Performance Evaluation of Routing Protocols for Mobile Ad-Hoc Networks (MANETs)

Pedro Lopez, Zornitza Prodanoff, and Sanjay Ahuja

University of North Florida
{pedro.lopez, zprodano, sahuja}@unf.edu

Abstract—Mobile Ad-Hoc Networks (MANETs) are a very active area of research at the present time due to their great potential to provide networking capabilities when it is not feasible to have a fixed infrastructure in place, or to provide a complement to existing infrastructure. The routing in these networks is more challenging than that of conventional networks due to their mobile nature and limited power and hardware resources. The Glomosim simulation environment is used in this study to investigate various statistics and draw comparisons among different routing protocols: Bellman-Ford, AODV, DSR, LAR, WRP, and Fisheye. In particular, we investigate protocol performance used in a military application assuming MANETs used for manpower, tank (e.g. T1), or helicopter (e.g. MQ-8B) connecting network configurations, however, the network configurations for all experiments are generic enough to be applied to other environments. This study encompasses a greater number of routing protocols than most other previous works, and investigates, among other things, some effects that are not commonly methodically investigated, such as radio range and physical domain aspect ratio. Our results show that with a few exceptions, when varying the number of nodes in the network layout, AODV and LAR outperform other routing protocols for most configurations. For higher node densities ate about 70 nodes and above, as the transmit power increases from of 7.005 to 10.527 dBm as expected all protocols perform better at lower mobility speeds, however, AODV and LAR exhibit a much smaller performance degradation, when this speed increases.

I. INTRODUCTION

Mobile ad-hoc networks (MANETs) are networks of mobile devices, typically referred to as nodes, that communicate with each otherwirelessly without having to resort to any kind of pre-existing infrastructure. However, some of the nodes can communicate with existing infrastructure (such as the Internet) as well if that is required. MANETs allow the quick set-up of networks “on the spot” in a quick fashion, without reliance on existing facilities and infrastructure [21], [22]. In this manner, an organization can set up a network just about anywhere, either in temporarily (such as in response to an emergency or in on-the-field, mobile military operations) or in a permanent or semi-permanent manner (such as in border monitoring). The inherent ability to move the nodes about and yet maintain the connectivity is an attribute that makes MANETs the only kind of network suitable to certain situations. This kind of flexibility makes MANETs an invaluable addition to traditional networking technologies, and one which is nowadays under heavy research and development. Wireless sensor networks (WSNs) are a specialized variant of MANETs whose main purpose is to sense or monitor a predetermined type of event, such as vibration levels, temperatures, pressure, etc. in various environments [1], many of them hostile to or difficult to access by humans. WSNs do not necessarily have to be mobile, although they can be, and often cannot rely on human intervention for operation once deployed. In contrast with regular MANETs, sensor networks often have numbers of nodes several 5 orders of magnitude larger, are more prone to failure (they are simpler and cheaper nodes that rely on large numbers and further deployments rather than upkeep/maintenance), are data-centric (“all sensors where the temperature reaches 100o must be woken up”), have more limited hardware resources (such as memory, etc., to keep cost down), and feature data aggregation (nodes aggregate local information before relaying the information back where it needs to go) [13], [22]. Economy of energy usage is even more important than in conventional MANETs due to WSNs deployment characteristics, leading to trade-offs between sensitivity and energy-usage [13], [25]. As such, their networking protocols at various layers are highly specialized and differ from those of conventional MANETs [22]. The special characteristics that distinguish MANETs from conventional networks gives rise to certain performance issues that they are particularly susceptible to. One does not just worry about the typical issues affecting a more conventional network, but also about issues such as node mobility (which implies constant topology changes), limited
and power conservation. Link unidirectionality is particularly important for MANETs [10], [21], since the nodes radio equipment may be heterogeneous, some nodes may be more susceptible to interference from various sources, etc., giving rise to different radio ranges for different nodes.

This project is directed at investigating the performance of various routing protocols in conventional, bidirectional MANETs. Various measures of performance will be evaluated and compared between the different routing protocols. Of special interest is how each protocol is affected by different levels of mobility, node density and radio range.

