

# Routing in Mobile Ad Hoc Networks

N. Schult, M. Mirhakkak  
The MITRE Corporation  
1820 Dolley Madison Blvd  
McLean, VA 22102

D. LaRocca  
The MITRE Corporation  
145 Wyckoff Road  
Eatontown, NJ 07724

J. Strater  
General Instruments  
101 Tournament Drive  
Horsham, PA 19044

**Abstract**-This paper describes a recent simulation-based evaluation of several unicast routing protocols tailored specifically for mobile ad hoc networks<sup>1</sup>. Four protocols were evaluated: the Wireless Internet Routing Protocol (WIRP), a Link State (LS) algorithm with constrained LS updates, a Distance Vector variant of WIRP, and Temporally Ordered Routing Algorithm (TORA). The goal was to determine how well these routing protocols worked in specific tactical conditions, supporting a given mix of traffic. Factors varied included tactical scenario, network size, and loading. Tactical scenario included different connectivities (e.g., “dense” versus “sparse”) and link fluctuation rates (e.g., “high” versus “low”). Metrics collected included average end-to-end delay per application, path length, total efficiency, and fraction of user messages received. We found that certain protocols performed better in densely connected networks than in sparser networks (e.g., TORA), while some performed better in sparser networks (e.g., LS). One protocol, WIRP, performed well in both types of networks over the scenarios evaluated. Several remaining issues and areas for continued research are identified.

## I. INTRODUCTION

Traditional routing protocols were developed to support user communication in networks with a fixed infrastructure with reliable, high-capacity links. However, in the mobile ad hoc network, the network infrastructure is dynamically changing, and the links are wireless with less capacity and more prone to errors. Mobile ad hoc networks will be critical to future deployed military units, and several Army programs (such as the First Digitized Division) have requirements for this type of network.

Recently, a number of routing protocols have been proposed for mobile ad hoc networks, as part of the Defense Advanced Research Project Agency’s (DARPA) Global Mobile (GloMo) program and the Internet Engineering Task Force (IETF) Mobile Ad hoc Network (MANET) working group. These protocols generally fall into one of two

categories: proactive or reactive<sup>2</sup>. Proactive routing attempts to maintain optimal routes to all destinations at all times, regardless of whether they are needed. To support this, the routing protocol propagates information updates about a network’s topology throughout the network. In contrast, reactive or on-demand routing protocols determine routes to given destinations only when there is data to send to those destinations. If a route is unknown, the source node initiates a search to find one.

Proactive routing protocols have the advantage of having short routes available at all times, thereby avoiding the delay of searching for a route on demand. They also avoid any traffic surge that results from reactive route querying. Reactive routing protocols have the advantage of only generating routing overhead to find routes when routes are needed, independent of network topology changes.

This paper describes a recent simulation evaluation conducted of several unicast routing protocols tailored specifically for mobile ad hoc networks. (A companion study investigated channel-access schemes, but is not addressed here). Four protocols were evaluated: the Wireless Internet Routing Protocol (WIRP) [2]; a Link State (LS) algorithm with constrained LS updates, based on ideas presented as part of the Mobile Multimedia Wireless Network (MMWN) system [3]; a Distance Vector variant of WIRP; and the Temporally Ordered Routing Algorithm (TORA) [4, 5]. The first three of these protocols can be considered proactive protocols, while TORA is a reactive protocol. The goal of the evaluation was to determine how well these routing protocols worked in specific tactical conditions, supporting a given mix of traffic. The next section gives an overview of the tactical scenarios considered in our evaluation. This is followed by a description of the simulation model and experimental design used to generate routing performance results. Finally, a set of results is presented, and areas for continued research are identified.

<sup>1</sup> This work was partially funded by the U.S. Army, Communications Electronics Command, Command and Control Directorate.

<sup>2</sup> Some hybrid protocols have also been proposed that are partly proactive and partly reactive, such as the Zone Routing Protocol (ZRP) [1].

