additional network-wide search for replacing the route.

3. All localized route discoveries involve K number of

routing packets, where $K = 2 \times k \times 3$. This is a reasonable figure for a network with uniformly distributed nodes, having $k \times n$ number of nodes within a distance of k hops on each side of an n-hop route.

Note that a localized search performed pre-emptively will always be successful, even though it might not return the shortest path between the source and destination nodes (which will happen if the restricted search zone does not include the shortest path). However, the localized search performed using the purely on-demand protocol may be initiated at a time when the restricted search zone may not contain any routes between the source-destination pair. The parameter β represents the time after which the localized search will fail, and will depend principally on the network dynamics and the parameter k. For our analysis, we only consider the case where $T < \beta$, as otherwise there will be route breakages before the timeout for a pre-emptive localized search, which may not be successful. With these, the ratio R of the number of routing packets transmitted per unit time in the proposed hybrid routing protocol to that in a purely on-demand protocol that also uses the localized search to replace a broken route, is given by:

$$R = \frac{1}{(1 - e^{-T/\lambda})(1 + \frac{N}{K} e^{-\beta/\lambda})} \qquad (3)$$

where $T = \alpha L$ is the time at which the hybrid protocol makes the pre-emptive local search for a better route if the existing one is still alive. Figure 5 shows how R varies with α for the set of parameters described above and $T < \beta$. It is observed that the number of routing packets for the hybrid routing protocol at $\alpha = 0.5$ is about 30% greater than the case where pre-emptive routing is not used. For $\alpha > 0.8$, the number of routing packets in the hybrid protocol is *actually smaller* than that expected using the purely on-demand protocol. This is due to the fact that for $T < \beta$, a local search is always successful, and the routing overhead of the hybrid protocol is K packets for every search. However, when routes are broken at a time $t > \beta$ in the corresponding on-demand protocol, the routing overhead is $(K + N)$ packets, where N is the total number of nodes in the network. Considering the advantages in terms of the route length and quality, we conclude that using the hybrid routing protocol with $T < \beta$ and values of α in the range 0.8 to 1.0 will be more efficient than an on-demand protocol.

5 CONCLUSIONS

We propose a hybrid routing protocol that uses a pre-emptive local search for an alternate route when a route has been in use for a pre-determined amount of time. The motivation for doing this is to disallow usage of routes for a very long time, even if they are alive, for the purpose of replacing them by better routes. We use computer simulations to show that the proposed hybrid scheme can reduce the average length of the routes used in an on-demand routing protocol, both in terms of the number of hops as well as the physical length of the path. This will reduce the average end-to-end delay in packet transmission.

We also present results indicating that the lifetime of wireless links in a mobile ad hoc network with uniform but random node movements may be represented by an exponential random variable. This is particularly useful for mathematical modeling and analysis.

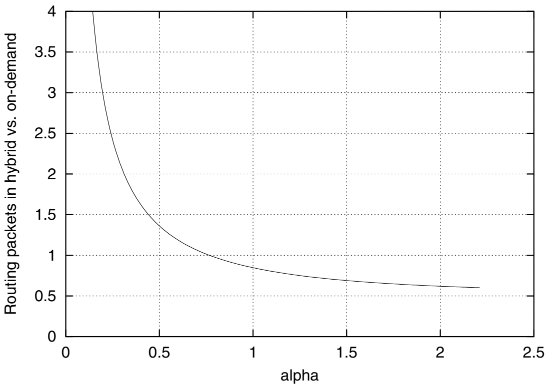


Figure 5: Ratio of the number of routing packets transmitted in the hybrid routing protocol over that in the corresponsding purely on-demand routing protocol. These results are obtained with $n = 3$, $k = 2$, and $\beta = 4$.

APPENDIX

Estimation of the Routing Overhead

Consider that a source is transmitting data packets to a destination node over a route which has n hops. We represent the lifetime of the route by an exponential random variable L_n, whose pdf is given by

$$f_{L_n}(t) = \frac{1}{\lambda} e^{-t/\lambda}, \quad t > 0 \qquad (4)$$

where $\lambda = L/n$ is the average lifetime of the route, i.e. time from its discovery until it breaks.

We assume that the timeout for initiating a pre-emptive search in the hybrid protocol, T, is less than β. Thus, for every route discovery, the total number of routing packets transmitted in this protocol is K. The interval between two successive route discoveries using the hyrbid protocol can be described by a random variable X, where

$$X = \begin{cases} L_n & \text{if } L_n \leq T \\ T & \text{if } L_n > T \end{cases} \qquad (5)$$

The average interval between successive route discoveries using the hybrid protocol is:

$$\begin{aligned} E[X] &= \int_0^T t f_{L_n}(t).dt + \int_T^\infty T f_{L_n}(t).dt \qquad (6) \\ &= \lambda(1 - e^{-T/\lambda}) \end{aligned}$$

