Scenario Standards for Rigorous MANET Routing Protocol Evaluation*

Stuart Kurkowski, William Navidi and Tracy Camp
Dept. of Math. and Computer Sciences
Colorado School of Mines
Golden, CO, 80401
skurkows, wnavidi, and tcamp@mines.edu

Abstract

In this paper we look at issues with the simulation of generic Mobile Ad Hoc Network (MANET) routing protocols. MANET simulation-based research is an involved process driven by the scenarios used in the simulations. Scenarios must be properly constructed in order to be effective in evaluating the performance of generic MANET routing protocols. For example, in scenarios with a low average hop count, little routing is needed, and poor protocols might appear successful. On the other hand, in scenarios with a high degree of partitioning, many pairs of nodes have no usable route between them, and good protocols might appear unsuccessful.

Many standards are needed to establish rigorous evaluations for MANET simulation research, from simulation scenario standards to random number generator standards to results analysis standards. We do not attempt to standardize all of these areas. We do, however, propose *two standards* that should be employed to ensure long routes are available and used in the evaluation of generic MANET routing protocols. That is, we qualify a simulation scenario to be used for rigorous generic MANET routing protocol evaluation, based on the values of two metrics: the scenario's average shortest-path hop count and its amount of network partitioning. We explore the relationship between average shortest-path hop count and network partitioning. We show that our algorithms can be used to generate scenarios with any values for the metrics that a researcher finds appropriate.

See `http://toilers.mines.edu` for information on obtaining code used in this study.

Index Terms

wireless networks, mobile ad hoc networks, MANET, simulation scenarios, network partitioning, rigorous evaluation

I. INTRODUCTION AND STANDARDS

A Mobile Ad Hoc Network (MANET) is a collection of wireless mobile nodes that cooperatively forms a network without infrastructure. Ad hoc networking allows devices to create a network on demand without prior coordination or configuration. This requires nodes within a MANET to be involved in routing and forwarding information between neighbors. The lack of coordination and configuration prior to setup of a MANET produces several challenges, including issues associated with wireless communication, limited power, and routing packets in a dynamic environment. Numerous MANET routing protocols have been proposed to address these challenges, and simulation is the leading method for the protocol evaluations.

Several papers (such as [6], [10], [11]) have raised the issue of a lack of credibility in network protocol evaluation. This lack of credibility covers all areas of simulation-based research and is sometimes attributed to a lack of standards. Standards establish a baseline for rigorous evaluations and can cover the entire simulation-based study process, from simulation scenario creation to random

---

*Technical Report MCS 06-03, Colorado School of Mines, May 2006. An early version of this work has been accepted by MASS 2006. This work supported in part by NSF Grants ANI-0208352 and ANI-0240558. Research group's URL is *http://toilers.mines.edu.*

number generation to results analysis. Many standards are needed to improve the quality and credibility of MANET simulation research. In this paper we focus on two of these standards as they apply to generic MANET routing protocols[1] and to the simulation scenarios used to evaluate their performance.

To execute a MANET simulation, the researcher must create a simulation scenario. In addition to the mobility model, important parameters of a simulation scenario include the number of nodes, width and height of the simulation area, shape of the simulation area, node speed, node pause time, and transmission range of the node. The values chosen for simulation parameters determine the rigor of a scenario in assessing the performance of the protocols being evaluated. Appropriate choices for these parameters have long been the subject of debate.

We propose two standards for rigorous evaluation of generic MANET routing protocols. Our proposed standards are not individual parameter settings, but a definition of two metrics that should be calculated and recorded with any simulation-based research that desires credit for rigorously testing a generic MANET routing protocol.

> *Standard 1: To rigorously evaluate generic MANET routing protocols, the average shortest-path hop count needs to be large.*

A scenario with an average shortest-path hop count of 1 or 2 is a scenario in which many packets are only sent between neighbors. In this environment, the generic MANET routing protocol's routing capability is not rigorously tested. Most protocols, even poor protocols, perform well in scenarios that have low average shortest-path hop counts.

> *Standard 2: To rigorously evaluate generic MANET routing protocols, only a small amount of network partitioning should exist.*

Since no routing protocol is able to route between a pair of nodes that is partitioned, most protocols, even good ones, perform poorly in scenarios that have a large amount of network partitioning. In other words, a large amount of network partitioning prevents rigorous evaluation of a generic MANET routing protocol.

The main contribution of this paper is to provide algorithms that researchers can use to create scenarios that meet our standards proposed. We first precisely define average shortest-path hop count and average network partitioning, the two metrics for our proposed standards, how we estimate these metrics in simulation, and our notation. We then explore the relationship between average shortest-path hop count and network partitioning, and develop algorithms for generating scenarios that meet our standards, using any values for the metrics that the researcher finds appropriate.

The rest of this paper is organized as follows. Section II defines terms used in this paper, describes the metrics we use, discusses our mobility model selection, and describes the notation used in this paper. Section III explores the relationship between average shortest-path hop count and network partitioning, as well as the impact of parameters on these two metrics. In Section IV, we develop the algorithms that allow a researcher to calculate the required number of nodes and simulation area to produce scenarios with their desired metric levels. Section V illustrates some example scenarios based on metric levels we have picked for our two standards, and Section VI presents our conclusions.