## II. LAYDOWN AND MOVEMENT SCENARIOS

To evaluate the routing protocols in tactical conditions, three laydown/movement scenarios were developed. These are referred to as the infantry open terrain (IOT), infantry urban terrain (IUT), and vehicular (NTC, for National Training Center) scenarios. This section briefly describes the scenarios, how they were generated and analyzed, and how they were used in the routing evaluation. For a more detailed discussion (including how the scenarios information is used in a channel access evaluation), the reader is referred to [6].

The methodology for generating all three scenarios consisted of first using the Modular Semi-Automated Forces (ModSAF) simulation application (computer-generated forces code [7]) to generate position updates based on operational information obtained. These updates were then analyzed to determine propagation loss, range, link connectivity, and link fluctuation characteristics between the scenario elements. The analysis covered the full duration of the scenarios and involved use of propagation loss models with and without terrain dependency. The analysis included querying ModSAF for terrain profile information between scenario elements when terrain dependent propagation loss calculations were employed.

Both infantry scenarios, IOT and IUT, were generated in ModSAF over Fort Hunter-Liggit terrain. Both scenarios consisted of 9 teams of 5 members each, with members moving approximately 3 kilometers(km) per hour (hr). In the open terrain scenario (IOT), teams are separated by approximately 2 km at the start, and the teams travel down valleys to a given destination (a city). In the urban terrain scenario (IUT), teams are clustered within a 1 km square area, and the teams move through the city.

The vehicular scenario was generated in ModSAF over Fort Irwin terrain for the National Training Center (NTC). It has a friendly battalion group of 3 companies (36 vehicles), and an enemy group of 2 companies with 10 vehicles each. In ModSAF the friendly companies are directed along a road towards the enemy at approximately 30 km/hr. At the end of the scenario, the battalion is dispersed over a wide area with distances between adjacent elements as large as 5 km.

To model propagation, the Terrain Integrated Rough Earth Model (TIREM) was used for the open terrain scenarios, and the Malaga urban model [8] used for the urban scenario. Radio frequency parameters assumed included a carrier frequency of 300 MegaHertz (MHz), transmit power of 1 Watt, antenna gain (transmit and receive) of 0 decibels (dB) (omnidirectional), 1 meter antenna height, and a received bit energy-to-noise density of 10 dB. The information burst rate of the radio was chosen to be 250 kilobits per second (kb/s). From this analysis the link connectivity characteristics for each scenario were derived. Links were considered up when propagation losses were less than 130 dB and down otherwise. Connectivity is highest for the IOT scenario,

followed by the IUT and finally NTC scenarios<sup>3</sup>. The IOT scenario has the highest connectivity because its members are relatively close and in open terrain. The IUT scenario has lower connectivity due to much higher urban propagation losses. NTC has the lowest connectivity since its elements are distributed over relatively wide ranges.

For the routing evaluation, connectivity matrices were used that indicated the type of connectivity between each node pair. Links between nodes were either permanently up, permanently down, or fluctuating, which is indicative of nodes moving generally in the same direction, but over varied terrain. Average link fluctuation characteristics were applied to the fluctuating links in the matrices for each scenario.

## III. SIMULATION MODEL

To evaluate the different routing protocols, we developed a network-layer network simulation model using MIL3's OPNET Modeler package. Our model includes detailed routing protocol models, with abstracted models for physical layer, channel access, and traffic. This section provides an overview of the models developed and assumptions made.

The network model developed (representing " $n$ " mobile hosts) consists of  $n$  fixed nodes and a link manager that manages the (bidirectional) links between them. Node mobility and terrain conditions are represented by the fluctuation of (implicitly-defined) links between nodes, which are controlled by the link manager. The links between nodes are derived from the connectivity matrices generated by the link analysis described in the previous section. For our evaluations, links were either always up, down, or fluctuating. When links are fluctuating, their up and down epochs are assumed to follow independent Markov-modulated Poisson processes, with the average lengths of the up and down epochs matched to the average link up and down times. For the IOT and IUT scenarios, these averages are 50 seconds (sec) up and 50 sec down. For NTC, the averages are 30 sec up and 10 sec down. Noise and background interference are approximated by assigning a low, residual link bit error rate (BER) to model thermal noise effects.

