Metrics to Enable Adaptive Protocols for Mobile Ad Hoc Networks

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***Abstract*— Adaptive ad hoc network routing protocols can obtain improved performance over a wide variety of node mobility and network dynamics when compared with non-adaptive protocols. A mobility metric, which quantifies the effect of node movement in order to measure the communication potential in a mobile network, can be used to develop an adaptive ad hoc network protocol. We provide a set of requirements necessary for a mobility metric to form a basis for an adaptive protocol. Next, we introduce a mobility metric, link duration, that meets our demanding requirements and is a good indicator of protocol performance. In addition, we investigate the suitability for enabling adaptive ad hoc network protocols of several previously proposed popular metrics.**

keywords: adhoc mobility adaptive protocols routing

I. INTRODUCTION AND MOTIVATION

Mobile Ad Hoc Network (MANET) protocols have been extensively studied and simulated in the past few years. Several comparative studies ([3], [5], [9] and [13]) have shown that there is no single protocol which works well in a wide variety of network conditions. A truly effective MANET protocol will combine the strengths of the best existing protocols while avoiding their weakenesses. An adaptive scheme that responds to the current network dynamics at each node shows promise in achieving this goal.

We use the term network dynamics to refer to the wide range of communication conditions a node can experience in a mobile ad hoc network. It refers to changing network topology, data congestion, shared medium contention, varying traffic patterns, varying traffic distributions, etc. For instance, node movement creates network topology changes via link breakages and link additions. These link changes require network protocol responses to ensure reliable data services continue. Routing protocols may need to change routes in response to link changes. Route changes in turn alter the traffic distribution in the network which also varies the congestion each node experiences. All these complex interactions result in certain network dynamics which are experienced differently by the nodes in the network.

A mobility metric provides feedback by quantifying the effect of node movement which signals the communication potential of the network. Such a mobility metric should be able to accurately indicate protocol performance, be protocol independent, and be obtainable by network nodes in real protocol implementations (i.e. it should not be dependent upon simulation artifacts such as mobility model parameters or movement patterns).

In this paper we first present our specific requirements of a mobility metric. Next, is a brief discussion of several alternative metrics used in the past along with some of their strengths and weaknesses. Finally we present link duration as a mobility metric that satisfies our requirements and accurately indicates protocol performance. Included are simulation results that demonstrate the potential of link duration as a mobility metric to indicate performance and enable adaptive protocols.[1]

II. METRIC REQUIREMENTS

Enabling adaptive protocols that can perform effectively throughout the demanding range of network dynamics requires a mobility metric that can accurately capture the networking challenges and effectively indicate the resulting performance of MANET protocols. Such a metric could provide feedback and allow the adaptation of a single protocol. Or the metric could facilitate a gradual change from one protocol to another in order to use the protocol that performs best in the current network scenario.

Past MANET simulation results have typically been reported by plotting protocol performance versus some parameter derived from the simulation mobility model being used. For instance, some papers report data packet delivery ratio or some other protocol metric (delay, overhead, etc.) as node pause time increases as in [3] and [5]. In these reports node pause time is the amount of time a node is paused between movements in the random waypoint mobility model. Mobility model input parameters are artificial quantities used as input into simulation models and are not suitable when MANET protocols are applied to real world networks. A mobility metric which is used as a MANET protocol feedback mechanism must be applicable to real networks with real nodes.

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Research group's URL is *http://toilers.mines.edu.*

[1] See Appendix for simulation environment details.

Our first step in a search for a mobility metric is to define a set of requirements that it must meet in order to enable adaptive MANET protocols.

