

MANET Simulation Studies: The Current State and New Simulation Tools

Stuart Kurkowski, Tracy Camp, and Michael Colagrosso
Department of Math. and Computer Sciences
Colorado School of Mines
Golden, Colorado 80401

Abstract—Simulation is the research tool of choice for a majority of the mobile ad hoc network (MANET) community. However, while the use of simulation has increased, the credibility of the simulation results has decreased. To determine the state of MANET simulation studies, we surveyed the 2000-2004 proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc). From our survey, we found significant shortfalls in credibility. We present the results of our survey in this paper. We then offer two simulation tools that we have developed to aid future MANET simulations (i.e., scenario development, model validation, protocol verification, and results analysis). The first tool is a visualization and animation tool called iNSpect (interactive NS-2 protocol and environment confirmation tool). Due to iNSpect, the credibility of our simulation studies have been drastically improved. The second tool generates characterization data from a simulation’s input parameters. We call this second tool SCORES (SCenario characterizER for Simulation), as it will provide an account (or score) on a given simulation scenario. We offer these tools to the community in the hope to improve the credibility of MANET simulation-based studies. Both of our tools have substantially impacted our own MANET research efforts.

Index Terms—wireless networks, mobile ad hoc networks, simulation tool, visualization, simulation credibility

I. INTRODUCTION

Mobile Ad Hoc Networks (MANETS) are wireless mobile nodes that cooperatively form a network without infrastructure. In other words, ad hoc networking allows devices to create a network on demand without prior coordination or configuration. Thus, nodes within a MANET are involved in routing and forwarding information between neighbors.

Because there is no coordination or configuration prior to setup of a MANET, there are several challenges. These challenges include routing packets in an environment where the topology is changing frequently, wireless

communications issues, and resource issues such as limited power and storage. The leading way to research solutions to these difficult MANET challenges is simulation.

In this paper, we consider the current state of MANET simulation studies. The results, unfortunately, are extremely discouraging; in general, results published on MANET simulation studies lack credibility. To improve the credibility of a MANET simulation-based study, we offer two tools to the community.

A. The Current State of MANET Simulation Studies

We conducted a survey of MANET research published in the premiere conference for the MANET community, i.e., the Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc) from 2000-2004 [4]; we only included the full papers in our survey, not the poster papers. Simulation is an often used tool to analyze MANETs, illustrated by the fact that 84 out of the 111 MobiHoc papers published (75.7%) used simulation to present research results.

There are many discrete-event network simulators available for the MANET community [24]. Unfortunately, only 63 of the 84 published MobiHoc simulation papers (75.0%) actually identified the simulator used in the research. Figure 1 shows the simulator usage results of the MobiHoc authors that did identify the simulator used. As shown, NS-2 is the most used simulator in MANET research; 28 of the 63 simulation papers that state the simulator used in the simulation study used NS-2.

When the simulator used is not specified within a published paper, the repeatability of the simulation study is directly compromised. In addition to repeatability, there are other factors involved in conducting credible simulation-based MANET research. Specifically, to be a credible research project, a simulation study must be:

- 1) Repeatable - A fellow researcher should be able to repeat the results for his/her own satisfaction, future reviews, or further development.
- 2) Unbiased - The results must not be specific to the scenario used in the experiment.

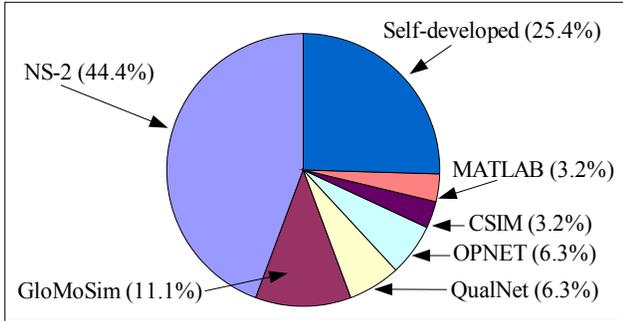


Fig. 1. Simulator usage results from our MobiHoc survey.

- 3) Realistic - The scenarios and conditions used to test the experiment must be of a realistic nature.
- 4) Statistically sound - The execution and analysis of the experiment must be based on mathematical principles.

The first way to make a research project repeatable is to provide the code and configuration files of the simulation study to the community. In addition, the researcher must identify the simulator and version, the operating system, and all variable settings. Repeatability is also based on the scenarios evaluated, the techniques used to avoid initialization bias, and the techniques used to analyze the results. Thus, a published paper must discuss all of these details in order to meet the repeatability criteria. To be an unbiased study, a project must address initialization bias, random number issues, and use a variety of scenarios. To be a realistic study, factors such as node density, node footprint, coverage, speed, and transmission range must be within realistic limits. Finally, to be a statistically sound study, a project must account for initialization bias, execute a number of simulation iterations, provide the confidence levels that exist in the results, and list any statistical assumptions made. In this paper we use the results of our MobiHoc survey to raise awareness of the low percentage of MANET research efforts satisfying these requirements.

The authors of [18] completed a similar evaluation of simulation studies in 1999. However, because the first MobiHoc conference was in 2000, this previous evaluation of simulation studies was unable to include simulations studies published in the MobiHoc conference. In addition, unlike our paper, the evaluation of simulation studies from 1999 was on network simulations in general, not on MANETs in specific. Because our research is focused on MANETs, and because MANET simulations are unique (e.g., mobility models), we completed a survey on the state of MANET simulations published in all the MobiHoc proceedings. We found that, although it has been five years since the previous simulation study, network simulation studies (at least in the MANET community) have not improved and, in some cases, have deteriorated even

further.

As an example where the credibility of simulation studies has not improved, consider the simulation type (i.e., terminating or steady-state) used in a simulation study. In [18], over 1100 of the 2200 papers (50%) did not state the type of simulation. In our MobiHoc survey, 39 of the 84 simulation papers (46.4%) did not mention the type of simulation used in the study. As an example where the credibility of simulation studies has deteriorated, consider the pseudo random number generator (PRNG) needed in a simulation study. In [17], over 1541 of the 2200 (over 70%) did not state the pseudo random number generator (PRNG) used in the research. In our MobiHoc survey, not a single paper mention the PRNG used.

We suspect that most MANET simulation studies are steady-state, because most studies are interested in the long-term performance of a MANET. We also suspect that most MANET simulation studies use the PRNG that is packaged with a given public simulator (e.g., the PRNG in NS-2, which is the most often used simulator in MANET simulation studies). Unfortunately, the NS-2 PRNG does not allow a separate request stream for each dimension (i.e., a unique request stream) that exists in a simulation study. A three dimension example is when a simulation has three different random pieces, such as jitter, noise, and delay. You want all three of these series (dimensions) of values to be uniformly distributed with each other and within each stream (e.g., the jitter stream needs to be uniformly distributed). The authors of [12], [17], [18], [19] show that a 2-dimensional request on a PRNG is valid for approximately $8\sqrt[3]{L}$, where L is the cycle length. In NS-2, the cycle length is $2^{31} - 1$, which means that only 10,000 numbers are available in a 2-dimensional simulation study. Thus, [19] estimates that the NS-2 PRNG is only valid for approximately four minutes of simulation. Because of these issues, our research group uses Akaroa-2 [5], an NS-2 compatible PRNG with a cycle of $2^{191} - 1$. The Akaroa-2 [5], [20] PRNG provides several orders of magnitude more numbers than the NS-2 PRNG and is valid to 82 dimensions.