II. BACKGROUND

To sufficiently exercise a generic MANET routing protocol, packet destinations need to be several hops from the source, and packets must have the opportunity to be delivered to the destinations. In this

---

[1] We define generic MANET routing protocols as those protocols that are used for direct end-to-end communication without any specific distinctive quality or application. The goals of these protocols are typically to minimize end-to-end delay, minimize control overhead, and/or maximize delivery ratio.

section, we consider one metric that is needed to obtain a large number of hops from the source to the destination (i.e., high average shortest-path hop count[2]) and one metric that is needed to give packets the opportunity for delivery (i.e., low network partitioning[3]). Other metrics could be considered; for example, a high average neighbor count metric. We chose, however, to focus our standards on average network partitioning and average shortest-path hop count, because they are both intuitive and can be employed to ensure long routes are available and used between sources and destinations. When long routes are available and used, then routing in a generic MANET routing protocol is rigorously tested.

In this section, we first precisely define our two metrics that are the basis for our standards: average shortest-path hop count and network partitioning. We also describe how we estimated these values for various scenarios using simulation. In addition, we describe both our selection of the steady-state Random Waypoint Model and our transmission range notation.

A. Average Shortest-path Hop Count

A hop in a MANET is the transition of a packet from one node to the next (within transmission range) on a communication link between two nodes. The hop count of a path between a pair of nodes is defined to be the number of communication links on the path. As an example, Figure 1 presents a snapshot in time of a network with six nodes. In Figure 1, the hop count between node 0 and node 2 is three.

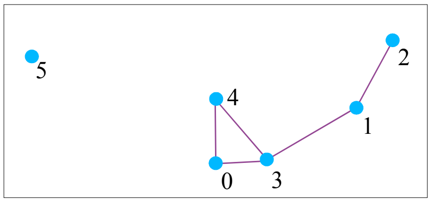

Fig. 1. Example network with six nodes at a certain point in time. The lines represent communication links between nodes.

When a protocol is being evaluated, it is common to calculate the average number of hops by counting the total number of hops of all successfully delivered packets, then dividing by the number of successfully delivered packets. This metric is not appropriate for our needs, because it is protocol dependent. We need a metric that measures the potential for a scenario to evaluate protocols in general, rather than one which depends on the performance of a particular protocol. For this reason we base our metric on the shortest-path hop count, which is the smallest number of hops along any path between the two nodes.

To calculate the average shortest-path hop count, we use a multi-hop connectivity matrix [8], [14] which stores the shortest-path between two nodes in the matrix. Figure 2 presents the multi-hop connectivity matrix for the network in Figure 1. Each non-zero entry in the matrix represents the shortest-path hop count for a particular pair of nodes. The zero entries represent partitioned pairs. The average shortest-path hop count for the network in Figure 1 at this point in time is found by summing the non-zero entries in the matrix, then dividing by the number of non-zero entries, i.e., $34/20 = 1.7$.

Our metric is the average shortest-path hop count, where the average is taken over all communicating node pairs over all points in time. We denote this by A_{sp}Hops. In practice, A_{sp}Hops is estimated by

---

[2] The shortest-path hop count is the smallest number of links needed to allow two nodes to communicate. The average shortest-path hop count is the average of all shortest-path hop counts for all node pairs. See Section II-A for details.

[3] Network partitioning exists when some pair of nodes has no route between them and thus cannot communicate with each other. See Section II-B for details.

	0	**1**	**2**	**3**	**4**	**5**
0	-	2	3	1	1	0
1	2	-	1	1	2	0
2	3	1	-	2	3	0
3	1	1	2	-	1	0
4	1	2	3	1	-	0
5	0	0	0	0	0	-

Fig. 2. Multi-hop connectivity matrix for the simulation scenario in Figure 1.

generating a large number of realizations of a scenario at various points in time, using the multi-hop connectivity matrix to compute the average shortest-path hop count at each point in time, and averaging. Specifically, A_{sp}Hops is calculated using the equation

$$\mathrm{A}_{sp}\mathrm{Hops} = \frac{\sum_{i=1}^{T} hops_i}{\sum_{i=1}^{T} paths_i}, \tag{1}$$

where T is the number of multi-hop matrices constructed, $hops_i$ is the total number of hops in the multi-hop matrix at time i, and $paths_i$ is the number of cells in the multi-hop matrix at time i that contain a non-zero entry.

B. Network Partitioning

We define the degree of network partitioning at any given time to be the proportion of node pairs between which no path exists. In Figure 1, there are a total of 15 ($6 \times 5/2$) pairs of nodes, and of these pairs, five (the ones involving node 5) have no path between them. To calculate the degree of network partitioning, we use the multi-hop connectivity matrix [8], [14]. Using the multi-hop connectivity matrix in Figure 2, the degree of partitioning is the proportion of the matrix with entries equal to 0. Thus, the degree of partitioning in this network, at this point in time, is $5/15 = 33.3\%$.

Our metric is the average amount of network partitioning over all points in time, and is referred to as “average network partitioning” or ANP. In practice, ANP is estimated by generating a large number of realizations of a scenario at various points in time, computing the degree of partitioning for each, and averaging. Specifically,

$$\mathrm{ANP} = \frac{z}{n(n-1)T} \tag{2}$$

where z is the total number of zeros in all the matrices constructed, n is the number of nodes, $n(n-1)$ is the potential number of links, and T is the number of multi-hop connectivity matrices constructed.

C. Mobility Models

We conducted a survey [6] of MANET research published in the 2000-2005 proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc) [3]. We included only the full papers in our survey, not the poster papers. Simulation is an often-used tool; 114 of the 151 MobiHoc papers published (75.5%) reported simulation studies. In addition, each of these studies using mobility required a mobility model.