Each node in our network model consisted of a number of modules, with each module containing a process model. Of particular note were the following modules: four modules representing four different types of application traffic, a "routing" module, an "ip\_encap" module that encapsulates/decapsulates application and routing traffic in an IP header, an "ip" module, and "data-link adapter" module. By changing the process model in the "routing" module, we were able to evaluate different routing protocols under identical conditions.

The application traffic types included in the model are Engagement Operations (EOPS), Command and Control

<sup>3</sup> Refer to [6] for quantitative classification of link connectivity and fluctuation statistics.

(C2), Situation Awareness (SA), and Voice. Some assumptions made about this traffic are listed below:

- The mix of application traffic stayed constant, although the aggregate load varied. We assumed a mix of 10%, 30%, 30%, and 30% for EOPS, C2, SA, and Voice, respectively.
- All application traffic was unicast, with destinations determined randomly from the set of all nodes.
- Interarrivals: All but SA assumed exponential interarrivals. For Voice, interarrivals were the time between calls; within a call, packets were generated deterministically. SA had constant interarrivals.
- Packet Sizes: EOPS packet sizes followed an exponential distribution, with a 50 byte mean. C2 packet sizes were exponential, with a mean of 500 bytes. SA packet sizes were constant with a mean of 50 bytes. Voice packets were generated at a 5 kilobits/second rate and 100 ms packet creation within a call (implying a 500 bit packet).
- Priority: Each type of data was assigned a priority, which was used to schedule packets for transmission in the ip module. The priorities were assigned as follows (0 is highest, 5 is lowest): 0 – Routing; 1 – EOPS; 2 – Voice; 3, 4, 5 – C2; 4 – SA.

In the ip module, packets are queued according to their priority. In this initial investigation, the scheduling discipline was strict priority with no preemption. When the “data-link adapter” module indicates it is ready to transmit, the ip module sends the highest priority packet waiting in the queue. Depending on the destination address, the “next hop” address is determined at this time. SA packets are additionally processed such that a maximum of only one SA packet from a given source is ever queued at a given node, with a newer packet replacing an older one.

The “data-link adapter” module handles the data link control and channel access functions, as well as any actions sent by the link manager. For our routing evaluation, the channel access was approximated with an ideal packet reservation approach. This approach did not include contention, but access was restricted by channel reservation around a receiving node. Data link control was approximated with an ideal connectionless, immediate-ACK approach. Data link control was only applied to EOPS, C2, and unicast routing traffic, which have reliability requirements. The maximum number of transmissions per frame was set to three.

Certain common capabilities were added to all the routing protocols evaluated in this study. This included a reliable network-layer neighbor broadcast capability. This consisted of a maximum of three transmissions per broadcast, with a list of neighbors attached from which the transmitting node expects acknowledgements. This is similar to a method described in [9].

#### IV. EXPERIMENTAL DESIGN

As previously mentioned, the goal of our study was to determine how well the routing protocols did under different tactical conditions. The factors and levels chosen, and metrics collected are discussed below.

Four factors were defined and varied in our experiments. These were: network scenario, routing protocol, number of nodes, and application traffic load. Three network scenarios were considered: IOT, IUT, and NTC. As mentioned above, embedded in each scenario is the node connectivity (e.g., whether a node is sparsely or densely connected to other nodes) and link fluctuation (e. g., the rate the link’s state changes). Four primary routing protocols were evaluated: WIRP, LS, DV, and TORA. The number of nodes was set to 10, 20, or 40. Application traffic load is defined here as a percentage of effective bandwidth per link, which was assumed to be 250 kb/s. For 10 nodes, total loads from 10% to 50% were used<sup>4</sup>; for 20 nodes, total loads from 10% to 130% were applied; for 40 nodes, total loads between 10% and 250% were used.<sup>5</sup>