As the MANET community moves forward toward implementation, it is imperative that the simulation research is credible. In Section II, we provide detailed descriptions and results from our survey of the published papers in the 2000-2004 proceedings of the MobiHoc conference. We then document a list of pitfalls that exist in simulation-based MANET studies in Section III. The list was developed from our survey of MobiHoc papers and our own experiences in MANET simulations. Our goal is to raise awareness of the issues and to provide tools to aid MANET researchers in conducting and reporting credible simulation results.

B. New Tools for MANET Simulations

We have developed two simulation tools that can be used to increase the credibility of MANET simulations (i.e., scenario development, model validation, protocol verification, and results analysis). The first tool is a visualization and animation tool called iNSpect (interactive NS-2 protocol and environment confirmation tool). The credibility of our simulation studies have been drastically improved due to iNSpect, because a visualization tool is needed to understand the large amount of data produced during network simulations. As one example, iNSpect showed us an error that exists in version 2.27 of NS-2. In Section IV-A, we demonstrate the ability of iNSpect and discuss how it has aided our research efforts.

The second tool that we have developed to increase the credibility of our MANET simulations is a SCenario characterizER for Simulation (SCORES) tool. SCORES takes simulation input parameters, such as number of nodes, simulation area dimensions, and transmission range, and generates characterization data for the scenario. Using SCORES, we analyzed the input parameters that have been published in MobiHoc. We present these results in Section IV-B, illustrating the wide range of simulation scenarios used to conduct MANET research. To improve the credibility of our simulation studies, the MANET community needs a way to characterize a simulation scenario in categories such as mobility, density, and coverage. The SCORES tool is our initial effort into providing this characterization.

Like iNSpect, SCORES has substantially impacted our own MANET research efforts. We offer both of these tools to the community in the hope of improving the credibility of other MANET simulation-based studies. We provide details on these two tools in Section IV.

II. SURVEY RESULTS

To evaluate the current state of credibility in MANET research we surveyed the published papers of MobiHoc, the premiere MANET conference. For each paper in the proceedings, we distilled the answers to several simulation study questions. Only the appropriate questions were asked of each paper, e.g., if a paper did not use plots, the detailed plot questions were not surveyed for that paper. The answers to the questions were recorded in a database. For consistency, the same person reviewed all of the papers; to validate the results, we had a second person review all of the papers with a subset of the questions and a third person to correct the few inconsistencies found.

We used the database of survey data to compile the results shown in Table I. The results in Table I indicate trends in the lack of credibility in MANET simulation research, even though using MANET simulation research to illustrate performance is prominent; that is, 84 out of the 111 (75.7%) published MobiHoc papers used simulation

as the basis for the study. Simulation is a large portion of the research in the MANET community making its lack of credibility a concern. Of the 84 simulation papers, only 63 (75.0%) stated the simulator that he or she used. Lack of a stated simulator immediately limits the repeatability of the study. Finally, we note that over half of the simulation papers (46 out of the 80 MANET protocol simulation studies) did not use mobility in evaluating research of *mobile* ad hoc networks.

Using the four factors that defines whether a simulation study is credible (see Section I-A), we found less than 15% of the published MobiHoc papers are repeatable. It is difficult, if not impossible, to repeat a simulation study when the version of a public simulator is unknown, and only 6 of the 47 MobiHoc simulation papers that use a public simulator (12.8%) mention the simulator version used. It is also difficult, if not impossible, to repeat a simulation study when the simulator is self-developed and the code is unavailable. (No MobiHoc paper made a statement about code availability.) In addition, only 6 of the 84 simulation papers (7.1%) addressed initialization bias and none of the 84 simulation papers (0%) addressed random number generator issues. Thus, we are concerned that over 90% of the MobiHoc published simulation results may include bias. In regards to compromising statistical soundness, 49 of the 84 simulations papers (58.3%) did not identify the number of simulation iterations used and 72 of the 82 papers that used plots to present simulation results (87.8%) did not include confidence intervals. Hence, only approximately 12% of the MobiHoc simulation results appear to be based on sound statistical techniques.

III. COMMON SIMULATION PITFALLS

We have developed a list of simulation pitfalls that impact the credibility of a simulation-based study. We have accumulated the list from our own experiences with simulations as well as the experience of others in the field. Pitfalls identified from our survey of MobiHoc papers are also included in the list. Because the pitfalls impact different phases of a simulation-based study, we have grouped the pitfalls into the following categories: simulation setup, simulation execution, output analysis, and publishing.

A. Simulation Setup

Simulation setup is the phase of a MANET research effort that is most often skipped or overlooked; and if the setup phase is done improperly, the credibility of the simulation study is flawed from the start. Setup begins with determining the simulation type and validating the model.

1) *Simulation Type*: Although selecting the type of simulation appears to be a trivial step, not identifying the type of simulation (terminating vs. steady-state) is a commonly overlooked step for researchers. That is, 39

TABLE I

SURVEY RESULTS FOR 111 PUBLISHED SIMULATION PAPERS IN ACM'S MOBIHOC CONFERENCE, 2000-2004.