There are many mobility models available for the MANET community to use to generate node position and movement [1], and the choice of mobility model can greatly affect the outcome of a simulation study. Figure 3 shows the distribution of the mobility models identified in our survey. As shown, 32 out of the 50 simulation papers (64%) that stated which mobility model was used in the study used the Random Waypoint Model (RWM). Because the RWM was the most popular, we used the RWM to generate simulation scenarios that meet our two standards; thus, the scenarios developed herein have the broadest application. We note, however, that our method can be modified to produce scenarios with any mobility model that is considered appropriate by the researcher. Herein, we used a steady-state version of the RWM [9] that starts all nodes in the steady-state distribution of the RWM. Use of the steady-state RWM allows us to analyze a simulation scenario from time zero, without initialization bias associated with initial node movement.

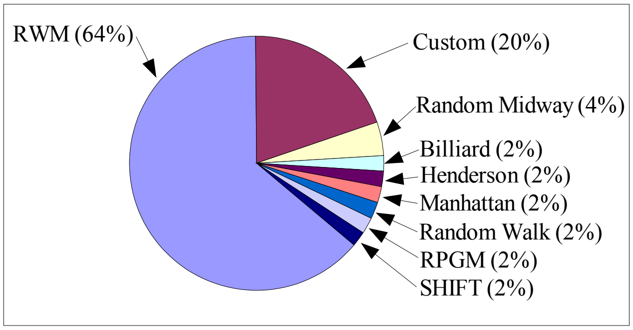

Fig. 3. Mobility model usage from our MobiHoc survey.

D. Using Transmission Range as the Unit of Distance

There are five main simulation parameters in the steady-state RWM [9]: the number of nodes, the width and height of the simulation area, which affect both the shape and size of the simulation area; and the node speed and pause time. One additional simulation parameter important to simulation scenarios, but not required by the steady-state RWM, is the transmission range of a node. The transmission range is the maximum distance at which the radio signal from a node can be received. When distances are measured in absolute units, such as meters, it is difficult to determine from the five main simulation parameters whether a scenario will effectively test a protocol. The reason for this is that the effect of distance is not determined by its absolute size, but by its size relative to the transmission range. For example, consider a simulation scenario with a 500 m × 500 m area. Then consider the different values of A_{sp}Hops if the transmission range is 500 m versus 50 m; a 50 m transmission range would require considerably more routing by a protocol than a 500 m transmission range. For this reason, it is appropriate to express distances in terms of the transmission range (R).

Using transmission range as the unit of distance, a simulation scenario with a 80 m × 200 m area, a node speed of 10 m/s, and a transmission range of 40 m, would be described as having a 2 R×5 R area and a node speed 0.25 R/s. Table I presents an example to show that a simulation scenario with a 80 m × 200 m area, a node speed of 10 m/s, and a transmission range of R = 40 m is equivalent to one with a 200 m×500 m area, a node speed of 25 m/s, and a transmission range of R = 100 m. In the rest of this paper, we express all distances in terms of an arbitrary transmission range R. Our results are, therefore, valid for any choice of transmission range.

E. Propagation Modeling

Several articles (e.g., [13]) in the literature have discussed the problems associated with specifying the transmission range of a node as a uniform circular representation of the transmission range [2]. We, therefore, use the Two Ray Ground propagation model as implemented in NS-2 [12]. The Two Ray

TABLE I

SIMULATION SCENARIO PARAMETERS EXPRESSED IN METERS, AND TRANSMISSION RANGE UNITS (R), FOR TWO SCENARIOS.

Parameter	**Scenario 1**		**Scenario 2**	
	Meters	R	Meters	R
Trans. Range	40 m	1 R	100 m	1 R
Width	200 m	5 R	500 m	5 R
Height	80 m	2 R	200 m	2 R
Node Speed	10 m/s	0.25 R/s	25 m/s	0.25 R/s

TABLE II

SIMULATION SCENARIO PARAMETERS FOR OUR SPEED AND PAUSE TIME STUDY.

Parameter	**Value(s)**		
# of Nodes	100	150	200
Width	6.75 R	7.25 R	8 R
Height	6.75 R	5.25 R	8 R
Avg. Speed (R/s)	0.075, 0.25, 0.5, 0.75, 1, 1.25		
Pause Time (s)	2, 5, 10, 20, 30, 40		

Ground model uses the Friis Free Space model [12] (factor of d^2) for nodes close to the source (less than the cross-over distance). For nodes farther from the source (greater than the cross-over distance), it uses a two ray reflection model with a factor of d^4, lowering the probability of a packet being recieved at the node's neighbor. The cross-over distance for the Two Ray Ground model to switch from d^2 to d^4 with an omnidirectional antenna at 1 m height is 38.6 m.

III. EFFECT OF PARAMETERS

In this section we explore the relationship between our two metrics described in Section II, transmission range, and the input parameters of the RWM. First, we evaluate the impact of node speed and node pause time on A_{sp}Hops and ANP. Second, we look at A_{sp}Hops, which is the metric that, when high, provides the best indicator of rigorous evaluation of a routing protocol. Third, we look at the relationship between A_{sp}Hops and ANP.