A variety of metrics were computed from measurements collected, to determine the effectiveness of the routing protocols. These metrics can be divided into two categories: user/traffic performance metrics and routing/network performance metrics. Traffic performance metrics included end-to-end packet delay, fraction of packets received, and packet throughput (both total and per application). Routing/network metrics included routing data efficiency, routing control efficiency, and path length. Routing data efficiency is the average number of data bits transmitted divided by data bits delivered, while routing control efficiency is the average number of control bits transmitted divided by data bits delivered [10]. Total efficiency is the average number of data and control bits transmitted divided by data bits delivered. (In the results below, the reciprocal of this value is actually plotted.) Independent replications were used (5 total) per experiment to compute 90% confidence intervals of these metrics. The duration of each experiment was 3000 seconds.

<sup>4</sup> This total load was evenly divided among the nodes.

<sup>5</sup> Loading was varied to see how well the routing protocols performed under stressed traffic conditions. The different range of loading values for the different number of simulated nodes reflects differences in net loading supportability.

V. RESULTS

Some highlights of results for the 20-node networks are discussed in this paper. In general, the 10-node and 40-node results show similar performances. For more detailed results, see [6].

The results of average aggregate end-to-end packet delay when using WIRP, LS<sup>6</sup>, and TORA routing are shown in Figs. 1-3 for the IOT, IUT, and NTC scenarios, respectively. A variation of WIRP called DV was also evaluated and found to be similar but somewhat deficient relative to WIRP, so it is not discussed here. These results show that average delay increases as the network becomes sparser (IOT represents a dense network, while NTC represents a sparse network) and aggregate load increases. In addition, as the network becomes sparser (i.e., from IOT to IUT to NTC), the average delays when using WIRP and LS remain relatively low, while the average delay when using TORA increases substantially. For the IOT scenario, the average delay when using TORA or WIRP is low, compared to the delay when using LS. The absolute delay for the IOT scenario is relatively lower however. Using the less dense scenario of IUT and the sparse scenario of NTC, the average delay with TORA increases as the network becomes more sparse, while the average delay with WIRP or LS remain relatively low.

The results of effective throughput for each scenario at 130% load (the highest load evaluated for the 20 node case) using WIRP, LS, and TORA routing are shown in Fig. 4. These results show that throughput for all three routing protocols is relatively high for the IOT scenario. We also found that the effective throughput when using TORA or WIRP is higher than LS routing, due to the higher overhead associated with control (routing) traffic.

Effective throughput decreases for sparser scenarios because of less connectivity and because of faster link fluctuations, in the case of the NTC scenario. Effective throughput when using TORA suffers the most for sparse scenarios because TORA uses non-optimal routes, which results in longer routes. TORA, it turns out, also generates a lot of overhead under these conditions.

The results of total efficiency at 130% load for WIRP, LS, and TORA routing for the three scenarios are shown in Fig. 5. As illustrated in the figure, WIRP has the highest total efficiency of the three protocols for all three scenarios. TORA's total efficiency is high for IOT, which is densely connected, and it is low compared to WIRP and LS as the network becomes sparser. Efficiency values are highest for IOT (approaches 0.5), but are lower for IUT and NTC (around 0.35 for IUT and 0.28 for NTC), indicating that total efficiency decreases as the network becomes sparser.

<sup>6</sup> For LS, we had to increase its 2 timer values, when evaluating higher loads and increased connectivity, to prevent network saturation. We also had to increase these values when we increased the number of nodes considered (i.e., from 10 to 20, 20 to 40).