1) **Computable in a distributed environment without global network knowledge.**
   Any metric which requires information from other network nodes and aggregates that information places an added demand on the network. This demand is nontrivial, and in some cases could require communication of mobility values from all, and to all, network nodes.
2) **A good indicator of protocol performance.**
   - **data packet delivery ratio**
   - **end-to-end delay**
   - **protocol overhead**

   A mobility metric must be able to indicate or predict the protocol's performance. For example, as the mobility metric's value changes, this would indicate a corresponding change in end-to-end delay. When the node receives feedback via the mobility metric it can proactively adjust the protocol to keep the delay within the required application bounds.
3) **Feasible to compute (in terms of node resources).**
   Limited energy (as a result of battery power), limited processing ability, and limited memory availability are all resource constraints that mobile nodes might have. A mobility metric must be feasible to compute by each node participating in the network. For example, a mobility metric which requires frequent communication may not be feasible to compute.
4) **Independent of any specific protocol.**
   Any feedback that is dependent on a specific protocol requires that protocol to be present. A general purpose mobility metric, which can be used by any protocol as a feedback mechanism for adaptive operation, is preferred. Furthermore, a protocol independent mobility metric is applicable to many network abstraction layers. The mobility metric can enable adaptive operation of a medium access control (MAC) protocol as effectively as a routing or reliable transport layer protocol.
5) **Computable in real network implementations.**
   A mobility metric must be available to real network nodes in real network implementations. As such, no simulation specific parameters or artifacts can be used. For example, actual node movements in real world networks will not always obey a previously studied pattern or model. The same is true for traffic model parameters or distributions.

III. METRIC ALTERNATIVES AND RELATED WORK

While searching for a mobility metric to meet the above requirments, several alternatives from the literature and elsewhere were considered. These are discussed in the following sections.

A. Mobility model parameters: node speed or pause time

Most research presents results according to node speed or some type of mobility model parameter such as pause time for the random waypoint model. Using mobility model input parameters as a mobility metric links the adaptability of protocols to an artificial input that may not be present in an implementation of the protocol in a real network. As a result, it is apparent that using node speed and pause time fail requirement 5.

B. Information unique to a protocol

Some protocols have an inherent feedback mechanism. For example, the Dynamic Source Routing (DSR) protocol [3] could adapt the route request timeout based on the end-to-end delay of its route requests. In DSR, the overall end-to-end delay could be reduced by adjusting the route request timeout, especially when network dynamics are high and frequent route requests are demanded. Enabling adaptivity in MANET protocols in this manner would require a custom feedback metric that is specific to each protocol, and possibly specific to each protocol parameter. This would require a great deal of work to identify, optimize, and show that the chosen unique protocol parameter was a good indicator of performance. In summary, using information unique to a protocol as the mobility metric fails requirement 4 and would be difficult to demonstrate adherence to requirement 2.

C. Average relative speed between all nodes

In [9] the authors present a mobility metric based on the average relative speed between nodes. While this does address the problem of two fast moving nodes which are able to maintain a stable link because they are traveling in similar directions, it violates requirement 1 by requiring speed information from other network nodes. In addition, this metric also violates requirement 3 because is not necessarily feasible to compute. Network nodes can benefit most from a good feedback mechanism when network dynamics are the highest. Communicating speed and direction among all nodes and calculating the resulting relative speed will be the most difficult, or not possible at all, in these network conditions.

The mobility metric in [9] (average relative speed) is compared to the number of link changes experienced by a mobile node. This comparison is presented as support for the metric's ability to capture one aspect of node mobility. The notion of tracking the change rate of links at a node provides valuable insight into a mobility metric that satisfies all our requirements (see section III-E).

D. Minimal route change metrics

In [8] the authors' goal for their mobility metric is to "evaluate the relative difficulty of routing in a given ad hoc network scenario." As such, they define two metrics that count the route changes between nodes. These types of mobility metrics fail two of our requirements. First, requirement 1 is not met since a network node can only know about multihop route changes with the assistance of and communication with intermediate nodes supporting the route. Second, while this notification is built into many MANET routing protocols, using this knowledge ties the mobility metric to a class of protocols and therefore does not meet requirement 4.

E. Link Change Rate

The primary difficulty in mobile ad hoc networks is created not by node mobility, but by the motion of nodes relative to one another that forces the network topology, or node interconnections, to change. This notion led us to initially focus on the link change rate experienced by a node as a mobility metric [1].