II. PREVIOUS WORK

The multiplicity of available MANET routing protocols and the availability of MANET simulators has led to numerous performance studies and comparisons. The studies in [16], [23], and [19] used the GloMoSim simulator. In [16], AODV, DSR, and STAR are compared in terms of data delivery, control overhead, and average latency under various scenarios of mobility, connectivity density, number of data flows, domain shape and initial node placement. AODV turned out to be the best protocol in terms of data delivery in densely connected scenarios, whereas STAR was found to be the best performer in all the remaining cases. The work described in [23] compared AODV, WRP, DV, and DSR. The metrics of interest in the experiments were end-to-end delay, packet delivery rate, and messaging overhead, with the control parameters being traffic load, node density, and node mobility. DSR was found to have the lowest messaging overhead but highest end-to-end delay of all. The proactive protocols, DV and WRP, proved to be less vulnerable to increases in traffic load than their reactive cousins; WRP, in particular, consistently demonstrated the lowest end-to-end delay of all the protocols and had excellent packet delivery rates. All the protocols suffered from low delivery rate when the mobility was perpetual, with DV showing the poorest scalability for node mobility in the end-to-end delay. The work carried out for [19] was not one to compare various protocols, but rather one to test various improvements to an existing protocol, AODV. Expanding ring search and query localization techniques were found to reduce the amount of overhead produced by the protocol, whereas the use of local route repair techniques improved the number of data packets that reached their destinations. The most popular MANET simulator, NS-2, was used in [9], [3], [4], [17], [8], [11], and [5]. The goal in [9], which compared LAR, DREAM, and DSR, was to stress the protocols at both low and high speeds (0 to 20 m/s). The data delivery ratio stayed pretty much constant for DREAM, where as for the other protocols it started out better than DREAM at low speeds but it quickly deteriorated at higher speeds, DREAM bettering all others at the high end of the speed spectrum, while DSR fared the worst. In terms of control packet overhead, DREAM started out with the worst performance at low speeds, but it again bettered all the other protocols at the high end of the speed spectrum; DSR in non-promiscuous mode performed the worst of all at high speeds, whereas DSR in promiscuous mode performed second best for high speeds, with LAR being just slightly worse than DREAM at high speeds. In [3], AODV, PAODV (Preventive AODV), CBRP, DSR, and DSDV were investigated in terms of throughput, average end-to-end delay, and overhead, using various scenarios of mobility, load, and size of the network. The findings revealed AODV to have the highest overhead of all, followed

<table>
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<tr>
<th>Network Layer/Physics</th>
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<tr>
<td>Application</td>
<td>Application CBR (Constant Bit Rate), HTTP, Generic FTP, FTP, Telnet</td>
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<tr>
<td>Transport</td>
<td>UDP, TCP</td>
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<td>Network (Routing)</td>
<td>Bellman-Ford, AODV, Fisheye (FSR), DSR, LAR 1, WRP</td>
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<td>Datalink (MAC)</td>
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<td>Packet Reception</td>
<td>SNR-bounded, BER-based Radio ACC-noise, no-noise</td>
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<td>Radio-wave Propagation</td>
<td>Free Space, Two Ray</td>
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<td>Mobility</td>
<td>Random Drunken, Random Waypoint, Trace</td>
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by CBRP and DSR; DSR and CBRP both showed very high throughput, whereas AODV showed a very short end-to-end delay. PAODV proved to be only very slightly better than AODV. The work in [4] is the same as that in [3], but only covering AODV, CBRP, and DSR in terms of throughput and end-to-end delay, whereas [5] is an extension of [4] by also considering overhead. A new mobility metric, \( M \), is developed in the work described in [17], which is an average of the absolute relative speed between all the node pairs in the network. In this study, DSDV, AODV, and DSR were compared in terms of throughput, delay, and overhead for different scenarios involving mobility (\( M \)) and offered load. The reactive protocols turned out to be superior to the table-driven one (DSDV), with both AODV and DSR behaving very similarly in terms of delay and throughput, and with DSR being superior at low traffic loads and AODV at higher loads. DSR was more efficient at low traffic loads, whereas AODV was more efficient at higher packet loads. The work in [8] compared DSDV, TORA, DSR, and AODV under a variety of mobility and workload scenarios with the goal of measuring the ability of the protocols to react to topology changes while continuing to deliver data to the destinations. The results in this work correlate very well with those in [17], DSR and AODV being the superior performers in all mobility scenarios. The work in [11] considers only DSR and AODV, which are emerging as possibly the two most promising protocols, under various load, mobility, node density, and domain shape scenarios. The parameters investigated were packet delivery fraction, average end-to-end delay, and normalized routing load. DSR almost always showed a lower routing load than AODV, but when the MAC (802.11 was used) overhead was taken into account, the overhead generated using both protocols was found to be very similar. AODV was found to provide better performance in terms of packet delivery fraction and delay when the network was more stressed, whereas DSR did better with less network stress. These results agree well with those found in [11] and [17]. The work in [20] is tailored to the ROKA (Republic of Korea Army) and it used the Opnet simulator. It compared the AODV, TORA and DSR protocols in a network of 20 apparently fixed nodes for varying data rates. No protocol was better than TORA in terms of packet delivery fraction, with AODV being second-best. AODV showed better delay and routing load than TORA except at the lower end of the packet generation rates investigated. The overall lower performer was DSR. The authors of the study ended up recommending the use of TORA. The experimental (with actual networking hardware) comparison of APRL, AODV, ODMRP, and STARA in [12] compared the protocols under a random, constant speed (walking pace) conditions of mobility and low network load using 33 nodes in a 225 x 365 square meters athletic field. The investigated parameters were message delivery ratio, communication efficiency, hop count, and end-to-end delay. The reactive approaches were found to be better in dynamic environments than the table driven ones; ODMRP was concluded to be able to handle higher mobility than AODV due to its higher message delivery ratios measured.