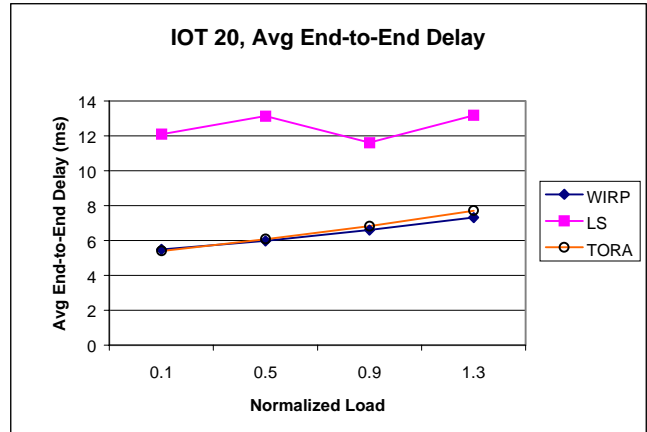


Fig 1. IOT 20 Results, Average End-to-End Delay (ms)

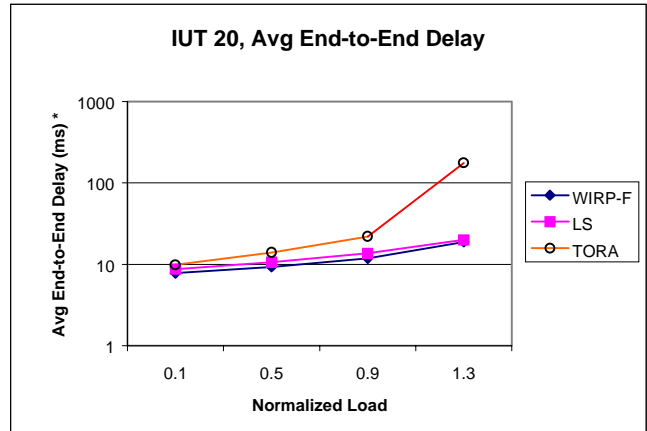


Fig 2. IUT 20 Results, Average End-to-End Delay (ms)

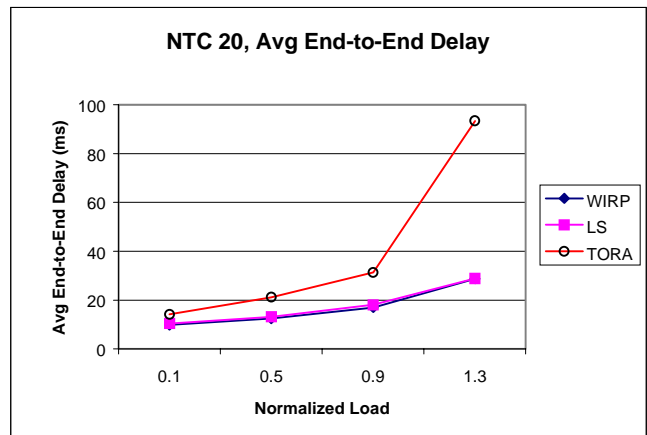


Fig. 3. NTC 20, Average End-to-End Delay (ms)