A. Effect of Speed and Pause Time

In this section, we show that speed and pause time have relatively little effect on A_{sp}Hops and ANP for the range of scenarios we evaluated. Using 36 different combinations of speed and pause time, and three combinations of number of nodes, width, and height, we created a total of 108 scenarios for this study. Table II presents the parameter values used in these scenarios. We then constructed multi-hop connectivity matrices to compute A_{sp}Hops and ANP for each scenario. We generated 200 independent iterations of each scenario and averaged the results.

Table III shows results from 12 of the 36 different simulation scenarios for 100 nodes; the other 24 scenarios for 100 nodes produced similar results. Neither ANP nor A_{sp}Hops vary greatly over the values of speed and pause time; the range of ANP is less than 1% and the range of A_{sp}Hops is less than 0.1 hops. Although not presented, we obtained similar results from the 150- and 200-node scenarios. We conclude that speed and pause time do not greatly affect ANP or A_{sp}Hops for the scenarios (see Table II) tested.

TABLE III

PARTIAL RESULTS FROM OUR SPEED AND PAUSE TIME STUDY FOR THE 100 NODE SCENARIO. FIXED PARAMETERS WERE 100 NODES, 6.75 R WIDTH, AND 6.75 R HEIGHT.

Spd (R/s)	**Pause (s)**	**ANP**	**A$_{sp}$Hops**
0.075	5	4.22	4.04
0.075	30	4.26	4.04
0.25	5	4.37	4.05
0.25	10	4.44	4.03
0.5	20	4.96	4.05
0.5	30	4.99	4.05
0.75	2	5.15	4.07
0.75	5	5.01	4.04
1.0	10	4.64	4.05
1.0	30	4.63	4.09
1.25	10	4.81	4.10
1.25	20	4.63	4.04

B. Effect of Number of Nodes

Due to the performance limitations of some simulators and the need to execute simulation studies quickly, researchers often conduct research studies with scenarios containing 200 nodes or less. This is validated by our MobiHoc paper survey [6]. Specifically, 48 of the 114 papers in our MobiHoc survey of published MANET protocol simulation papers provided the number of nodes, the dimensions of the simulation area, and the transmission range that were used in their simulations. There were 59 scenarios described in these 48 papers, and Table IV presents the parameters used in each of them. Even though the number of nodes varies from 10 to 1000, the majority of scenarios have 200 nodes or less.

We note that scenarios with a small number of nodes are scenarios with low A$_{sp}$Hops, especially when network partitioning is low [4]. To illustrate, we generated 200 independent scenarios using the steady-state RWM for numbers of nodes from 10 to 230. We adjusted the area of the scenarios to achieve nearly no network partitioning (ANP $< 0.2\%$) for each node. Figure 4 shows A$_{sp}$Hops versus number of nodes, with 95% confidence intervals. We note that scenarios with 50 nodes or less and small ANP (i.e., ANP $< 0.2\%$) means A$_{sp}$Hops is less than 2 hops. And, as previously mentioned, a scenario with an average shortest-path hop of 1 or 2 is a scenario in which many packets are only sent between neighbors. Thus, the generic MANET routing protocol's routing capability is not rigorously tested. Most protocols, even poor protocols, perform well in scenarios that have low average shortest-path hop counts. Of course, scenarios with more nodes result in poor simulator performance and longer times to generate results. An alternative is to introduce some level of network partitioning that allows scenarios with fewer nodes and larger A$_{sp}$Hops. We begin to explore the relationship between A$_{sp}$Hops and ANP in the next section.

C. Relationship between A$_{sp}$Hops and ANP

Using the descriptions and equations of Sections II-A and II-B, we explored square areas over the full possible range of ANP. Table V contains the values for each of the input parameters (i.e., number of nodes, width, and height of the simulation area) used to cover the partitioning range (0% to $\approx$90%). We fixed the node speed and node pause time parameters at 0.25 R/s and 10 s, respectively. Additionally, we paired equivalent width and height parameters to maintain square simulation areas. Our analysis was based on 36 different simulation scenarios, which are shown in Table V.

TABLE IV

SCENARIO PARAMETERS FROM 59 PUBLISHED MANET SCENARIOS IN THE PROCEEDINGS OF THE MOBIHOC CONFERENCE, 2000-2005, SORTED BY NUMBER OF NODES AND SIMULATION AREA.

No.	Nodes	Area (m x m)	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	25	200 x 200	100
6	25	900 x 900	250
7	30	350 x 350	100
8	36	3000 x 3000	1061
9	40	350 x 350	100
10	40	900 x 900	250
11	40	5000 x 5000	250
12	50	40 x 40	10
13	50	350 x 350	100
14	50	500 x 500	100
15	50	1500 x 300	250
16	50	1500 x 300	275
17	50	1000 x 1000	250
18	50	1000 x 1000	100
19	60	350 x 350	100
20	70	25 x 25	10
21	70	350 x 350	100
22	80	350 x 350	100
23	90	350 x 350	100
24	100	100 x 100	20
25	100	350 x 350	100
26	100	400 x 400	100
27	100	150 x 1500	250
28	100	500 x 500	100
29	100	575 x 575	250
30	100	575 x 575	125
31	100	650 x 650	67
32	100	300 x 1500	250
33	100	1000 x 1000	250
34	100	1000 x 1000	150
35	100	1000 x 1000	50
36	100	1000 x 1000	100
37	100	1000 x 1000	100
38	100	1000 x 1000	100
39	100	2000 x 600	250
40	100	2200 x 600	275
41	100	1200 x 1200	250
42	100	3000 x 900	250
43	110	350 x 350	100
44	120	2500 x 1000	250
45	200	100 x 100	40
46	200	500 x 500	70
47	200	1700 x 1700	250
48	200	1981.7 x 1981.7	250
49	225	100 x 100	20
50	225	600 x 600	100
51	400	100 x 100	20
52	400	800 x 800	100
53	500	3000 x 3000	67
54	600	3000 x 3000	250
55	625	1000 x 1000	100
56	1,000	40 x 40	3
57	1,000	81.6 x 81.6	300
58	1,000	100 x 100	10
59	1,000	500 x 500	20