III. EVALUATION OF MANET ROUTING PROTOCOLS

A. Testbed Description

The experiments and data processing for this project were executed on a personal computer with an AMD Athlon 2200+, 32-bit processor, and 1 Gigabyte of memory running a Fedora Core 4 Linux operating system. The software testbed consisted of a network simulator, a preprocessor (input file creator), a batch-running facility, and the post-processing components. These software elements will now be discussed in more detail.
The chosen MANET simulator is Glomosim (Global Mobile Information System Simulator) [26], [2]. Glomosim was designed using the parallel discrete-event simulation afforded by the Parsec (Parallel Simulation Environment for Complex Systems) C-based simulation environment developed at UCLA [6]. Parsec implements a process interaction approach to the simulation of discrete events. In this approach, the representation of objects (or entities) in the physical system under simulation is accomplished via logical processes. These logical processes interact among themselves by means of time-stamped message exchanges; the time-stamps correspond to the actual times when the corresponding physical events take place.

Extensibility is a key attribute in the design of Glomosim. To achieve it, Glomosim makes use of a layered approach that follows the networking layered approach and adds the additional layers needed to simulate the transmission and mobility physics. Standard APIs are provided so that different models for each different layer can be added in a standardized manner with a minimum level of difficulty by various developers independently and then used interchangeably within each layer. This extends and improves the modeling capabilities of Glomosim. A user can select from among the various models available at each layer those that best suit his purposes via a standard Glomosim input file (a sample input file is included in the Glomosim distribution files); if a model he needs is not available, he can make use of Glomosim's built-in extensibility and write his own model. The principal layers that are currently present in Glomosim are presented in Table 1.

Scalability is another very important attribute of Glomosim, since it was conceived from inception to be able to simulate very large networks of up to a million nodes [2]. In order to be able to scale to such an extent, Glomosim implements the concept of network gridding or partitioning [2]. Applying the common-sensical approach of using one Parsec entity per network node would result in severe performance penalties as the number of nodes increased more and more. Instead, Glomosim breaks up the network into a number of geographical partitions and uses one entity to represent all the nodes in that partition. Thus a node's membership to a particular partition (entity) is based on the node's geographical location, which will vary with time as mobility is introduced. Within each partition entity, a data structure for each member node is used to maintain the state of that node. This way, an increase in the number of nodes does not require an increase in the number of partition entities. The only requirement in the number of partition entities is that it must at least equal the number of processors being used to run the simulation. Each partition entity incorporates all the Glomosim layers (see Figure 1); communication among them is handled via function calls.

### B. Metrics and Methodology

The work in [21] provides an extensive discussion of metrics necessary to evaluate the performance and suitability of MANET routing protocols. It states the need to have metrics that are independent of any routing protocol so that comparisons can be drawn, and it groups them in two main categories: qualitative and quantitative. The qualitative metrics discussed are: 1. Distributed operation: This is inherent in MANETs; 2. Loop Freedom: Although not required (as long as the packets eventually get where they are supposed to), it increases efficiency of the algorithm by reducing unnecessary hops; 3. Demand based operations: Network and energy resources in MANETs are much more limited than in conventional networks, therefore it is desirable for the routing algorithm to do its operations only when needed; 4. Proactive operation: Desirable to reduce the latency induced by on-demand operations when resources permit it; 5. Security: The wireless nature of MANETs puts them specially at risk of attack, therefore security must receive a great deal of attention; 6. Sleep period operation: The routing protocol must be able to gracefully handle nodes going to sleep and waking up. Those modes of operation should be an important consideration in MANETs due to the limited energy resources; 7. Unidirectional Link support: It is desirable to be able to handle nodes that have 31 different radio transmission and reception ranges to support heterogeneous nodes and differing conditions for each node. The quantitative properties discussed are 1. End to end data throughput and delay: These are measurements of the routing policy's effectiveness / performance from the “external” perspective of other policies / protocols that make use of the routing; 2. Route Acquisition time: How long it takes to obtain a route to the destination. It is specially important for applications that are time-sensitive; 3. Percentage out-of-order delivery: The transport layer protocols prefer in-order delivery; increasing it therefore reduces the amount of processing needed to rearrange the data; 4. Efficiency, in terms of various ratios, such as average number of data bits transmitted to those delivered, average number of control bits to those delivered, average number of control and data packets transmitted to data packet delivered, etc. These efficiency measures quantify how effective the routing protocol is “internally”, that is, how many resources it must use to provide a given level of performance to the “external” users of the routing. Those metrics have to be expressed in the context of other parameters that must be varied. Some of the most important are network size, network connectivity, topological rate of change, link capacity, fraction of unidirectional links, traffic patterns (for instance, bursty vs. non-bursty), mobility, fraction and frequency of sleeping modes, physical domain shape.
IV. EXPERIMENTS DESCRIPTION

The goal of the experiments performed was to evaluate and compare the performance of five routing protocols implemented in Glomosim, namely Bellman-Ford, AODV, LAR (with the underlying protocol being DSR), WRP, and Fisheye, under various scenarios. The selected application to test the networks was FTP. Glomosim has two varieties of FTP: “Generic FTP” in which there is no acknowledgment of packet receipt on the part of the receiving node, and the standard FTP, in which the TCP layer functions as it normally does, that is, with acknowledgments from the receiving node. The second type is the one used in this project. The standard FTP in Glomosim is implemented such that the client sends messages of random size at random times during the simulation to its intended server during the stipulated time in the simulation, as determined by the tcplib library [x59]. The transmitting nodes in each case were free to start their transmissions from the moment the simulation began, and the transmissions continued throughout the simulation.