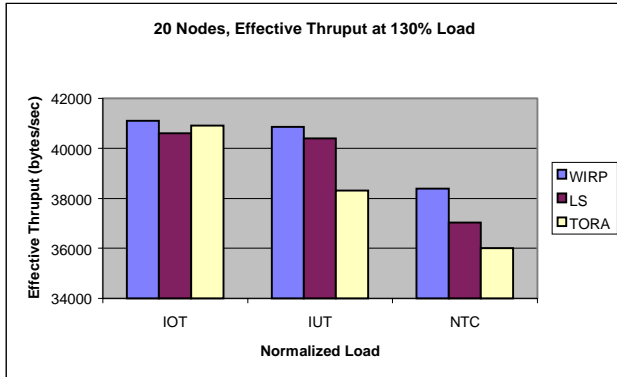


Fig. 4. Effective Thruput at 130% Load

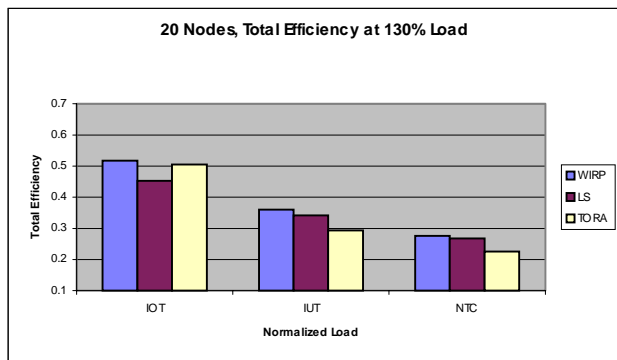


Fig. 5. Total Efficiency at 130% Load

A comparison of performance over all results (Figs. 1-5) indicates that traffic in sparser scenarios experiences higher average delay and lower effective throughput. The sparser networks also experience lower total efficiency. This means that the routing protocols in the IOT scenario are more efficient than in the IUT scenario, and least efficient in the NTC scenario. In general, performance gets worse as the network becomes sparse because routes become longer and overhead increases. Net partitioning can also occur more frequently.

The results show that WIRP performs well under all network scenarios and is suitable for sparse and dense network scenarios. LS has best relative performance when the network is sparse, and its performance deteriorates relative to WIRP slightly, as the network becomes less sparse because of the increase in control traffic that it generates. We found LS performance to be sensitive to its two timer values, which we needed to adjust as load and link connectivity increased. TORA performs best when the network is densely connected, when routes are short and overhead is low (due to less frequent queries).

## VI. FUTURE WORK

This paper provides some selected highlights of an evaluation of several unicast routing protocols for mobile ad hoc environments. Three laydown and movement scenarios were generated and used in this evaluation, and the performance of the protocols was compared over a variety of metrics. However, these scenarios should not be considered comprehensive and the routing protocols should also be evaluated under other conditions. For example, the impact of these routing protocols when the network size increases to 100 nodes and even 1000 nodes would be a very interesting study.

A number of assumptions were made to evaluate these protocols using simulation, and these should be revisited. Although our abstracted representation of channel access and the physical layers allowed us to do a first-cut comparison of protocols, the fidelity of these models should be increased to more realistically represent the radio environment. We are currently extending this network simulation model to include more realistic radio representation, as part of an effort to evaluate multicast routing protocols in a mixed satellite and wireless environment.

## ACKNOWLEDGMENT

We gratefully acknowledge the contributions of Vicki Yu and Mike Snyder on generating the laydown and movement scenarios.

## REFERENCES

- [1] Haas, Z., and M. Pearlman, "The Zone Routing Protocol (ZRP) for Ad Hoc Networks", Internet Draft, draft-ietf-manet-zone-zrp-01.txt, August 1998, Work-in-progress.
- [2] Murthy, S., and J. Garcia-Luna-Aceves, "An Efficient Routing Protocol for Wireless Networks", *ACM/Baltzer Journal on Mobile Networks and Applications*, Vol. 1, No 2, 1996.
- [3] BBN, "System Design Specification for Mobile Multimedia Wireless Network (MMWN)", Oct. 30, 1996.
- [4] Park, V., and S. Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks", *Proceedings of Infocomm'97*, 1405-1413, April 1997.
- [5] Park, V., and S. Corson, "Temporally-Ordered Routing Algorithm (TORA) Version 1 Functional Specification", Internet Draft, draft-ietf-manet-tora-spec-01.txt, August 1998, Work in progress.
- [6] Strater, J, N. Schult, M. Mirhakkak, D. LaRocca, M. Snyder, V. Yu, *Evaluation of Network Protocols for Ad Hoc Networks*, MITRE Technical Report, MTR 98W0000152, September 1998.
- [7] *ModSAF Software Architecture and Overview Document*, Loral Advanced Distributed Simulation Technology Program Office, ADST/WDL/TR--95--W003339B, 28 April 1995.
- [8] Malaga, A., "An Empirical Path Loss Model for HF/VHF Propagation in Urban Areas", *Radio Science*, May 1981.
- [9] Corson, S., S. Papademetriou, P. Papadopoulos, V. Park, and A. Qayyum, "An Internet MANET Encapsulation Protocol (IMEP) Specification", Internet Draft, draft-ietf-manet-imep-spec-01.txt, August 1998, Work-in-progress.
- [10] Corson, S., and J. Macker, "Mobile Ad hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations", RFC 2501, January 1999.