Simulator and Environment		
Totals	Percentage	Description
84 of 111	75.7%	Used simulation in the research.
0 of 84	0.0%	Stated the code was available to others.
21 of 84	25.0%	Did not state which simulator was used.
63 of 84	75.0%	Stated which simulator was used.
28 of 63	44.4%	Used the NS-2 simulator.
7 of 63	11.1%	Used the GloMoSim simulator.
4 of 63	6.3%	Used the QualNet simulator.
4 of 63	6.3%	Used the OPNET simulator.
2 of 63	3.2%	Used the CSIM simulator.
2 of 63	3.2%	Used the MATLAB/Mathematica.
16 of 63	25.4%	Used self-developed or custom simulators.
41 of 47	87.2%	Did not state which version of the public simulator was used.
82 of 84	97.6%	Did not state which operating system was used.
6 of 84	7.1%	Addressed initialization bias.
39 of 84	46.4%	Addressed the type of simulation.
0 of 84	0%	Addressed the PRNG used.
Simulation Input Parameters		
Totals	Percentage	Description
80 of 84	95.2%	Conducted MANET protocol simulation studies.
44 of 80	55.0%	Did not state the number of nodes used in the study.
41 of 80	51.2%	Did not state the size of the simulation area.
30 of 80	37.5%	Did not state the transmission range.
44 of 80	55.0%	Did not state the simulation duration.
50 of 80	62.5%	Did not state the traffic send rate.
57 of 80	71.2%	Did not state the traffic type (e.g., CBR, etc.)
47 of 80	58.7%	Did not state the number of simulation runs.
34 of 80	42.5%	Used mobility in the study.
6 of 34	15.8%	Did not state the speed of the nodes.
13 of 34	34.2%	Did not state the speed delta.
17 of 34	44.7%	Did not state the pause time of the nodes.
21 of 34	55.2%	Did not state the pause delta.
31 of 34	91.2%	Stated which mobility model was used.
20 of 31	64.5%	Used the random waypoint mobility model [10].
2 of 21	9.5%	Used the steady-state version of the random waypoint mobility model [15].
2 of 31	6.4%	Used a group mobility model [7], [22].
3 of 31	9.6%	Used a grid/road mobility model (e.g., [2]).
4 of 31	12.9%	Used the random direction mobility model (e.g., [21]).
Plots/Charts/Graphs		
Totals	Percentage	Description
82 of 84	97.6%	Used plots to illustrate the simulation results.
2 of 84	2.4%	Did not use plots to illustrate the simulation results.
72 of 82	87.8%	Did not place confidence intervals on the plots.
8 of 82	9.7%	Did not have legends on the plots.
20 of 82	24.3%	Did not have units on the data or labels.

out of the 84 simulation papers (46.4%) in our MobiHoc survey did not state whether the simulation was terminating or steady-state. We suspect most simulations are steady-state because MANET researchers are typically interested in the long term average behavior of an ad hoc network.

Not determining the simulation type can lead to unrealistic simulations with statistically unsound results. The most common error made by researchers is to execute one type of simulation and apply the results to the other type of simulation. For example, executing a terminating simulation for a set number of seconds and claiming the results represent the steady-state behavior.

2) *Model Validation and Verification:* After the type of simulation is determined, the simulation model itself must be prepared. As stated in [14] the model must be validated as a baseline to start any experimentation. Many researchers download the NS-2 simulator, compile it and begin to execute simulations with a model that has not been validated in his or her environment. Likewise, the protocol that is being evaluated must be verified to ensure it has been coded correctly and operates in accordance with the protocol specifications. Not validating the model or verifying code is a common pitfall.

3) *Variable Definition:* NS-2 uses hundreds of configurable variables during an execution in order to meet its general wired and wireless network simulator requirements. There are 538 variables defined in the `ns-default.tcl` file of NS-2.1b7a and there are 674 variables defined in the `ns-default.tcl` file of NS-2.27. The large number of variables makes it difficult to track each variable's default setting. Additionally, an increase in the number of variables between the different NS-2 versions indicates there is a rising number of variables with each new version of NS-2. Our review of the Tcl driver files from our protocols, as well as the examples provided by NS-2, show that many simulation driver files leave key parameters undefined. For example, 3 out of 12 (25%) of the wireless examples in NS-2 do not define the transmission range of a node.

B. Simulation Execution

Executing the simulation is where a lot of time is spent. Therefore, it is important to conduct the execution portion correctly. We highlight several execution pitfalls we have discovered; these pitfalls impact data output, analysis, and ultimately results.

1) *Setting the PRNG Seed:* One mistake we have seen in NS-2 based simulation studies concerns not setting the seed of the pseudo random number generator (PRNG) properly. NS-2 uses a default seed of 12345 for each simulation run [16]. Thus, if an NS-2 user does not set the seed, each simulation will produce identical results. Additionally, if the seed is not set or is set poorly, it can negate the

independent replication method which is typically used in analysis. In our MobiHoc survey, none of the 84 simulation papers (0%) addressed PRNG issues.

2) *Scenario Initialization:* Another pitfall is not initializing the scenario correctly. On terminating simulations, the network is usually started in a certain configuration that represents the start of the simulation window. For example, if the researcher is trying to simulate a protocol's response to a failure event, he or she needs to have the failure as the initialization of his or her analysis. Likewise, simulations often start with empty caches, queues, and tables. The simulation fills the caches, queues, and tables until a steady-state of activity is reached. Determining and reaching the steady-state level of activity for the queues, caches, and tables is part of the initialization. After steady-state is reached, simulated data can be used for performance comparison. Only 6 of the 84 simulation papers (7.1%) addressed initialization bias, and all six use the non-credible method of arbitrarily deleting data (see Section III-C).

3) *Metric Collection:* Another area of concern is the metric measurements collected during execution. If the simulation executes properly, but the researcher does not obtain the data he or she needs from the simulation, the simulation is worthless. Appropriate output is especially critical if output has to be correlated. For example, if the researcher is trying to track steady-state protocol performance after a certain configuration change, the researcher has to be able to identify the configuration change occurrence in the output.

4) *Generating Sufficient Runs:* A final pitfall with discrete-event simulation execution is not accounting for the model's innate randomness in the experiment. Executing the simulation once will produce results, maybe even good results. However, the single point estimate produced will not give the researcher sufficient confidence in the unknown mean. In our MobiHoc survey, 49 of the 84 simulation papers (58.3%) did not state the number of simulation runs executed.

C. Output Analysis

Output analysis is the downfall of many simulation studies. Typically, the preceding steps take longer than planned, which means sufficient time is not provided for output analysis at the end of the schedule. Whether it is the publication deadline, or a thesis defense date, proper analysis is often compromised in the following ways.

1) *Single Set of Data:* This pitfall is taking the first set of results from a simulation and accepting those values as "truth". The decision to take the first set is not a credible way to conduct research. The random nature of discrete-event simulation requires proper statistical analysis and a single simulation will not produce the results the researcher needs. In our MobiHoc survey, 49 of the

84 simulation papers (58.3%) did not state the number of simulation runs executed.

2) *Initialization Bias*: This pitfall usually occurs from a lack of understanding of the two types of simulation. Steady-state simulations require that the researcher address initialization bias. Deleting the first portion of the data collected is not a credible solution. There needs to be statistical rigor in determining a simulation has truly reached steady-state. In our MobiHoc survey, only 6 of 84 papers (7.1%) addressed initialization bias. In each of the six papers, the non-credible method of discarding data was used. The arbitrary discard periods ranged from 50 seconds to 1000 seconds.

3) *Statistical Analysis*: This pitfall concerns not using the correct statistical formulas with the different forms of output. For example, using the standard formulas for mean and variance without ensuring the data is *iid*. Use of *iid* based formulas can reduce credibility by producing biased results. From the survey in [18] 76.5% of the papers did not discuss the statistical methods used in analysis.

4) *Confidence Intervals*: This pitfall is a culmination of several of the previous analysis issues. Confidence intervals are a tool to provide a range where we think the true value is located relative to the point estimate. Confidence intervals account for the randomness and varied output from a stochastic simulation. However, in our survey study, 72 of the 82 simulation papers using plots (87.8%) did not show confidence intervals on the plots.