The motion of the nodes was simulated using the Random Waypoint Mobility Model [18], [7]. The validity of this model has been verified against real life traces in [24]. In this mobility model a node moves between a current starting point to a randomly selected destination point within the physical domain at a velocity selected within a given speed range. Once the node arrives at its destination point, it pauses for a set period of time and then it starts on its way to the next random destination point. In this project, the speed range is set to a single velocity, so each of the nodes simply moves to its next destination at the same fixed speed.

The radio wave transmission model selected was the free-space model, which assumes the sender and receiver have an unobstructed line of sight between them. In this model, the transmission power is attenuated in proportion to the square of the distance between sender and receiver. There is another transmission model in Glomosim, the two-ray model, which predicts the transmission power to be attenuated in proportion to the distance between sender and receiver raised to the fourth power by taking into consideration ground wave reflection effects. This last model has a hard-coded 1.5m height for the radio antenna. The radio bandwidth is set to 2Mbit per second. This is the default value in the sample Glomosim main input file distributed with the simulator, and it is the maximum value supported in the original 802.11 standard in 1997 (http://compnetworking.about.com/cs/wireless80211/a/aa80211standard.htm). For comparison, the standard (no proprietary enhancements) 802.11b and 802.11g bandwidths are 10.4Mbit per second and 54Mbit per second, respectively. A simulation run can be reproduced since the (pseudo-) randomization is based on a seed given to Glomosim via its main input file.

The size of the terrain was set at 2,000 m x 2,000 m (6,561.7 ft x 6,561.7 ft, which is approximately 1.54 square miles), and the simulations were set to model 10 minutes of actual time network traffic. For each routing protocol, the following parameters were varied:

a. Number of Nodes: 36, 49, 64, 81, 100. All of these number of nodes values are the square of integers. The reason for this is that the nodes were evenly distributed on the square-shaped terrain at the beginning of each simulation run, and square numbers facilitate this distribution easily and cleanly. The lower limit for the number of nodes is 36 because 6 is the lowest squared number that was judged to give a “reasonable” node density in the given terrain. The highest limit of 100 was set due to computational concerns with the physical time that it actually took to compute all the cases, and because it was judged to provide a reasonable upper limit for nodal density in the given terrain.

b. Node Mobility Speed: Two speeds were investigated, a low speed of 2.682 m/s (6 mph), and a “high” speed of 26.822 m/s (60 mph).

c. Node Mobility Pause: It was decided to simulate continuous (“perpetual”) motion, so the pause time selected was 0 seconds.

d. Radio range: 375.0 m (1230.3 ft), 300.0 m (984.2 ft), and 250.0 m (820.2). These were obtained by keeping the default Glomosim radio and wave propagation input values for the highest radio range, and varying just the radio transmission power to obtain the lower radio range value. The values for the radio transmission power respectively equivalent to the given radio ranges were 15 dBm (decibel milliwatts), 11 dBm, and 8 dBm. The radio range was calculated using the radio_range routine included with the Glomosim simulator. The radio transmission power units used are related to the more familiar milliwatts by:

\[ \text{Power}_{mW} = 10^{\frac{\text{Power}_{dBm}}{10}} \]

At the higher radio range, it would theoretically take approximately 5.3 “maximum radio range” hops to move a packet from one side of the terrain to the opposite end; at the lower radio range the corresponding number of hops is about 8.

e. Percent of communicating pairs: 10, 25. This represents the percentage of the number of nodes that are servers (receivers), which is set equal to the number of nodes that are clients (senders). Thus, for the value of 25, 25% of the nodes send messages to 25% of the nodes. A node's role as a server or client stays constant throughout the simulation, and no node acts as both. If the percentage of the total nodes was not an integer, it was rounded up to the next integer. At the lower percentage, then only 20% of the nodes in the network are then data-flow endpoints, whereas at the higher percentage half of the nodes are data-flow endpoints for each data flow.

All the combinations obtainable using the parameters that were varied as described were run for each protocol. Thus
number of cases run were 5 (protocols) x 5 (node counts) x 2 (speeds) x 3 (radio ranges) x 2 (percentages of communicating pairs) = 300 cases. Each case was run ten times, and the average of the results taken. Each time a case was run, it was run using a different set of seeds for pseudo-random number generation in both the InputCreator class used for Glomosim input file generation and for Glomosim itself. In the case of InputCreator, a given seed determines how the nodes are “paired-up” in terms of clients and servers. In regards to Glomosim, the pseudo-randomness will control items such as the selection of a new destination point and the time and size of a new FTP transmission. The initial distribution of the nodes was always the same, in a homogeneous grid of equally-spaced nodes of dimensions (number of nodes)$^{1/2}$ x (number of nodes)$^{1/2}$, where each node always occupies the same initial position.