Therefore, the average number of routing packets transmitted per unit time using the hybrid routing protocol is given by

$$N_{hybrid} = \frac{K}{\lambda(1 - e^{-T/\lambda})} \tag{7}$$

The purely on-demand protocol also generates K routing packets while using the localized search, i.e. when $L_n < \beta$. However, if this search is not successful, which happens when when $L_n > \beta$, an additional N routing packets are generated due to a global search. Hence, for this case, the number of routing packets generated when the existing route is broken, is a random variable Y, that can be described by

$$Y = \begin{cases} K & \text{if } L_n \leq \beta \\ K + N & \text{if } L_n > \beta \end{cases} \tag{8}$$

Hence, the average number of routing packets generated using the on-demand protocol whenever a route is broken is given by

$$\begin{aligned} E[Y] &= KP[L_n \leq \beta] + (K + N)P[L_n > \beta] \quad (9) \\ &= K + Ne^{-\beta/\lambda} \end{aligned}$$

Therefore, the average number of routing packets transmitted per unit time using the on-demand protocol is obtained as

$$N_{on-demand} = \frac{K + Ne^{-\beta/\lambda}}{\lambda} \tag{10}$$

Using equations 7 and 10, we get the expression given in equation 3.

REFERENCES

[1] R. V. Boppana and S. P. Konduru, "An adaptive distance vector routing algorithm for mobile ad-hoc networks", *Proc. IEEE INFOCOM'2001*, April 2001.

[2] J. Broch, D. A. Maltz, D. B. Johnson, Y-C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols", *Proc. 4th Intl. Conf. Mobile Computing and Networking (ACM MOBICOM'98)*, October 1998.

[3] Josh Broch, David Johnson, and David Maltz, "The dynamic source routing protocol for mobile ad hoc networks", http://www.ietf.org/internet-drafts/ draft-ietf-manet-dsr-01.txt, Dec 1998, IETF Internet Draft (work in progress).

[4] R. Casteñada and S. R. Das, "Query localization techniques for on-demand protocols in ad hoc networks", *Proc. ACM MOBICOM'99 Conf.*, 1999.

[5] S. R. Das, C. E. Perkins, and E. M. Royer, "Performance comparison of two on-demand routing protocols for ad hoc networks", *Proc. INFOCOM 2000.*

[6] R. Dube, C. Rais, K. Wang, and S. Tripathi, "Signal stability based adaptive routing (SSA)for ad hoc mobile networks", *IEEE Pers. Comm.*, pages 36–45, 1997.

[7] Z. J. Haas and M. R. Pearlman, "The zone routing protocol (ZRP) for ad hoc networks", `http://www.ietf.org/internet-drafts/draft-ietf- manet-zone-zrp-00.txt`, 1997, IETF Internet Draft.

[8] Z. J. Haas and M. R. Pearlman, "The performance of query control schemes for the zone routing protocol", *Proc. ACM SIGCOMM'98 Conf.*, pages 167–177, Vancouver, Sept. 1998.

[9] Y. Ko and N. H. Vaidya, "Location-aided routing (LAR) in mobile ad hoc networks", *Proc. ACM/IEEE MOBICOM'98 Conf.)*, pages 66–75, November 1998.

[10] David Maltz, Josh Broch, Jorjeta Jetcheva, and David Johnson, "The effects of on-demand behavior in routing protocols for multi-hop wireless ad hoc networks", *IEEE J. Sel. Areas Comm.*, 1999.

[11] A. Bruce McDonald and Taieb Znati, "A dual-hybrid adaptive routing strategy for wireless ad-hoc networks", *Proc. IEEE Wireless Comm. and Networking Conf. (WCNC'2000)*, 2000.

[12] S. Murthy and J. J. Garcia-Luna-Aceves, "An efficient routing protocol for wireless networks", *Mobile Networks and Applications*, 1(2):183–197, Oct. 1996.

[13] A. Nasipuri, R. Castaneda, and S. R. Das, "Performance of multipath routing for on-demand protocols in mobile ad hoc networks", *Mobile Networks and Applications (MONET) Journal*, to appear 2001.

[14] A. Nasipuri, J. Mandava, H. Manchala, and R. E. Hiromoto, "On-demand routing using directional antennas in mobile ad hoc networks", *Proc. of IEEE Intl. Conf. Computer Comm. and Networks (ICCCN 2000)*, 2000.

[15] V. Park and S. Corson, "Temporally ordered routing algorithm (TORA) version 1, functional specification", `http://www.ietf.org/ internet-drafts/ draft-ietf-manet -tora-spec-01. txt`, 1998. IETF Internet Draft.

[16] Charles Perkins and Elizabeth Royer "Ad hoc on-demand distance vector routing", *Proc. 2nd IEEE Workshop on Mobile Computing Sys. and Appl.*, pages 90–100, Feb 1999.

[17] Charles E. Perkins and Pravin Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers", *Proc. ACM SIGCOMM '94 Conf*, pages 234–244, August 1994.

[18] R. Sivakumar, P. Sinha, and V. Bharghavan, "Core extraction distributed ad hoc routing (CEDAR) specification", `http://www.ietf.org/internet-drafts/ draft-ietf-manet-zone-cedar-00.txt`, October 1998. IETF Internet Draft.

[19] C.-K. Toh, "Associativity-based routing for ad hoc mobile networks", *Wireless Personal Comm.*, 4:103–139, 1997.