D. Publishing

The biggest pitfall in publishing is breaking the “repeatable” criteria for credible research. In NS-2 there are 674 variables defined in the `ns-default.tcl` file of NS-2.27. To ensure repeatability the researcher must document the `ns-default.tcl` file used and any changes made to the settings of the variables in the file.

Table I lists all the data from our MobiHoc paper survey. The lack of consistency in publishing simulation-based study results directly impacts the credibility of these studies. In addition, the inconsistency prevents the direct comparison of results, limiting research advancements. Finally, the publishing pitfalls prevent the MANET community from taking advantage of new researchers interested in these studies. A new researcher cannot repeat the studies to start his or her own follow-on research.

Several of the results in Table I are significant inefficiencies in publishing simulation based results. None of the studies stated the code was available to others. 21 out of 84 simulation papers (25.0%) did not mention the simulator that was used; and of the 47 papers that stated a public simulator was used, only 6 (12.8%) stated the simulation version used. 30 of the 80 MANET protocol simulation papers (37.5%) did not state the transmission

range of the nodes. Also, 57 out of the 80 MANET protocol simulation papers (71.2%) did not mention the packet traffic type used in the simulation.

At the bottom of Table I are publishing specific statistics. Plots of the results are common, i.e., 82 of the 84 simulation papers (97.6%) used plots to describe results. However, 8 of the 82 simulation papers with plots (9.8%) did not provide legends or labels for his or her charts. Additionally, 20 of the 82 simulation papers with plots (24.3%) did not provide units for the data being shown. The lack of labels and units can cause readers of these papers to misinterpret or misunderstand the results.

IV. NEW SIMULATION TOOLS

In the previous two sections, we discussed the results of our survey of MobiHoc conference proceedings and the common simulation pitfalls that exist in simulation studies. The survey results indicate that MANET simulation studies are lacking credibility. To improve the credibility of a MANET simulation-based study, we offer two tools. Our goals of this paper is to raise awareness of the issues and to offer these two tools to researchers to improve the credibility of future MANET simulation results.

A. A Visualization Tool

A visualization tool is needed to understand the large amount of data produced during network simulations. The human visual system is unrivaled in pattern recognition and offers the ability to process large amounts of data quickly and clearly [1]. A visualization tool aids at least three specific areas of wireless simulation based research. First, the display of the node topology is necessary to understand the results of the simulation. To validate the simulation inputs, e.g., the mobility model or a manually developed topology, a visualization tool is needed. A visualization tool makes it possible to see the new generation of more realistic mobility models and the complex node behaviors. Second, new versions of NS-2 appear regularly and researchers are responsible for verifying the simulations are valid with the model implemented in NS-2 [25]. Third, after developing new protocols and techniques the results of the NS-2 simulation (in the form of trace files) must be analyzed both statistically and visually to ensure the output matches the research hypothesis and analysis. For these reasons, there have been several emails on the NS-2 mailing list [6] asking for video or animation support for wireless networks in NS-2. We have, therefore, implemented a graphical visualization and animation package for NS-2 called iNSpect.

1) *Related Work*: The developers of NS-2 implemented a visualization tool, the Network Animator (NAM). NAM allows users to create Tcl based NS-2 scripts through a graphical user interface [13] as well as view NS-2 trace

files in playback form. Cartesian coordinates have been added to NAM to playback NS-2 generated trace files for wireless simulations. However, the playback for wireless based scenarios is limited node movements and emitting a circular pattern to represent the node's transmission signal. The concepts of links and queues are not supported in the NAM wireless animations, because NAM does not show the wireless links.

The wireless extension to NS-2 initially included a visualization tool called *ad-hockey* [23]. The Monarch Project that offered the extensions to NS-2 planned to have *ad-hockey* visualize NS-2 wireless trace files and provide a graphical environment to build wireless scenarios. The first release of *ad-hockey* was in 1997, and the final release was in 1998 [23]. These early versions produced the trace file visualization, but became incompatible with the NS-2 wireless trace format and with the Tcl versions used in NS-2 in 1999.

2) *iNSpect Overview*: Our interactive NS-2 protocol and environment confirmation tool (iNSpect) allows the visualization and animation of NS-2 based wireless simulations. Because it can animate a mobile ad hoc network without executing NS-2 itself (by reading the mobility file, which is an input to NS-2), and because it can post-process successful NS-2 simulations (by reading the trace file, which is an output from NS-2), iNSpect is an agile tool that can be utilized with minimal overhead. We have made iNSpect available to other interested researchers.

3) *iNSpect Details*: The iNSpect tool is a C++ OpenGL-based [27] visualization tool that allows animation of wireless networks simulated in NS-2. The iNSpect tool reads in NS-2 mobility files and then plays back simulation results, producing a visual display of the nodes in a wireless scenario. The display is based on Cartesian (x,y) coordinates used by NS-2. The iNSpect tool has an event builder that reads a mobility file directly and schedules the movements and pauses of each individual node. The event builder functionality allows iNSpect to be used directly with mobility files generated by external mobility models. There is no requirement to generate a trace file from NS-2. Mobility file analysis outside of NS-2 makes iNSpect a must for mobility file validation, eliminating the overhead of additional lengthy executions of NS-2.

If and when a trace file has been generated, iNSpect uses the same event builder to read the trace file and schedule the packet transmissions with the node movements. Unlike NAM, iNSpect shows the wireless routes and the success or failure of a packet transmission. The transmissions are displayed with route lines and color coded nodes. When a node is transmitting to another node, a line is drawn between the two nodes. The line represents the attempt to transmit between the two nodes, similar to the link object in the NAM wired scenarios. The initiating node of the transmission attempt turns blue to indicate it is sending.

The receiving node turns red until the packet is successfully received, then it turns green. The blue nodes along a path leading to a green node indicate a successful transmission to a destination, while blue nodes along a path leading to a red node shows failure of the packet to reach the destination and at which hop the packet failed. The graphical representation of the network activity gives the researcher more clues about individual success and failures of packets than the overall delivery ratio printed at the end of a scenario.

The iNSpect tool allows a user to display overlay objects such as circles, rectangles, and the current (x,y) location of each node. The geometric overlays may identify regions of interest. We use circular overlays with a new mobility model that implements congestive movement for nodes in a given area of the simulation. We use the rectangular overlays in evaluating geocast routing protocols. In geocast routing, packets are forwarded to nodes in a specific geographical area of the simulation [9]. The representation of the rectangle on the display allows visual analysis of a packet's route to the geocast area.

The geometric overlays of iNSpect can be used to represent obstacles as well. As stated in [8], obstacles make mobility models more realistic. The obstacles affect both transmission and movement of nodes. The iNSpect tool can be used to observe the affects of the obstacles on the movement of nodes and the transmission of packets.