Sample reference potential vehicles that could act as nodes in a MANET matching quite well the parameters selected in this study (in particular, examine the speeds, mobility model, and radio wave propagation models selected) are helicopter-type UAVs (unmanned air vehicles) like the French Infotron IT 180-5 coaxial-rotor helicopter drone [15], with an empty weight of 10 kg-force (22 lb), a full load weight of 15 kg-force (33 lb), a maximum speed of 90 km/h (25 mps = 60 mph), a ceiling of 3,000 m (9,842 ft), and an endurance of 90 minutes, and (vertical) ducted-fan UAVs such as the American Honeywell Micro Air Vehicle [14], with a wet (with gas) weight of 5.7 kg-force (12.5 lb), a maximum speed of 92.6 km/h (25.7 mps = 57.5 mph), a ceiling of 3,200 m (10,500 ft), and an endurance of 40 minutes at 5,500 ft (1,676 m). This last vehicle in particular is inaudible at 100 m, and it has an interchangeable modular sensor package that can detect a man-sized object at 250 m during the day (electro-optical sensor option), or 125 m at night (infra-red sensor option).

V. EVALUATION RESULTS

In order to measure network performance, the following statistics were collected for each case run: Application Bytes Received (Absolute and Normalized), Delivered BPS (Normalized Application Byte Delivery Ratio, Routing Control Packets Transmitted (Absolute and Normalized), TCP Data Packets Sent (Normalized) and TCP Data Packet Retransmit Ratio.

The data is presented as a series of graphs and corresponding tables. Each graph represents the value of the chosen statistic (y-axis) versus the number of nodes (x-axis) at a certain combination of values for mobility pause, percent communicating pairs, and radio transmission power (that is, radio range), for every protocol. Each graph contains ten data curves, one data curve for every protocol (five protocols) at every speed (two speeds). Additionally, each graph lists the parameters that differentiate it from the other graphs of the same type under the main title.

Normalization has been used for data presentation when appropriate. Normalization of a given statistic was done by dividing it by the number of communicating pairs (that is, data flows). If we define a “network building block” as a relatively small collection of nodes where the ratio of clients to servers to the number of nodes in the building block is constant, then, for tests that only differ in the number of nodes, increasing the number of nodes is akin to adding additional “network building blocks” together to make a larger network. Increasing the size of the network in this manner we preserve the basic makeup of the network, which is in contrast to simply increasing the number of nodes while keeping the total number of clients and servers constant. Thus, it is easier to look at true scalability issues in this manner. Normalization as done therefore allows the statistic so treated to already convey how it is behaving as the network is scaled up. Notice that some of the statistics collected were not normalized by the number of communicating pairs as just described. Some of these statistics were ratios themselves – such as the byte delivery ratio – and were thus implicitly normalized, just not by the number of communicating pairs. Some others simply looked at absolute performance measures, such as bytes received by the servers during the simulation time.

**Experiment 1:** Application Bytes Received – Perpetual Mobility with 10% communicating pairs.

Graphs in Figure 2 through Figure 4 show the application bytes received by the servers at the lowest data flow density for increasing radio power, respectively. In Figure 2 at the low speed, it is noted that almost none of the protocols manages to move any bytes from the clients to the servers at the lowest nodal density. The one notable exception is LAR, which moves 82,551 bytes. The trend continues at the next nodal number of 49 for that speed, but interestingly LAR's performance worsens. This is explained by the tenuousness of the connectivity at this low density for the low speed, so we can infer that the performance of the LAR protocol at these that data points is better than all the other protocols but not “reliable”. It is at the next nodal value of 64 nodes that we begin to see signs of overall improvement, with the best performing being LAR with 198,778 bytes moved, closely followed by B-F, AODV, WRP, and Fisheye all of which with similar performance at around the 140,000 byte mark. Past this point, both LAR and AODV improve dramatically to final values at 100 nodes of 1,704,449 bytes and 1,352,277 bytes, respectively. Of the other protocols, B-F shows no improvement initially but then it increases at a moderate rate to its final value of 672,813 bytes. Fisheye sees more modest gains, ending at a final value of 489,578 bytes. WRP has a mild gain from 64 to 81 nodes, increasing to 223,538 bytes. At the higher speed in Figure 2 all of the protocols show large gains in performance at the three lowest node densities, with the largest gains by far being made by AODV to 1,377,817 bytes and LAR to 1,251,630 bytes, both at 64 nodes. The other protocols in the meantime improved their performance to the range 133,260 to 230,471 bytes at 64 nodes. AODV continues to
gain in performance throughout to the highest node density, with a very sharp gain from 81 to 100 nodes, ending up delivering 2,282,226 bytes at 100 nodes, whereas LAR levels off between 64 and 81 nodes and then it shows a large gain to 1,606,955 bytes. The other protocols do not show much improvement on their way from 64 to 81 nodes; at the higher node densities, FishEye and B-F's performance deteriorate with respect to their respective performances at the lower speed, ending up with 263,788 bytes and 80,835 bytes, respectively.