Figure 5 and Table VI show the average network partitioning and A_{sp}Hop results of the 36 simulation scenarios. We note that the full range of no network partitioning (0%) to large network partitioning (90%) is shown. The results illustrate that a scenario with near-zero ANP (less than 1%) means A_{sp}Hop is low (less than 2.5 hops). As the percentage of ANP increases, A_{sp}Hop initially increases. However, as the percentage of partitioning continues to increase, A_{sp}Hop begins to decrease. At large network partitioning percentages (i.e., over 80%), the only nodes that are not partitioned are in close proximity to each other. As a result, the overall A_{sp}Hop is low.

Figure 5 shows that although the peak A_{sp}Hop value increases with number of nodes, the overall trend of each result is similar. Figure 5 also shows some standard metrics are impossible, e.g., a scenario with 50 nodes and at least 4 A_{sp}Hop is not possible. We continue to explore the relationship between A_{sp}Hop and ANP in Section V.

In the next section, we develop algorithms that take the average shortest-path hop count and average network partitioning desired for a simulation scenario as inputs. The algorithms then output the number of nodes and simulation area required to generate a simulation scenario that meets the inputs desired.

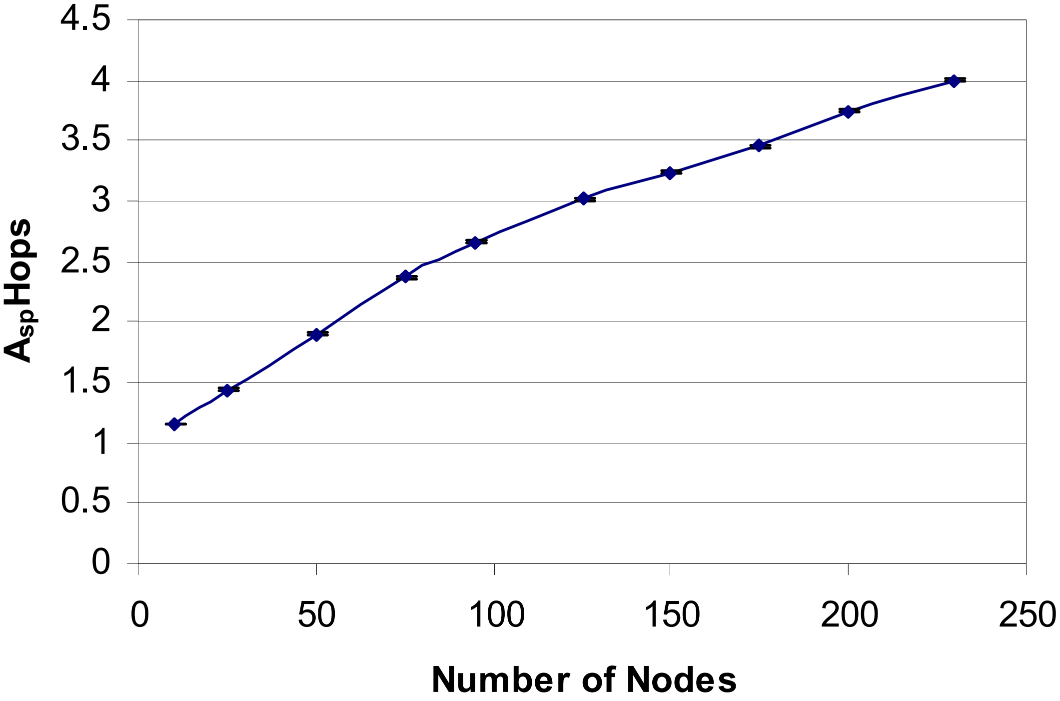

Fig. 4. A_{sp}Hops versus number of nodes with 95% confidence intervals, and ANP ≈ 0. Each dot in the plot is the average result from 200 realizations of the given simulation scenario.

TABLE V

SIMULATION SCENARIO PARAMETERS FOR THE SQUARE A_{sp}HOP VERSUS ANP STUDY. AVERAGE NODE SPEED IS 0.25 R/S AND PAUSE TIME IS 10 S.

# Nodes	Width & Height
50	4R, 5R, 6R, 7R, 8R, 10R
100	4R, 6R, 6.8R, 7R, 8R, 9R, 10R, 11R, 12R, 14R
150	4R, 6R, 8.1R, 9R, 10R, 11R, 12R, 13R, 15R, 16R
200	4R, 8R, 9R, 9.3R, 10R, 12R, 14R, 15R, 16R, 18R

IV. GENERATING RIGOROUS SCENARIOS

For generic MANET routing protocol evaluation, Standard 1 and Standard 2 should be followed. To follow the standards, a researcher needs to be able to predict the average shortest-path hop count and average network partitioning for a scenario a priori. We have developed several models that take the desired values of A_{sp}Hops and ANP as inputs, and outputs the area and number of nodes required to create a scenario with the standards specified. We consider square simulation areas in Section IV-A, and rectangular simulation areas in Section IV-B.