4) *iNSpect Capabilities*: We have identified three main areas for iNSpect use: topology analysis and validation, model analysis and validation, and simulation results analysis. We discuss each of these areas in this section.

a). *Topology Analysis and Validation*

Until the development of iNSpect, the only way to visually validate a topology or mobility file was to generate the mobility file, simulate it with NS-2 to produce a NAM trace file, and use NAM to analyze the mobility file for errors. This process can take several minutes or more, depending on the NS-2 simulator and the machine executing the simulation. Additionally, the NAM trace file can grow to be on the order of hundreds of megabytes. These steps are tedious and wasteful for a developer of a mobility model, especially if there are multiple iterations.

Unlike NAM, iNSpect can process an NS-2 based mobility file directly. The iNSpect engine calculates the node movements from the mobility file in the same way as NS-2. Each update of the iNSpect display updates the node movements based on the playback speed. This capability streamlines the development of individual topologies or mobility files generated from an automated script or mobility model, because the nodes can be displayed and animated outside of NS-2. Not burdened with the other things NS-2 does in a simulation, iNSpect can produce visual validation instantly for a given mobility file. Thus, quicker results for the model developer are obtained, and

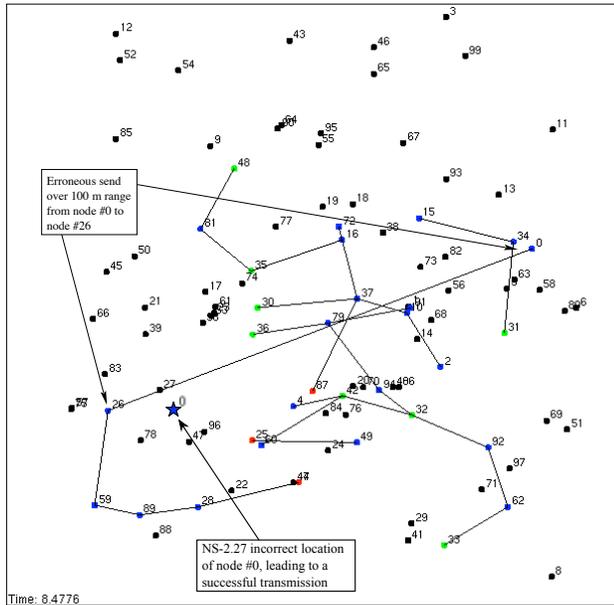


Fig. 2. iNSpect showing an NS-2.27 model error. The node 0 transmission exceeds the 100m transmission range, because NS-2’s incorrect view of node 0’s location places node 0 in range of node 26. The simulation area is 600 m x 600 m.

no trace files are written to disk.

b). Model Analysis and Validation

As stated at the beginning of the NS-2 documentation [25] “users of NS-2 are responsible for verifying for themselves that the simulations are not invalidated by bugs.” The question is how does one ensure a simulation is correct? While there is no way to guarantee correctness, iNSpect can help.

As an example, we recently installed the new 2.27 version of NS-2 and, similar to several accounts on the NS-mailing list (e.g., [3]), we noticed a significant drop in the performance of our simulations (e.g., delivery ratio). Using iNSpect, we discovered an error in the simulator. Specifically, NS-2.27 does not update the position of a node unless there is an event for that node. (The error was concurrently located by the author of [26].) Figure 2 provides an example of the NS-2.27 error. In Figure 2 the simulation area is 600 m x 600 m and each node’s transmission range is 100 m. As shown, there are nodes that successfully transmit a packet outside the 100 m range, e.g., node 0 to node 26 in Figure 2. In Figure 2, the actual distance between node 0 and node 26 is 453.4757 meters, which is well over the 100 m transmission range. We also show NS-2.27’s incorrect view of node 0’s location in Figure 2 with a star. The incorrect view places node 0 in range of node 26, explaining the successful transmission.

In summary, iNSpect quickly illustrated the inconsistencies of the simulation output under the new version of NS-2.27. We also note that NAM could not have shown the

problem for two reasons. First, NAM’s output is based on the NS-2 model, therefore the nodes shown in NAM would be in the locations seen by NS-2 (e.g., the incorrect location of node 0 in Figure 2). Second, NAM does not show the links and packet flows. Thus, even if the nodes were in a different location, an analyst would not have seen the extreme transmission distance.

c). Simulation Results Analysis

An entire simulation (using both the mobility file and iNSpect trace file) can be animated with iNSpect. The iNSpect display shows each transmission, with lines between nodes for transmission attempts and color codes for the sending nodes, nodes that receive a transmission successfully, and nodes that do not receive a transmission successfully. iNSpect shows the virtual link in a transmission, instead of the transmission ring shown in NAM.

By knowing the path a packet takes from source to destination, we can learn more about the behavior of a protocol. Figure 3 shows a snapshot of a Location Aided Routing (LAR) simulation [11]. LAR routing uses knowledge of the destination node’s location to build routes for a packet transmission. We can use iNSpect to evaluate the number of hops a given successful transmission takes, and whether a protocol can be improved to reduce the number of hops. For example, in Figure 3 we see a successful transmission from node 5 to node 44. The path from node 5 goes through nodes 84, 22, 4, 101, 82, 45, 57, 11, 93, 64, 24, 77, and 44 (a total of 13 hops). From the iNSpect tool we have the time the event occurs and we see other more direct paths such as the one from node 101 to nodes 112 or 97, to 24. With the additional knowledge we can look at which routes were in the cache for node 5 and see why it did not discover the shorter route. Individual analysis like route debugging would be impossible with only performance statistics and no iNSpect animation.

With the help of iNSpect, we developed improvements to LAR that utilize the location information disseminated to find more direct routes. Our route optimization (see Figure 4) found a route with eight fewer hops (from node 5 to 76, 19, 92, 77, to 44) compared to the route shown in Figure 3. Visualizing our LAR projection method is a valuable step in designing, analyzing, and communicating our improvements to the protocol.

5) *Future Work Planned on iNSpect:* Our goal is to make iNSpect a complete analysis tool. During the playback of a mobility file or NS-2 trace file, iNSpect has access to a large amount of data. We plan to use this available data to create real-time displays and summary reports in the following two ways. First, we plan to augment iNSpect to calculate precise neighbor counts throughout the simulation. This analysis will also indicate partitioned nodes, and produce a report giving details of when and how the network was partitioned. Second, we plan to add a statistical graphing capability to iNSpect. These graphs will

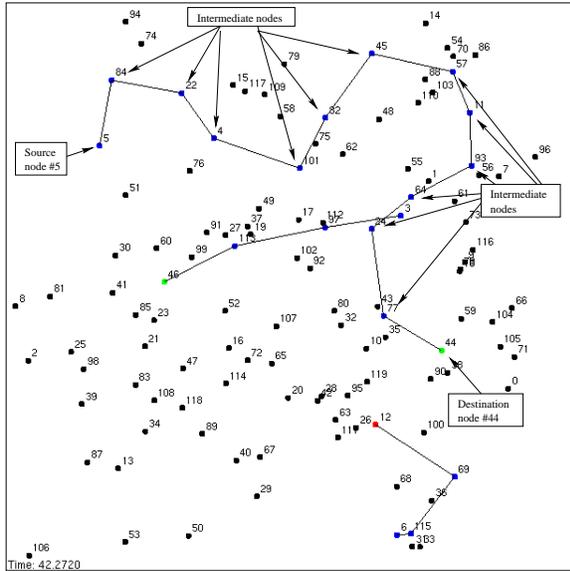


Fig. 3. iNSpect showing a Location Aided Routing route selection for a transmission from node 5 to node 44 in a 600 m x 600 m simulation area with a 100 m transmission range.