Figure 1 shows the data packet delivery ratio achieved by a MANET routing protocol as the link change rate increases.[2] Data packet delivery ratio appears to decrease as the number of link changes each node experiences increases. For example, ratios for link change rate near 1000 range from about 89% to 96%. Those for link change rate near 2000 range from 82% to 92%. When two networks have similar link change rates, the one whose nodes tend to move more slowly will often have a substantially better data packet delivery ratio. When a linear fit is applied to the data in figure 1, it demonstrates a coefficient of determination just below 50%.

Figures for end-to-end delay (see figure 2) and protocol overhead (see figure 3) show similar results. Delay and overhead both increase with increasing link change rate, but there exist "tails" in the plots that are similar to those seen in figure 1 and correspond directly to differing node speeds. The figures demonstrate a coefficient of determination when a linear function is fit of 24% and 56% respectively.

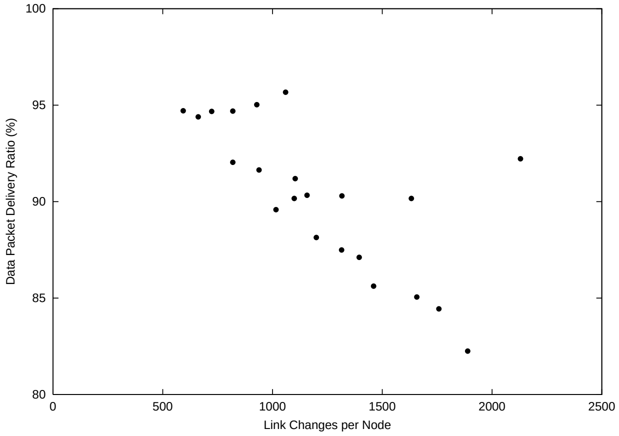

Fig. 1. Data packet delivery ratio vs. link change rate.

IV. Link Duration

As shown in figures 1 through 3, link change rate does not reliably indicate the performance of a protocol. In our analysis we realized that link change rate does not capture the longevity of communication links. Longer lasting links create more network stability, while shorter duration links create less network stability. An average link duration metric accurately captures this effect. It combines the link change rate and weights the changes by their stability (measured as number of seconds duration).

In the following sections (IV-A to IV-C) we present link duration's predictive value as a mobility metric, discuss how link duration meets the requirements of section II, and finally we discuss the use of link duration in real networks. In section IV-A we have fitted curves to the figures to illustrate that there is a smooth and predictable relationship between link duration and protocol performance.

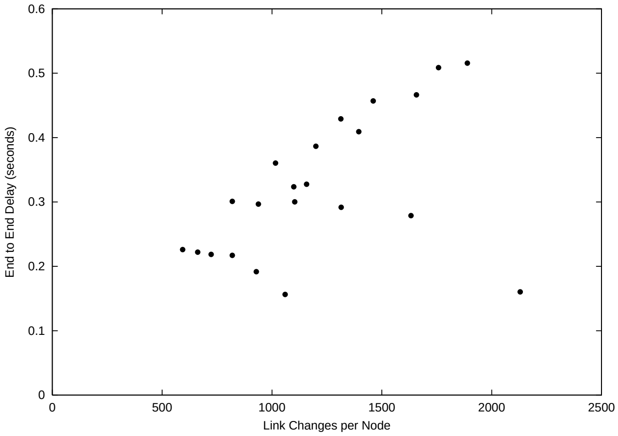

Fig. 2. End-to-end delay vs. link change rate.

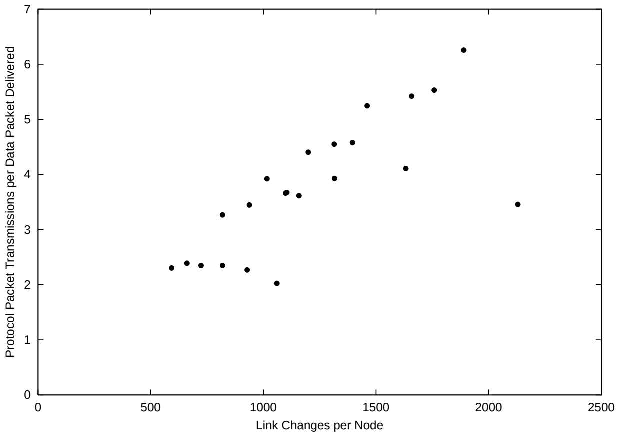

Fig. 3. Protocol packet transmissions per data packet delivered vs. link change rate.