Overall, in the two scenarios depicted in Figure 2, AODV and LAR are by far the better performers, with AODV being the better performer as the node density increases but LAR proving superior at the lower end of the nodal density spectrum. At the lower nodal densities of 64 nodes or less, the higher speed actually makes performance better for all the protocols, whereas at the highest node density only AODV and LAR continue to show improvement, with the remaining protocols worsening.

In Figure 3 at the low speed, the same trend is true as in the previous curve at the lowest nodal density: LAR is able to move data from clients to servers, but the other protocols are not. The LAR performance at this lowest node density stays at the same level as in the previous graph. At the next node density of 49 nodes, all the protocols start to show perceptible gains, with LAR improving the most, to 179,820 bytes, followed by AODV, B-F, and WRP to about 19,000 bytes, and FishEye bringing up the rear with basically no improvement. A large performance gain is shown by all the protocols to the next nodal density of 64 nodes, the largest gains by far being those of AODV and LAR, which are very similar in absolute terms, and which now are around the 1,400,000 byte level. B-F also shows a large gain at 64 nodes, attaining almost 1,200,000 bytes. The other protocols stay in the 440,000-640,000 byte range. LAR and B-F deteriorate to the next node density of 81 nodes, to 1,308,207 and 757,017 bytes, respectively, to then show an improvement at 100 nodes to 1,617,377 and 1,081,649 bytes, respectively, which is similar to their performance at 64 nodes. AODV and FishEye show continued improvement past the 64 node mark, AODV quite sharply and FishEye quite mildly, to end up at 2,276,474 and 790,123 bytes at 100 nodes, respectively.

At the higher speed in Figure 3, the higher performers are LAR and AODV, as in the lower speed but now by an even larger margin. Both display similar performance throughout all node levels. Furthermore, this performance stays in each case within a narrow range which opens up slowly as the node density increases. Both start out at around 600,000 bytes, stay at a similar level to 49 nodes and then sharply increase to around 1,600,000 bytes. This very large increase in performance is followed by moderate drop in performance at the 81-node mark to 1,258,802 bytes (LAR) and 1,434,969 (AODV) bytes, and then another large increase in performance to 1,940,365 bytes and 2,349,985 bytes at 100 nodes, respectively.

All the other protocols at the higher speed attain a much lower level of performance at all node levels. B-F and WRP start out at 36 nodes at an almost identical performance level in the range 118,000 to 123,000 bytes, whereas FishEye starts out at a low performance level of 37,622 bytes. Performance worsens at 49 nodes, to slightly worse than at the previous node level for B-F and FishEye, and to a level similar to B-F for WRP. All three protocols peak in performance at 64 nodes to 331,821 (B-F), 387,946 (FishEye) and 513,242 (LAR) bytes. B-F continues on with an almost imperceptible and linear increase in performance to 478,482 nodes at 100 nodes. FishEye worsens to 81 nodes and then to 100 nodes, finishing at 257,000 bytes, whereas WRP displays the same worsening trend to 81 nodes. In Figure 3 AODV and LAR are the best performers by far, displaying comparable performance between them with AODV being somewhat better. All protocols show their largest gain in performance from 49 to 64 nodes at both speeds, whereas many show a slowdown in performance gain or a loss to the next node level.

In Figure 4, at the lower speed, all the protocols move a significant number of bytes even at the lowest density, unlike in the previous two graphs at the lower power levels where only LAR was able to transfer a significant number of bytes. In this case at the 36 node level the bytes transferred are in the range 160,988 bytes (FishEye) to 424,175 bytes (LAR), with AODV and WRP achieving a similar performance at approximately 337,000 bytes and B-F coming in at 264,781 bytes. From that point on AODV becomes the best performer and interestingly its performance becomes indifferent to speed, being almost identical at both speeds and following the trends it displayed at the previous power level at the high speed. It has the greatest increase in performance from 49 nodes to 64 nodes at 100 nodes, the largest gains by far being those of AODV and LAR, which are very similar in absolute terms, and which now are around the 1,400,000 byte level. B-F also shows a large gain at 64 nodes, attaining almost 1,200,000 bytes. The other protocols stay in the 440,000-640,000 byte range. LAR and B-F deteriorate to the next node density of 81 nodes, to 1,308,207 and 757,017 bytes, respectively, to then show an improvement at 100 nodes to 1,617,377 and 1,081,649 bytes, respectively, which is similar to their performance at 64 nodes. AODV and FishEye show continued improvement past the 64 node mark, AODV quite sharply and FishEye quite mildly, to end up at 2,276,474 and 790,123 bytes at 100 nodes, respectively.

At the higher speed in Figure 3, the higher performers are LAR and AODV, as in the lower speed but now by an even larger margin. Both display similar performance throughout all node levels. Furthermore, this performance stays in each case within a narrow range which opens up slowly as the node density increases. Both start out at around 600,000 bytes, stay at a similar level to 49 nodes and then sharply increase to around 1,600,000 bytes. This very large increase in performance is followed by moderate drop in performance at the 81-node mark to 1,258,802 bytes (LAR) and 1,434,969 (AODV) bytes, and then another large increase in performance to 1,940,365 bytes and 2,349,985 bytes at 100 nodes, respectively.