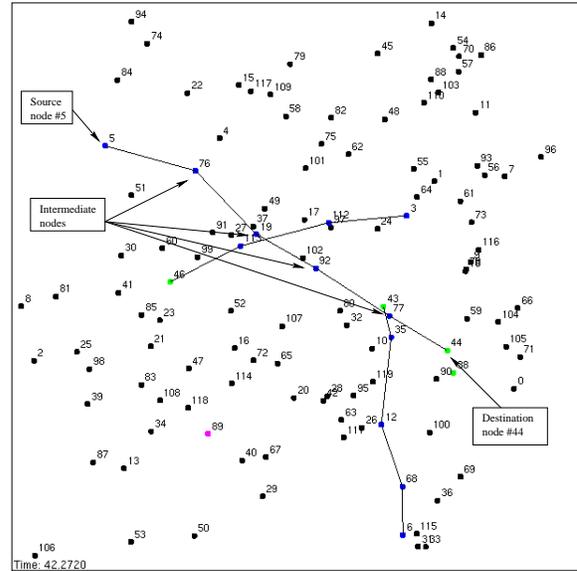


Fig. 4. iNSpect showing our *projection method* of Location Aided Routing route selection for a transmission from node 5 to node 44 in a 600 m x 600 m simulation area with a 100 m transmission range.

include instantaneous and cumulative node distribution histograms to aid in determining when steady-state of a given mobility model has been reached. The graphs will also include real-time tracking of performance metrics such as average delivery ratio and number of hops.

B. A Scenario Characterization Tool

Table II lists the parameters used by the authors who provided parameters (44 scenarios within 38 of the 84 mobility-based simulation papers) in our survey of published MobiHoc papers. The table shows the wide range of values simulated in each category. The number of nodes in a scenario ranged from 10 nodes to 1000 nodes. The simulation area ranged from 40 m x 40 m to 5000 m x 5000 m. The transmission ranges varied from 10 m to 1061 m. The data also reflects that the parameter values are often very specific, e.g., a 1981.7 meter square simulation area. The survey results highlight the wide range of simulation scenarios used to conduct MANET research.

There have been several emails on the NS-2 mailing list [6] asking what a valid scenario is for MANET research. The MANET community needs a way to characterize simulation scenarios to evaluate protocols and performance against more realistic scenarios. Characterizing a scenario means to describe the scenario's standing in categories such as mobility, density, and coverage. Knowing the characterization of a scenario provides a medium for comparison and contrast with other similar or dissimilar scenarios.

One way to characterize simulation scenarios is to generate summarizing statistics for the scenario. Mobility mod-

els use input parameters to generate a mobility file. A characterization tool can use these same input parameters to calculate statistics that describe the scenario. Our SCenario characterizER for Simulation (SCORES) tool calculates these statistics.

Our SCORES tool is a C++ based program that generates characterization data from the input parameters such as number of nodes, simulation area dimensions, and transmission range. Our tool is configuration file driven, and currently calculates the derived parameters and topology change rates for a given scenario. We have made SCORES available to other interested researchers.

1) *Derived Parameters:* The input parameters to a simulation can be used to characterize the simulation's scenario. Table III shows a list of possible derived scenario parameters. Currently the SCORES tool calculates these derived parameters, which enables a researcher to generate the derived parameters on a large set of input parameters quickly. In fact, we used our SCORES tool to calculate the derived parameters for the 44 sets of input parameters that were given within 38 of the 84 MobiHoc mobility-based simulation papers. The range of values in the derived parameters is as large as the range of input parameters (see Table II). For example, the node density values ranged from 0.0000016 nodes/square meter to 0.04 nodes/square meter. Node coverage ranged from 353657 square meters to 314.16 square meters. The transmission footprint ranged from 87.2% to 0.15%. Furthermore, network diameter ranged from 63.32 hops to 3.25 hops. The wide range in these values translates to inadequate com-

TABLE II

INPUT PARAMETERS FROM 44 PUBLISHED SCENARIOS IN THE PROCEEDINGS OF THE MOBIHOC CONFERENCE, 2000-2004, SORTED BY NUMBER OF NODES.

No.	# Nodes	Area (mxm)	Range (m)
1	10	1000 x 1000	100
2	20	350 x 350	100
3	20	1000 x 750	250
4	24	800 x 1200	250
5	30	350 x 350	100
6	36	3000 x 3000	1061
7	40	350 x 350	100
8	40	5000 x 5000	250
9	50	40 x 40	10
10	50	350 x 350	100
11	50	1500 x 300	250
12	50	1500 x 300	275
13	50	1000 x 1000	250
14	50	1000 x 1000	100
15	60	350 x 350	100
16	70	350 x 350	100
17	80	350 x 350	100
18	90	350 x 350	100
19	100	100 x 100	20
20	100	350 x 350	100
21	100	1200 x 1200	250
22	100	500 x 500	100
23	100	575 x 575	250
24	100	575 x 575	125
25	100	650 x 650	67
26	100	1000 x 1000	250
27	100	1000 x 1000	150
28	100	1000 x 1000	50
29	100	1000 x 1000	100
30	100	2200 x 600	275
31	100	2000 x 600	250
32	100	150 x 1500	250
33	100	3000 x 900	250
34	100	1000 x 1000	100
35	110	350 x 350	100
36	200	100 x 100	40
37	200	500 x 500	70
38	200	1700 x 1700	250
39	200	1981.7 x 1981.7	250
40	225	100 x 100	20
41	400	100 x 100	20
42	500	3000 x 3000	67
43	600	3000 x 3000	250
44	1000	500 x 500	20

TABLE III

DERIVED SCENARIO PARAMETERS.