TABLE VI

Results for 36 simulation scenarios in square area study.

Nodes	**Width**	**Height**	**Part %**	**Avg Hops**
50	4R	4R	0.72	2.41
50	5R	5R	4.67	3.06
50	6R	6R	18.37	3.64
50	7R	7R	38.42	4.07
50	8R	8R	59.91	3.87
50	10R	10R	85.40	2.67
100	4R	4R	0.04	2.30
100	6R	6R	1.61	3.51
100	6.8R	6.8R	4.55	4.07
100	7R	7R	6.10	4.27
100	8R	8R	14.71	4.93
100	9R	9R	25.20	5.87
100	10R	10R	46.48	5.81
100	11R	11R	64.64	5.35
100	12R	12R	76.04	4.86
100	14R	14R	90.59	3.50
150	4R	4R	0.01	2.26
150	6R	6R	0.50	3.35
150	8.1R	8.1R	4.58	4.72
150	9R	9R	8.65	5.45
150	10R	10R	16.75	6.20
150	11R	11R	28.68	6.81
150	12R	12R	41.26	7.35
150	13R	13R	60.53	7.10
150	15R	15R	81.16	5.98
150	16R	16R	90.19	4.35
200	4R	4R	0.0	2.24
200	8R	8R	1.55	4.52
200	9R	9R	4.14	5.21
200	9.3R	9.3R	4.86	5.40
200	10R	10R	7.48	5.95
200	12R	12R	22.96	7.51
200	14R	14R	45.88	8.55
200	15R	15R	61.77	8.35
200	16R	16R	73.60	7.78
200	18R	18R	89.03	5.73

A. Square Simulation Areas

We used linear regression to construct models that predict the values of A_{sp}Hops and ANP for a given scenario. We considered square networks in which nodes move according to the Random Waypoint Model. The input variables are number of nodes, simulation area, node speed, and node pause time. We considered 21 values for number of nodes, the simulation area, and node pause time, and we considered 26 values for node speed. These values are presented in Table VII. Our parameters provided a total of $21^3 \times 26 = 240,786$ scenarios. We randomly chose 1,200 of these scenarios. For each of these 1,200 scenarios, we generated 200 independent snapshots of the network, computed the average shortest-path hop count and average degree of network partitioning for each snapshot, and averaged over the 200 snapshots.

To construct the models, we set A_{sp}Hops or ANP as the dependent variable, and considered the input variables (number of nodes, simulation area, node speed, and node pause time) as potential predictors. We found that models using the logarithm of the predictors and dependent variables provided a better

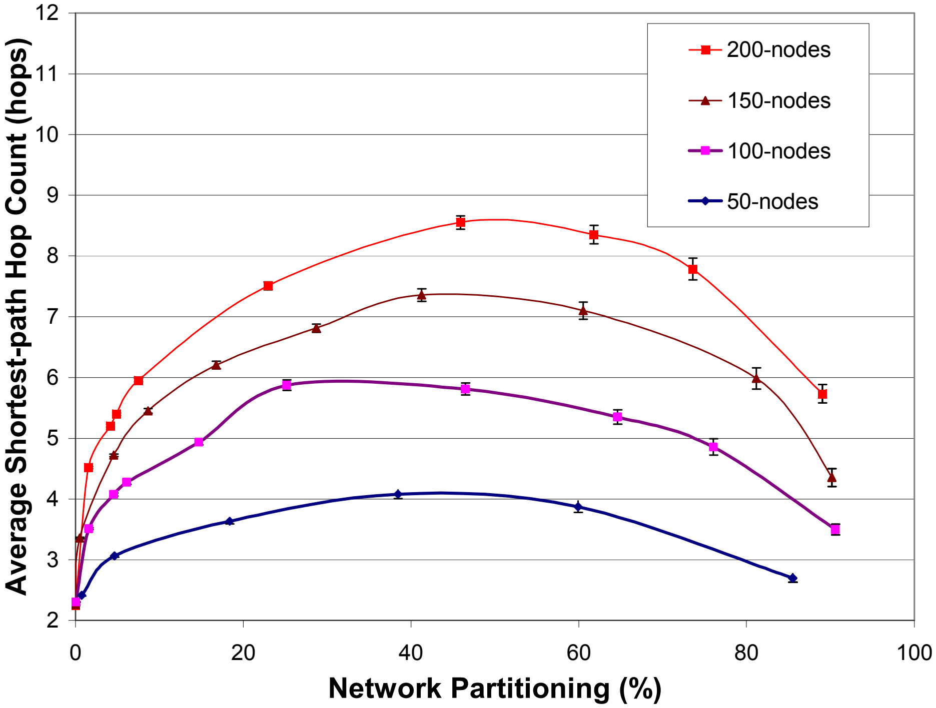

Fig. 5. ANP versus A_{sp}Hop with 95% confidence intervals. Each dot in the plot is the average result from 500 realizations of the given simulation scenario.

TABLE VII

THE PARAMETERS AND THEIR VALUES USED IN THE STUDY. NOTE: WE DO NOT CONSIDER SCENARIOS WITH LESS THAN 50 NODES, AS FIGURE 5 ILLUSTRATES SCENARIOS WITH LESS THAN 50 NODES WILL NOT MEET STANDARD 1.