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At the higher speed in Figure 4, the best performing protocol is AODV, followed by LAR. AODV, LAR, and WRP achieve better performance at the lowest node density at the high speed than at the low speed, with 661,596, 682,322, and 406,126 bytes, respectively. FishEye and B-F suffer from the opposite effect at 36 nodes, with 107,760 and 128,051 bytes, respectively. As already mentioned, from 49 nodes on AODV shows almost complete imperviousness to speed with performance almost identical at all node levels to its performance at the lower speed, peaking at 100 nodes with 2,654,324 bytes, which is just a bit higher than at the lower speed. LAR's performance, on the other hand suffers with the increased speed, with peaks at 64 (1,340,895 bytes) and 100 nodes (1,813,496 bytes), and a trough at 81 nodes, with 1,112,055 bytes. WRP's performance remains within a narrow range for all its node values, peaking at 565,393 bytes at 64 nodes. B-F and WRP performance does not see a real improvement until 64 nodes, where they peak at values very similar to that of WRP, which they
follow very closely also to the 81 node mark. Then B-F improves greatly when reaching 100 nodes, where it attains 1,330,291 bytes, whereas Fisheye see a modest improvement to 506,301 bytes. Overall in Figure 4, AODV seems to be if anything slightly helped by the higher speed, in contrast to the other protocols that are affected negatively by the higher speed. Also, at both speeds, there is a clear trough in performance at 81 nodes.

Experiment 2: Application Bytes Received – Perpetual Mobility with 25% communicating pairs.

Graphs in Figure 5 through Figure 7 show the application bytes received by the servers at the highest data flow density for increasing radio power, respectively. In Figure 5 at the low speed, all the protocols essentially fail to successfully transmit any bytes at the lowest two or three values of node density. The 64 node mark is when WRP, AODV and WRP begin to display some significant data transfer, at 264,246 bytes for LAR and around 205,000 for the other two. From that point on LAR increases quite rapidly in an almost linear fashion, peaking at 2,042,431 bytes at 100 nodes. WRP and AODV increase in a similar and moderate fashion to a performance level of 563,983 bytes (WRP) and 679,403 (AODV) bytes at 81 nodes. At that point AODV displays a large performance increase to 2,839,306 bytes at 100 nodes, which bests LAR. B-F and Fisheye do not see significant data transfer until they reach 81 nodes, with 320,161 and 216,503 bytes, respectively, from which point B-F sees a large performance increase to 1,499,530 bytes at 100 nodes and Fisheye continues on an almost linearly increasing path to 509,452 bytes at 100 nodes.

At the higher speed in Figure 5, the protocols performance clearly breaks up into two groups. The first group, formed by AODV and DSR, shows very similar performance which is very superior to that of the other protocols. Both steadily increase their performance from 926,739 (AODV) to 1,251,241 (LAR) bytes at 36 nodes to 3,569,589 (AODV) to 2,817,049 (LAR) bytes at 100 nodes. It must be noticed that LAR leads AODV up to 49 nodes, at which point it suffers a drop in performance and AODV surpasses it for good. In the second group, Fisheye, WRP, and B-F show a repeated mild up and down performance pattern in a narrow overall range up to 81 nodes, ranging from 63,800, 102,680, and 122,515 bytes at 36 nodes, respectively, to around 360,000 bytes for B-F and WRP, and 623,595 bytes for WRP at 81 nodes. From that point on B-F and Fisheye modestly increase to 559,073 and 639,848 bytes at 100 nodes, respectively.

Overall for Figure 5, at the higher speed LAR and AODV display the strongest performance at all node densities, particularly excelling at the higher speed. The remaining protocols display similar performance among themselves, but significantly lower at the high speed at all node densities and at the higher node densities at the lower speed.

In Figure 6 at the low speed, all the protocols display a small amount of data transfer at the lowest node density, with LAR transferring the most with 28,913 bytes. The same occurs at 49 nodes, except for LAR which improves significantly to 285,200. LAR's greatest increase occurs at the next node value, to 2,227,655 bytes, from where there is a more moderate and almost linear in nature increase to the final value of 3,122,790 bytes at 100 nodes. All the other protocols have their first significant increase in performance at 64 nodes, with AODV increasing in an almost linear fashion to 3,074,343 bytes at 81 nodes, at which point it surpasses LAR's performance, WRP emulating AODV's behavior attaining 2,770,452 bytes at 81 nodes and Fisheye increasing more slowly to 1,509,870 at 81 nodes. AODV continues its increase, albeit at a slower pace, to 3,648,441 bytes at 100 nodes, whereas B-F and Fisheye suffer from a performance deterioration at 100 nodes, attaining 2,175,131 and 1,143,681 bytes, respectively.