Before continuing, a quick discussion of the calculation of link duration is appropriate. For the simulation results presented below, the duration of one link is calculated as the time that two nodes are within transmission range of one another. Average link duration is then calculated on a per node basis by averaging the individual link durations experienced with all neighbors. The link duration presented below on the x-axis of the figures is then the global network average of each individual node's link durations. In our simulation scenarios, all mobile nodes had similar movement parameters and the variation of link duration between nodes therefore was typically less than ten percent.

When performing simulations it is possible to obtain a node's average neighbor link duration over the total simulation length, and then average these link durations over all nodes. This sort of ideal link duration metric which results from using global knowledge is appropriate for our study con-

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[2] See Appendix for simulation environment details.

cerning the suitability of link duration as a mobility metric in general.

In a real implementation, neither global knowledge, nor an infinite window size (the time duration used to average the link connections) will be available to calculate link duration. Our aim is for each node to calculate average link duration independently. Sharing of this information with neighboring nodes or the the rest of the network nodes is not required as it violates requirement 1 above. Finally, and perhaps most importantly, is the determination of the appropriate window size used for averaging link durations. If the window size is too long, past link durations will influence the current average link duration value heavily, and the feedback provided will be less responsive. A window size which is too short might create widely varying, unstable feedback, or not be able to capture the duration of longer links at all. The determination of the window size used to average link connection times is critical to the quality of the link duration value used for feedback. As we implement our feedback agent for simulation and real use the appropriate values for this parameter are under investigation.

A. Link Duration as an Indicator of Protocol Performance

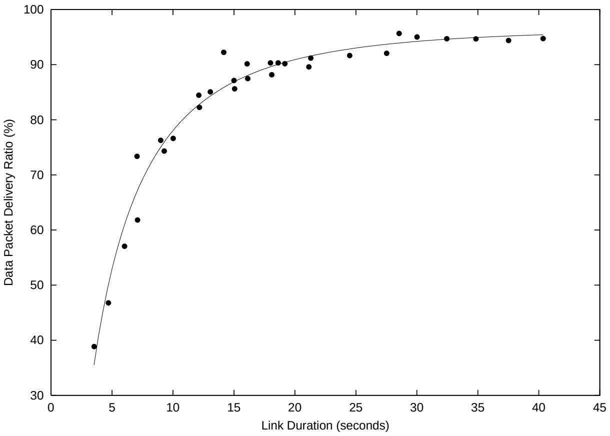

Fig. 4. Data packet delivery ratio vs. link duration.

Figure 4 plots the data packet delivery ratio as the link duration increases.[3] The figure shows that longer lived links create a more stable network, which in turn allows for the successful delivery of data packets. In fact, as long as communication links exist on average for longer than 15-20 seconds, over 90% of the transmitted packets are delivered successfully. The fitted curve has a coefficient of determination of over 97%.

Figure 5 plots the end-to-end delay as average link duration increases. Again we see a strong relationship between link duration and delay. Longer lived links result in shorter end-to-end delays. As in figure 4, we see that average link durations greater than approximately 15 seconds result in low delay, and the curve nearly "flattens" out at higher link durations. The fitted curve has a coefficient of determination of 96.7%.

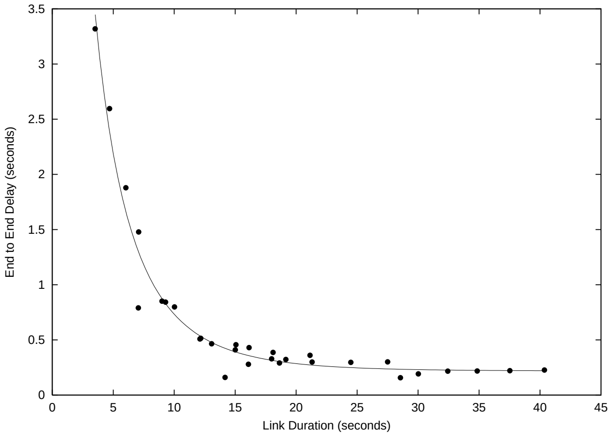

Fig. 5. End-to-end delay vs. link duration.