Parameter	**Levels**
Nodes	50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250
Area (R^2)	40, 43, 46, 49, 53, 56, 59, 62, 66, 69, 72, 75, 79, 82, 85, 88, 92, 95, 98, 101, 105
Speed (R/s)	0.01, 0.02, 0.05, 0.10, 0.20 0.25 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1.0, 1.05, 1.1, 1.15, 1.2, 1.25
Pause (s)	1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40

fit (i.e., goodness of fit of 98.8% with logarithms versus 71.2% without logarithms); however, to consider a value of zero pause time (constant motion), we did not use the logarithm of pause time. We also found that the linear relationship between ANP and the predictor variables is less strong for large values of ANP, making its prediction more difficult (i.e., goodness of fit drops from 99.3% for ANP $< 40\%$ to 86.2% for ANP $> 40\%$). Thus, we constructed our models using only those scenarios with ANP $< 40\%$. We expect that scenarios with ANP $< 40\%$ is satisfactory for most routing protocol research.

The fitted models are:

$$\begin{aligned}\ln(\text{ANP}) = & - 2.3774 - 3.04714 \ln(\text{nodes}) \\ & + 3.4626 \ln(\text{area}) \\ & + 0.00425 \ln(\text{speed}) \\ & - 0.00068(\text{pause}) \end{aligned} \tag{3}$$

and

$$\begin{aligned}\ln(\text{A}_{sp}\text{Hops}) = & - 0.33827 - 0.10941 \ln(\text{nodes}) \\ & + 0.5847 \ln(\text{area}) \\ & + 0.00015 \ln(\text{speed}) \\ & + 0.00014(\text{pause}), \end{aligned} \tag{4}$$

where $nodes$ is the number of nodes, $area$ is the R^2 simulation area, $speed$ is the node speed, and $pause$ is the node pause time. These models fit well; the coefficient of determination is 99% for Equation 3 and 99.1% for Equation 4.

Equations 3 and 4 can be used to construct scenarios that have any desired values of A$_{sp}$Hops and ANP. Specifically, a researcher provides values for A$_{sp}$Hops and ANP, along with any two of the independent variables. Equations 3 and 4 then become two equations with two unknowns, which can be solved to yield values for the two remaining independent variables. However, we note that node speed and node pause time have little effect on the values of A$_{sp}$Hops and ANP in Equations 3 and 4. For example, pause time of 40 seconds instead of pause time of 0 seconds decreases ANP by a factor of $e^{-0.00068*40} = 0.973$, a decrease of only (approximately) 5%. Similarly, node speed of 1.25R instead of node speed of 0.25R increases ANP by a factor of $(1.25/0.25)^{0.00425} = 1.007$, an increase of only (approximately) 6%. We, therefore, removed node speed and node pause time from the models and refit. The resulting models are:

$$\begin{aligned}\ln(\text{ANP}) = & - 2.39377 - 3.04704 \ln(\text{nodes}) \\ & + 3.46258 \ln(\text{area}) \end{aligned} \tag{5}$$

and

$$\begin{aligned}\ln(\text{A}_{sp}\text{Hops}) = & - 0.33795 - 0.1094 \ln(\text{nodes}) \\ & + 0.5848 \ln(\text{area}), \end{aligned} \tag{6}$$

where $nodes$ is the number of nodes and $area$ is the R^2 simulation area.

Equations 5 and 6 enable a researcher to input a desired level of A$_{sp}$Hops and ANP, and then solve for the number of nodes and the simulation area. Of course, with two equations and two unknowns, we can solve the equations for number of nodes and simulation area. The solved equations are:

$$Nodes = e^{-0.1637} \times ANP^{-0.4168} \times A_{sp}Hops^{2.468} \tag{7}$$

and

$$Area = e^{0.567} \times ANP^{-0.0769} \times A_{sp}Hops^{2.159}. \tag{8}$$

For example, to generate a scenario in which the average network partitioning is approximately 5% and the average shortest-path hop count is approximately 4, the number of nodes should be $e^{-0.164} \times 0.05^{-0.42} \times 4^{2.47} \approx 91.6$, and the R^2 area of the simulation should be $e^{0.567} \times 0.05^{-0.0769} \times 4^{2.159} \approx 44.2$. These results confirm our results presented in [7], in which we showed a network with 95 nodes and an area of 44.2 R^2 would have an average shortest-path hop count of approximately 4 and an average network partitioning of approximately 5%. We checked the accuracy of our results for 5% ANP and 4 A_{sp}Hops with a simulation. Specifically, we generated 25 scenarios with 92 nodes, an area of 44.4 R^2, and different values for node speed and node pause time (see Table VIII). For each scenario, we generated 200 independent snapshots within the scenario (or 5,000 snapshots) and then computed the shortest-path hop count and network partitioning for each snapshot. We then averaged over these 5,000 snapshots to estimate the resulting A_{sp}Hops and ANP for a scenario with 92 nodes and area of 44.4 R^2. The resulting ANP was 0.052 and the resulting A_{sp}Hops was 4.01, which are close to the target values of 0.05 and 4, respectively.

TABLE VIII

SPEED AND PAUSE TIME PARAMETERS FOR THE MODEL ERROR ANALYSIS.

Parameter	Levels
Speed (R/s)	0.075, 0.25, 0.50, 0.75, 1.25
Pause (s)	1, 5, 10, 15, 20

TABLE IX

A_{sp}HOPS AND ANP TARGETS FOR THE MODEL ERROR ANALYSIS.