At the higher speed in Figure 6, AODV and LAR are clearly the better performing protocols at all node densities. It is observed that AODV significantly benefits from better performance, at all node densities but the highest (where it has about equal performance), as compared to its performance at the lower speed. Both LAR and AODV start out at around 1,800,000 bytes at 36 nodes, followed by a small performance drop at 49 nodes. At that point AODV continuously increases its performance at a fairly uniform pace up to 3,449,783 bytes at 100 nodes, whereas LAR increases more slowly to 81 nodes where it attains 1,996,284 bytes, followed by a sharp increase to 3,361,351 at 100 nodes. B-F and Fisheye alternate around each other throughout the node density range and moving within a narrow, overall slowly increasing, performance band. They start out in the range 226,771 (B-F) to 386,458 bytes (Fisheye) at 36 nodes and finish up in the range 753,676 (B-F) to 525,759 (Fisheye) at 100 nodes. WRP strats out at a performance value slightly below that of B-F at 36 nodes, 171,101 bytes, but it initially increases quickly in a close to linear fashion to 1,201,421 bytes at 64 nodes to suffer a performance slow-down at 81 nodes with 889,993 bytes.

Overall for Figure 6, the behavior at high speed is similar to that in the previous Figure 5, with the two clear groupings of AODV and LAR versus the remaining protocols. At the lower speed there is a sudden increase in performance starting at approximately 64 nodes with closer performance values among protocols than at the higher speed, and all protocols either losing performance or improving more slowly as they get to the 100 node mark.

In Figure 7 at the low speed, LAR and AODV are the best performers and behave in a similar fashion throughout the nodal density range, with LAR slightly outperforming AODV. LAR displays an almost linear performance increase, from 1,073,664 bytes at 36 nodes to 4,122,256 bytes at 100 nodes, whereas AODV is steadily increasing as well oscillating a bit but overall close to linearly, from 667,026 bytes at 36 nodes to 4,004,738 bytes at 100 nodes. WRP displays a behavior close to that of AODV from 36 nodes to 81 nodes, beginning at a slightly higher performance level at 36 nodes of 779,886 bytes and progressing increasingly losing performance compared to AODV to end up at 2,550,459 bytes at 81 nodes, where AODV has attained 3,224,019 bytes. B-F closely tracks WRP all the way to 64 nodes where it attains 1,974,575 bytes, past which point it
improves more slowly in a close to linear fashion ending up at 2,770,773 bytes at 100 nodes. Fisheye begins at 524,770 bytes at 36 nodes and increases linearly to 1,830,809 bytes at 64 nodes to then very slowly decrease to 1,814,052 bytes at 100 nodes.

At the higher speed in Figure 7, AODV and LAR are clearly the best performers by a large margin. Their performance paths behave in almost exactly the same way, with AODV being somewhat better. They start at 1,919,809 (AODV) and 1,770,976 (LAR) bytes at 36 nodes, after which both slightly decrease in performance, to then go on a continuous increase to 3,934,18 (AODV) and 3,859,002 (LAR) bytes at 100 nodes. Interestingly each one just about intersects the other's performance curve form the lower speed at 64 nodes, after which point both show modest gains to 81 nodes, leading to large performance jumps to 100 nodes. Fisheye displays a linear and slight performance deterioration form 994,926 bytes at 36 nodes to 751,933 bytes at 64 nodes and then a linear and slight performance increase to 1,449,005 bytes at 100 nodes. B-F oscillates up and down slightly starting out at 932,961 bytes at 36 nodes and ending up at 1,117,478 bytes at 100 nodes. WRP follows a behavior similar to that of LAR from 36 to 81 nodes but at a lower performance levels, starting out at 1,197,093 bytes at the lowest node density and achieving 1,683,992 bytes at 81 nodes.

Overall for Figure 7, at the high speed AODV and LAR are by far the best performers with overall increasing performance, whereas WRP and Fisheye hardly make any gains throughout and WRP falls in the middle. At the slow speed AODV and LAR are also the best performers but by a smaller margin specially up to 81 nodes, past which point their performance superiority margin increases greatly. All the protocols at the lower speed show an overall increasing performance trend, except for Fisheye which seems to stall in the middle of the node density range.
Figure 3: FTP Application Bytes Received
Figure 4: FTP Application Bytes Received
Figure 5: FTP Application Bytes Received
Figure 6: FTP Application Bytes Received
VI. CONCLUSION

Our results indicate that for transmit power of 7.005 to 10.527 dBm and speed of movement of 2.6 meters per second the routing protocols performance is similar as long as there are no more than about 50 nodes in the configuration. For higher speeds of 26.822 meters per second motion, their performance is quite different with AODV and LAR outperforming the rest of the protocols three or more times in terms of overall application bytes received for low node densities – up to about 50 total nodes. For higher node densities AODV and LAR result in even higher performance improvement over all other protocols used in this study. It is interesting to observe that for higher node densities, as the transmit power increases from of 7.005 to 10.527 dBm, all protocols perform better as expected at the low mobility speed, however, AODV and LAR exhibit a much smaller performance degradation, when both the transmit power and speed increase.

REFERENCES

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