Parameter	Description	Formula
Simulation Area	Square meter area of the topology.	$(w \times h)$
Node Density	Density of nodes in the simulation area.	$\frac{n}{(w \times h)}$
Node Coverage	Average area covered by a node transmission.	$\pi \times r^2$
Footprint	Percentage of the simulation area covered by a node's transmission range	$\frac{(\pi \times r^2)}{(w \times h)} \times 100$
Maximum Path	The maximum linear distance a packet can take from source to destination.	$\sqrt{(w^2 + h^2)}$
Network Diameter	The minimum number of hops a packet can take along the maximum path from source to destination.	$\frac{\sqrt{(w^2 + h^2)}}{r}$
Neighbor Count	The average number of neighbor nodes based on transmission and simulation area. It does not account for the edge of the simulation area.	$\frac{(\pi \times r^2)}{\left(\frac{w \times h}{n}\right)}$
Neighbor Count Edge Effect	It simulates the node placements accounting for nodes by the edges having fewer neighbors	Simulation with n, r, and $(w \times h)$
w = width, h = height r = transmission range, n = # of nodes		

comparisons between studies, and difficulty determining conclusive results.

Figure 5 is a scatter plot of the derived scenario parameters for the 44 sets of input parameters given in Table II. The scatter plot reflects the wide range of scenarios and the lack of correlation between parameters. Likewise correlation does not even occur among derived scenario parameters. In fact, according to Figure 5, the *only* correlation that exists among the derived parameters is with two parameters that are calculated similarly, i.e., Neighbor Count and Neighbor Count Edge Effect. The lack of complete characterization and correlation within a scenario emphasizes the need for new statistics. Also, the

extreme values in the derived parameters do not correlate with the extreme input parameters. For example, the highest number of nodes (1000) is the 12th lowest value for the neighbor count derived parameter.

2) *Topology Change Rate:* There are events and information that occur in the scenario that can only be collected by stepping through the scenario. For example, our SCORES tool can execute a mobility file by processing the node movements contained in the file. The execution of the mobility file allows our SCORES tool to track duration dependent statistics for topology change. SCORES collects statistics on link additions, link deletions, link durations, and neighbor counts. The link information is based on the transmission range and not the propagation model used in NS-2 or another simulator. The results are therefore idealistic, but provide consistent information without replicating NS-2 execution in SCORES.

The topology change rate reflects the behavior of the scenario beyond the projections made by the derived parameters. For example, a researcher that generated a mobility file with fast average node speed for all nodes may conclude the resulting scenario has poor connectivity. The topology change rate, however, might be low if the nodes are all grouped together or are all moving in the same direction. The topology change rate provides an added dimension to the SCORES derived parameter calculations.

3) *Future Work Planned on SCORES:* Our next step for the SCORES tool is to add NS-2 metamodels for delivery ratio, end-to-end delay, throughput, and overhead. The metamodels will allow SCORES to calculate a performance prediction for a given scenario. The prediction will characterize and “score” scenarios, which will provide an indication of how realistic and difficult a scenario is for a particular performance measure. For example, a high “score” on end-to-end delay will mean a protocol offers low end-to-end delay in scenarios known to challenge end-to-end delay. As a result, researchers that use SCORES and cite the resulting “score” as benchmarks for the performance metrics will have more credibility. The MANET community will have confidence knowing the “scored” research results were not produced with a biased, unrealistic, or trivial scenario.

V. CONCLUSIONS

MANET simulation-based research is an involved process with plenty of opportunities to compromise the credibility of the study. In this paper, we have identified several pitfalls throughout the simulation lifecycle. Each of the pitfalls discussed in Section III takes away from the goals of making the research repeatable, unbiased, realistic, and statistically sound. Documenting these pitfalls and sharing knowledge about how to address these common issues will increase the credibility of studies in the MANET community. Our survey of MobiHoc papers showed the current

state of MANET research and the lack of credibility, re-enforcing the need for simulation study guidance.

To help simulationists in the areas of validation, verification, and analysis, we offer iNSpect, a quick, low-overhead solution to animating mobility model files and topologies for NS-2. By using the iNSpect tool, a researcher can quickly discover anomalies in topology files, the NS-2 model itself, or even in the results of a particular protocol. In addition, because iNSpect executes outside of NS-2, it is fast and can save hours of detailed detective work trying to validate results. iNSpect can be used in different ways to enable the quick and accurate inspection of wireless network scenarios with NS-2. As we have seen in our own research, iNSpect can reveal issues that summary statistics cannot. From analyzing node movement to packet routing, iNSpect can provide insight not available from totals and averages. Our visualization tool is useful for simulations of large sensor networks, a simple wireless LAN, or a mobile ad hoc network. iNSpect supports wireless network capabilities of NS-2 and lets the human visual system participate in the analysis.

To help simulationists produce unbiased and realistic simulations, we offer SCORES, a scenario characterization tool. The input and derived parameters from the MobiHoc survey highlight the diverse scenarios used in MANET research. As the MANET community strives for more realistic scenarios, there will continue to be a wide range of scenarios available to researchers. If the MANET community has a means to characterize a scenario, results could be compared from paper to paper and group to group. A common characterization would allow a researcher to prove that a solution works for more than one particular weak scenario. SCORES provides a consistent framework for characterization.

VI. ACKNOWLEDGMENTS

We thank Dr. Krzysztof Pawlikowski for alerting us to the poor state of simulation based studies in the networking community. Thank you also to Feng Sun, Patrick Milvich, and Tuli Mushell who reviewed the MobiHoc papers.

REFERENCES

- [1] E. Angel. *Interactive computer graphics: a top-down approach with OpenGL*. Addison Wesley, 1997.
- [2] L. Briesemeister and G. Hommel. Role-based multicast in highly mobile but sparsely connected ad hoc networks. In *Proceedings of the 1st ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, pages 45–50. IEEE Press, 2000.
- [3] J. Chen. DSR performance is too bad in ns-2, why? URL: <http://mailman.isi.edu/pipermail/ns-users/2004-March/040565.html>. Page accessed on June 14, 2004.
- [4] Association for Computing Machinery. The ACM international symposium on mobile ad hoc networking and computing (MobiHoc). URL: <http://www.sigmobile.org/mobihoc>. Page accessed on September 23, 2004.