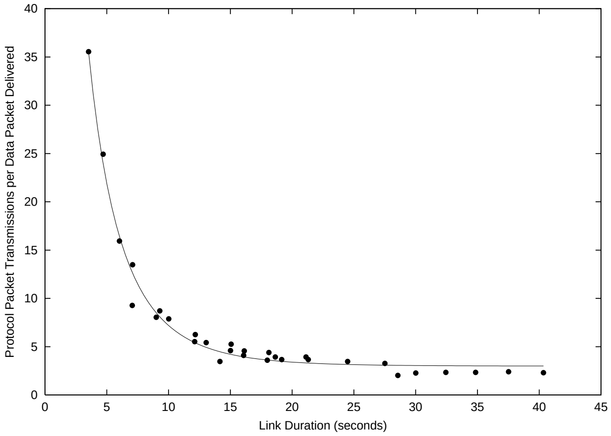

Fig. 6. Protocol packet transmissions per data packet delivered vs. link duration.

Lastly, figure 6 plots the protocol overhead as average link duration increases. Here again we see a smooth relationship between link duration and protocol performance (overhead). Longer lived links result in lower protocol overhead. As in figures 4 and 5, protocol overhead is at its lowest when average link durations are longer than 15 seconds. The fitted curve has a coefficient of determination of 98.5%.

B. Link Duration Meets Our Requirements

Link duration satisfies our requirements for a mobility metric. Specifically, it is:

1) **Computable in a distributed environment without global network knowledge.**
   The only information needed by a network node to calculate link duration is knowledge of its local changes in link status.
2) **A good indicator of protocol performance.**
   Section IV demonstrates that link duration is a good indicator of data packet delivery ratio, end-to-end delay, and protocol overhead.
3) **Feasible to compute (in terms of node resources).**
   The efficient gathering of link durations is possible and is discussed in more detail below.

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[3] See Appendix for simulation environment details.

4) **Independent of any specific protocol.**
Measuring the duration of communication links is by its very nature independent of any protocol.
5) **Computable in real network implementations.**
Link duration makes no reference to any artificial parameters. It measures a quantity that exists in all networks.

The distributed computation of link duration at each node is a key aspect of this metric's utility (see requirement 1), and has broad implications on node resource usage (see requirement 3). A node can gather link durations in a resource efficient, distributed manner by passively recording link information. In other words, every time a mobile node hears a transmission from neighboring nodes, the node records the link availability. Passively gathering link duration information has the obvious benefit of adding only a negligible processing burden and minimal state information to each node. The key to successful feedback from passive gathering is that if network traffic is high, and many or all nodes are involved in network communications, then the performance and accuracy of passive gathering approaches the actual link durations of the network. This is precisely the demanding network condition (high congestion and contention) that demands the most feedback and protocol adaptation. In times of light traffic between relatively few network nodes, passively gathered link duration information is less accurate, but ad hoc network protocols are minimally stressed by this environment and would probably benefit little from adaptation.

C. Using Link Duration for Adaptation

Examination of figure 4 indicates link duration regions where protocol performance is similar. For instance the data packet delivery ratio is above 90% as long as the link duration is longer than approximately 20 seconds. Also, as link durations get shorter, performance drops off quickly; for link durations less than 5 seconds, fewer than half the data packets are deliverable. Figure 5 also has well defined regions of protocol performance. When link durations are greater than approximately 25 seconds, delay is minimal (≈ 0.25 seconds) and unaffected by longer durations. For link durations between 10 and 25 seconds, delay begins to increase in both value and variablitity. If nodes are experiencing link durations below 10 seconds, delay grows extremely quickly and may have unacceptable values. In figure 6 the regions are also quite similar to those for delay (figure 5). Link durations above 25 seconds produce consistently low overhead. For the range between 10 and 25 second link durations, overhead is more variable, and begins to increase noticeably. For link durations shorter than 10 seconds, protocol overhead, like delay, grows quickly to possibly unacceptable levels.