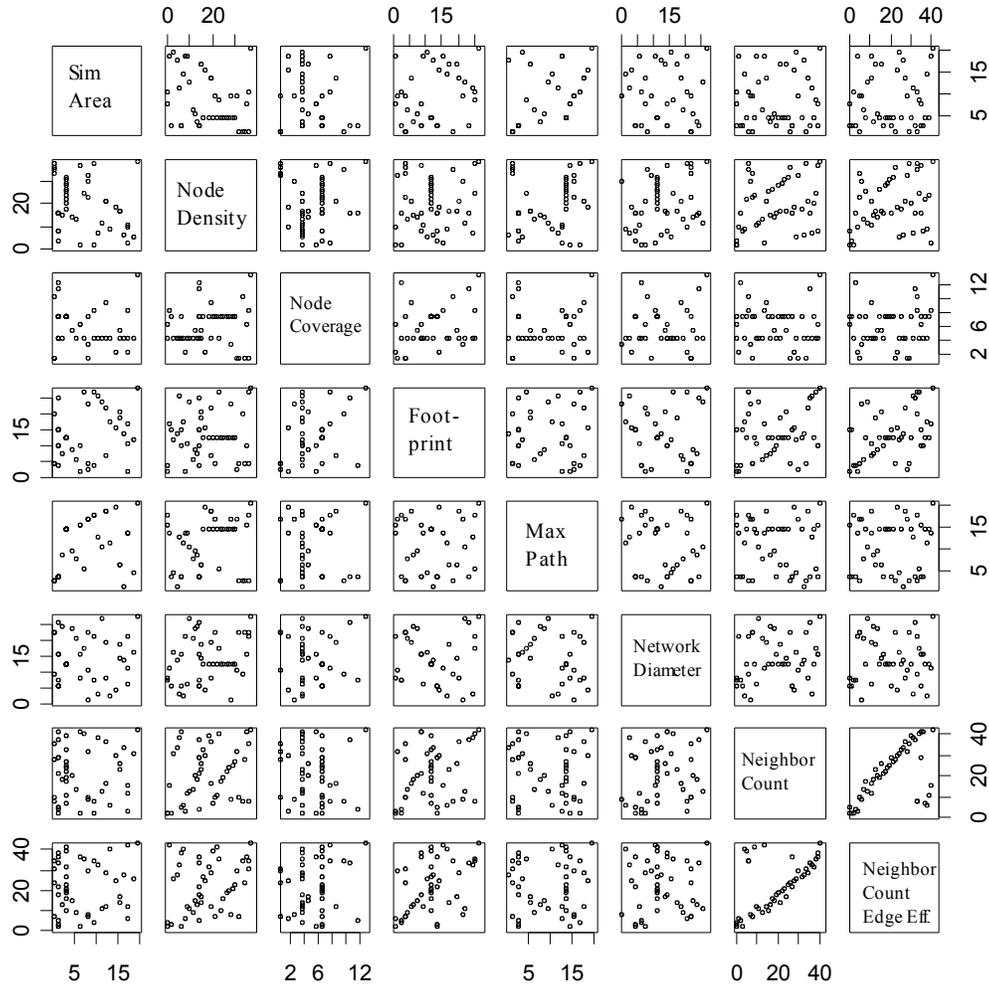


Fig. 5. A scatter plot of the derived scenario parameters, showing the wide range of values that exist.

- [5] Akaroa Research Group. Akaroa2. URL: http://www.tkn.tu-berlin.de/research/ns-2_akaroa-2/ns.html. Page accessed on September 1st, 2004.
- [6] The VINT Group. Ns-users mailing list. <http://mailman.isi.edu/mailman/listinfo/ns-users>. Page accessed on October 23rd, 2004.
- [7] X. Hong, M. Gerla, G. Pei, and C. Chiang. A group mobility model for ad hoc wireless networks. In *Proceedings of the ACM International Workshop on Modeling and Simulation of Wireless and Mobile Systems (MSWiM)*, pages 53–60, August 1999.
- [8] A. Jardosh, E. Belding-Royer, K. Almeroth, and S. Suri. Towards realistic mobility models for mobile ad hoc networks. In *Proceedings of ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom)*, pages 217–229, 2003.
- [9] X. Jiang and T. Camp. A review of geocasting protocols for a mobile ad hoc network. In *Proceedings of the Grace Hopper Celebration (GHC)*, pages 1–5, 2002.
- [10] D. Johnson and D. Maltz. Dynamic source routing in ad hoc wireless networks. In T. Imelinsky and H. Korth, editors, *Mobile Computing*, pages 153–181. Kluwer Academic Publishers, 1996.
- [11] Y. Ko and N.H. Vaidya. Location-aided routing (LAR) in mobile ad hoc networks. In *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom)*, pages 66–75, 1998.
- [12] P. L'Ecuyer and R. Simard. On the performance of birthday spacing tests for certain families of random number generators. *Mathematics and Computers in Simulation*, pages 131–137, 2001.
- [13] J. Mehringer. The NAM editor: A graphical tool for creating ns scripts. A presentation for the CONSER retreat, slide 3, 2001. URL: <http://www.isi.edu/nsnam/nam/nam-editor.ps>. Page accessed on November 15, 2004.
- [14] S. Midkiff. Simulation: Methodology. Presentation to ECE590 class. URL: http://fiddle.visc.vt.edu/courses/ece594-net2/lectures/09_sim.pdf. Page accessed on November 15, 2004.
- [15] W. Navidi and T. Camp. Stationary distributions for the random waypoint mobility model. *IEEE Transactions on Mobile Computing*, pages 99–108, 2004.
- [16] *The NS manual: formerly known as notes and documentation*, 2003. URL: <http://www.isi.edu/nsnam/ns/>. Page accessed on September 1st, 2004.
- [17] K. Pawlikowski. Do not trust all simulation studies of telecommunication networks. *International Conference on Information Networking (ICOIN)*, pages 899–908, 2003.
- [18] K. Pawlikowski, J. Jeong, and R. Lee. On credibility of simulation studies of telecommunication networks. *IEEE Communications Magazine*, pages 132–139, 2001.
- [19] K. Pawlikowski, J. Jeong, and R. Lee. Letters to the editor. *IEEE Communications Magazine*, pages 132–139, 2002.

- [20] K. Pawlikowski and V. Yau. *Akaroa-2 Manual*, 1995. Department of Computer Science, University of Canterbury, ChristChurch New Zealand. URL: <http://www.tkn.tu-berlin.de/research/ns-2.akaroa-2>. Page accessed on September 1st, 2004.
- [21] M. Pearlman, Z. Haas, P. Sholander, and S. Tabrizi. On the impact of alternate path routing for load balancing in mobile ad hoc networks. In *Proceedings of the 1st ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, pages 3–10. IEEE Press, 2000.
- [22] G. Pei, M. Gerla, X. Hong, and C. Chiang. A wireless hierarchical routing protocol with group mobility. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1538–1542, 1999.
- [23] The CMU Monarch Project. *ad-hockey Visualization Tool For ns Scenario and Trace Files*, 1998. Carnegie Melon University, version 1.1.0, URL: <http://www.monarch.cs.rice.edu/cmuns.html>. Page accessed on November 18th, 2004.
- [24] The SEACORN Project. SEACORN simulation tools. URL: http://seacorn.ptinovacao.pt/sim_tools.html. Page accessed on September 23, 2004.
- [25] The VINT Project. The network simulator - ns-2. URL: <http://www.isi.edu/nsnam/ns/>. Page accessed on June 1st, 2004.
- [26] K. To. Bug in ns-2.27 wireless channel. URL: <http://mailman.isi.edu/pipermail/ns-users/2004-April/041388.html>. Page accessed on May 1st, 2004.
- [27] M. Woo, J. Neider, and T. Davis. *OpenGL Programming Guide: The official guide to learning OpenGL*. Addison Wesley, 1997.