Initial application of link duration to protocol adaptation could easily be done using this type of coarse grained information. Protocols can adapt in discrete ways with relatively big "steps", or changes in protocol control parameters. For example, a reactive protocol such as DSR could proactively adjust the route request (RREQ) timeout based on link duration feedback ([3]). Using the three adaptive regions outlined above, the protocol could set the RREQ timeout quite low when link durations are longer than 25 seconds; if a route request is going to succeed, the route reply will be returned very quickly. If on the other hand, link durations begin to shorten to the middle range (10-25 seconds), a slightly increased RREQ timeout would be warranted; nodes requesting routes need to be more "patient" and wait longer for the route reply in this network environment. Finally, when link durations get very short (below 10 seconds), performance has grown to unacceptable levels, and route requests may not be possible. In circumstances like this, if network congestion and contention allow it, the most prudent protocol reaction may be to flood a high priority data packet to the destination. If the data packet is low priority, then the protocol may decide to buffer the packet until a more stable network conditions exist.

V. CONCLUSIONS AND FUTURE DIRECTION

A mobility metric can enable MANET protocols to adapt. We have enumerated the requirements for a mobility metric and discussed several alternative metrics and their adherence to these requirements. In general, the previously proposed mobility metrics fall short either by not being good indicators of protocol performance, or by requiring global data from other nodes to be calculated. One metric, link duration, has been shown to satisfy our mobility metric requirements with one protocol, mobility model, and traffic pattern. Further work is needed to evaluate link duration's ability to meet requirement 2 with

- alternative protocols,
- alternative mobility models,
- varied traffic patterns, and
- varied traffic loads.

A mobility metric will allow the real time adaption of MANET protocols. Some existing protocols are ideally suited to take advantage of an accurate feedback mechanism provided by a mobility metric. For example,

- Zone Routing Protocol (ZRP) [7]
  Varying the zone size of ZRP makes it perform in a more reactive or proactive way. It has been shown that there are network circumstances that can benefit from either method. Using link duration as a feedback mechanism to appropriately set the zone size "on the fly" could enable ZRP to effectively adapt to network conditions and improve protocol performance.
- Mesh-Based Geocast Routing [2]
  Recent work [11] indicates that actively adapting the forwarding zone in mesh-based geocast routing can improve the data packet delivery ratio over a wide range of network conditions. Integrating link duration as the feedback mechanism may provide more accurate control over the adaptation than using a protocol parameter as is currently being done.
- Cluster Based Routing Protocol (CBRP) [12]
  CBRP uses a combination of two reactive protocols to

route packets within and between clusters. Accurately determining and adapting cluster size in response to changing network conditions may lead to improved performance.

In the future we will continue to evaluate link duration as an appropriate mobility metric that meets our requirements, and we will begin to enable protocols to adapt using link duration as the mobility feedback mechanism.

REFERENCES

[1] J. Boleng. Normalizing mobility characteristics and enabling adaptive protocols for ad hoc networks. In *LANMAN 2001: 11th IEEE Workshop on Local and Metropolitan Area Networks*, pages 9–12, March 2001.

[2] J. Boleng, T. Camp, and V. Tolety. Mesh-based geocast routing protocols in an ad hoc network. In *Proceedings of the 15th International Parallel and Distributed Processing Symposium (IPDPS): Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing (PDC)*, April 2001.

[3] J. Broch, D. Maltz, D. Johnson, Y. Hu, and J. Jetcheva. Multi-hop wireless ad hoc network routing protocols. In *Proceedings of the ACM/IEEE MOBICOM*, pages 85–97, 1998.

[4] T. Camp, J. Boleng, B. Williams, L. Wilcox, and W. Navidi. Performance evaluation of two location based routing protocols. submitted 2001.

[5] Samir R. Das, Charles E. Perkins, and Elizabeth M. Royer. Performance comparison of two on-demand routing protocols for ad hoc networks. In *Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, pages 3–12, 2000.

[6] K. Fall and K. Varadhan (Editors). Ucb/lbnl/vint network simulator - ns (version 2). http://www-mash.cs.berkeley.edu/ns/, 1997.

[7] Z. Haas. A new routing protocol for reconfigurable wireless networks. In *Proceedings of the IEEE International Conference on Universal Personal Communications*, Oct. 1997.

[8] Yih-Chun Hu and David B. Johnson. Caching strategies in on-demand routing protocols for wireless ad hoc networks. In *Proceedings of the ACM/IEEE MOBICOM*, pages 231–242, 2000.

[9] P. Johansson, T. Larsson, N. Hedman, B. Mielczarek, and M. Degermark. Routing protocols for mobile ad-hoc networks - a comparative performance analysis. In *Proceedings of the ACM/IEEE MOBICOM*, pages 195–206, 1999.

[10] Y. Ko and N.H. Vaidya. Location-aided routing (LAR) in mobile ad hoc networks. In *Proceedings of the ACM/IEEE MOBICOM*, pages 66–75, 1998.

[11] Y. Liu. A hybrid forwarding approach for the mesh-based geocast routing protocol in an ad hoc network. Master's thesis, Colorado School of Mines, 2001.

[12] Jiang Mingliang, Li Jinyang, and Y.C. Tay. Cluster based routing protocol. Internet Draft: draft-ietf-manet-cbrp-spec-01.txt, July 1999.

[13] Guangya Pei, Mario Gerla, and Xiaoyan Hong. LANMAR: Landmark routing for large scale wireless ad hoc networks with group mobility. In *Proceedings of the ACM/IEEE MobiHOC*, pages 11–18, 2000.

APPENDIX

This section contains the simulation parameter specifics for the data presented in figures 1 to 6.

Input Parameters	
Number of Nodes	50
Simulation Area Size	300m x 600m
Transmission Range	100m
Simulation Duration	2000 seconds, data transmitted 500-2000 seconds

Derived parameters are calculated directly from the input parameters [1]. Node density is simply the number of nodes divided by the total simulation area. Coverage area is the area of the circle whose radius is the transmission distance. The transmission footprint of a node is the percentage of the simulation area covered by a node's transmission. It is derived from the transmission range of the node and the size of the simulation area. The maximum path length is the distance from the lower left corner to the upper right corner in the simulation area. The network diameter is the maximum path length divided by the transmission range. Finally, the network connectivity indicates the number of one hop neighbors a node will have. The value labeled "no edge affect" is calculated by dividing the coverage area by the node density. The value labeled "edge affect" takes into account the fact that nodes near the edges do not have neighbors on all sides of the node.

Derived Parameters	
Node Density	1 node per 3,600 m^2
Coverage Area	31,416 m^2
Transmission Footprint	17.45%
Maximum Path Length	671m
Network Diameter (max. hops)	6.71 hops
Network Connectivity (node degree)	8.73 (no edge affect)
Network Connectivity (node degree)	7.76 (edge affect)
Data Traffic Model	
Communication Model	Communicating Pairs (peer-to-peer)
Number of Senders	20
Number of Receivers	20
Data Packet Size	64 bytes
Data Packet Frequency	4 packets per second
Traffic Type	Constant Bit Rate (CBR)
Link Bandwidth	2 Mbps
Mobility Model	
Mobility Model	Random Waypoint
Mobility Model Parameters	Speed = [5, 10, 20, 30, 40] Pause Time = [0, 10, 20, 30, 40, 50]
Simulator	
Simulator Used	NS-2 (version 2.1b6)
Medium Access Protocol	IEEE 802.11
Number of Trials	10 minimum, 20 on some cases
Confidence Interval	95%

Specific details about the routing protocol used (Location Aided Routing, or LAR) can be found in [10]. The NS-2 (see [6]) implementation details for LAR can be found in [4].

Protocol	
Routing Protocol	Location Aided Routing (LAR)
Timeout for 1 hop route request	30 ms
Route request timeout	500 ms
Forwarding error factor	0.0
Size of header with n addresses	4n + 40 bytes
Buffer size	64 packets
Packet lifetime in buffer	30 seconds