Parameter	Levels
A_{sp}Hops	2, 3, 4, 5, 6
ANP	1%, 3%, 5%, 10%, 20%

We repeated this accuracy check for a total of 25 combinations of A_{sp}Hops and ANP, which are shown in Table IX. For each combination of A_{sp}Hops and ANP, we used Equations 7 and 8 to compute the number of nodes and simulation area needed to obtain the specified values of A_{sp}Hops and ANP. We then generated 5,000 independent snapshots of networks with these values for number of nodes and simulation area, using various values for node speed and node pause time (see Table VIII). Finally, we estimated the resulting A_{sp}Hops and ANP by averaging over the 5,000 snapshots. The results are presented in Figure 6. In general, the resulting values of A_{sp}Hops and ANP are close to the target values. The accuracy is best for target values of A_{sp}Hops of 4 and above or ANP less than 10%.

We also verified the accuracy of our original model and our assumption that node speed and pause time have little impact. We executed the same verification tests from Tables VIII and IX with our original model that included node speed and node pause time (Equations 3 and 4). That is, we included node speed and node pause time in each equation, and then solved for A_{sp}Hops and ANP to produce two equations and two unknowns. We then estimated the resulting A_{sp}Hops and ANP by averaging over the 5,000 snapshots. The results are presented in Figure 7. Although Figures 6 and 7 differ, the difference is not significant enough to warrant the use of our original model with two more parameters. The mean squared error between the two models is 0.0001. As a result, we recommend using Equations 7 and 8 over our original model.

We note that both A_{sp}Hops and ANP measure average behavior of the network in the long run. Thus, scenarios constructed by our method will exhibit approximately the target shortest-path hop count and degree of network partitioning on the average over the long run. The shortest-path hop

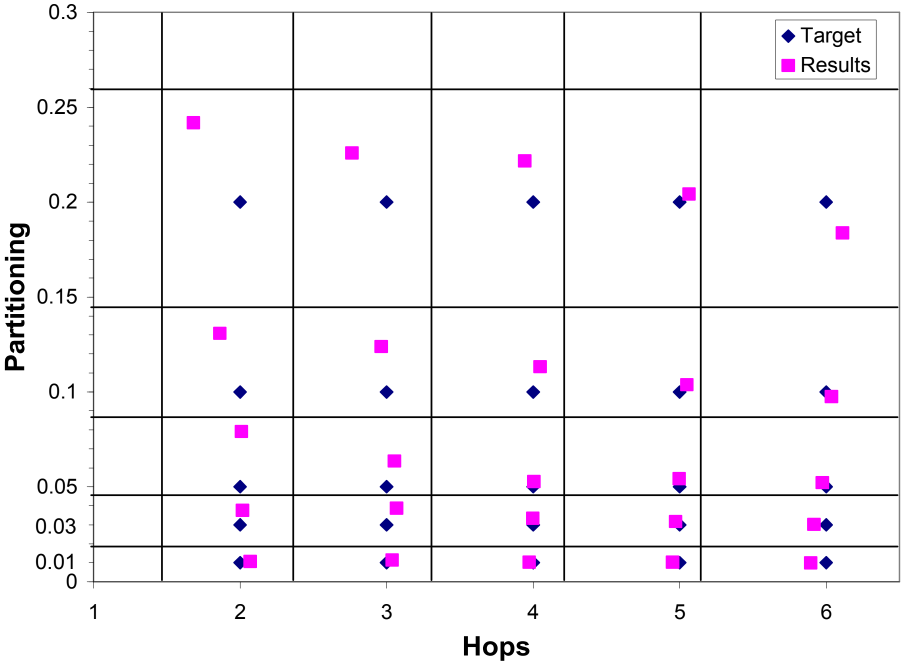

Fig. 6. Plot of A$_{sp}$Hops and ANP for both the target values and the resulting simulated values for square simulation areas using our recommended model (Equation 7 and Equation 8).

count and degree of network partitioning will vary around these averages when measured at specific time points, or when measured over short periods of time. This is appropriate, as one would not expect the average number of hops and degree of partitioning to be constant over time in a realistic network scenario.

B. Rectangular Simulation Areas

In our MobiHoc survey, a majority of MANET simulation studies, 49 of the 59 scenarios (83%) [6], used square simulation simulation areas; 10 of the 59 scenarios used rectangular simulation areas. In this section, we consider rectangular scenarios with aspect ratios[4] of 1×2, 1×3, and 1×4.

Similar to our square simulation area study (in Section IV-A), we constructed our rectangular models using only those scenarios with ANP $< 40\%$. Also, similar to our square simulation area study, we used linear regression to construct models that allow us to input target values for A$_{sp}$Hops and ANP. We used the Random Waypoint Model with input values for number of nodes, node speed, and node pause time from Table VII. In addition, similar to our square simulation area study, we used 21 values for the simulation area for each aspect ratio; however, due to results presented in [7], we set the simulation areas for the rectangular simulation area study to be slightly less than the simulation areas for the square simulation area study. Specifically, the simulation areas for the 1×2, 1×3, and 1×4 aspect ratio studies ranged from 35-100R^2, 30-95R^2, and 25-90R^2, respectively.

1×2 Simulation Areas: Similar to our square simulation area study, we found that node speed and node pause time have relatively little effect on A$_{sp}$Hops and ANP for a 1×2 aspect ratio simulation

---

[4] The aspect ratio is the ratio of the shorter side of the simulation area to the longer side of the simulation area. For a square simulation area, the aspect ratio is 1×1.

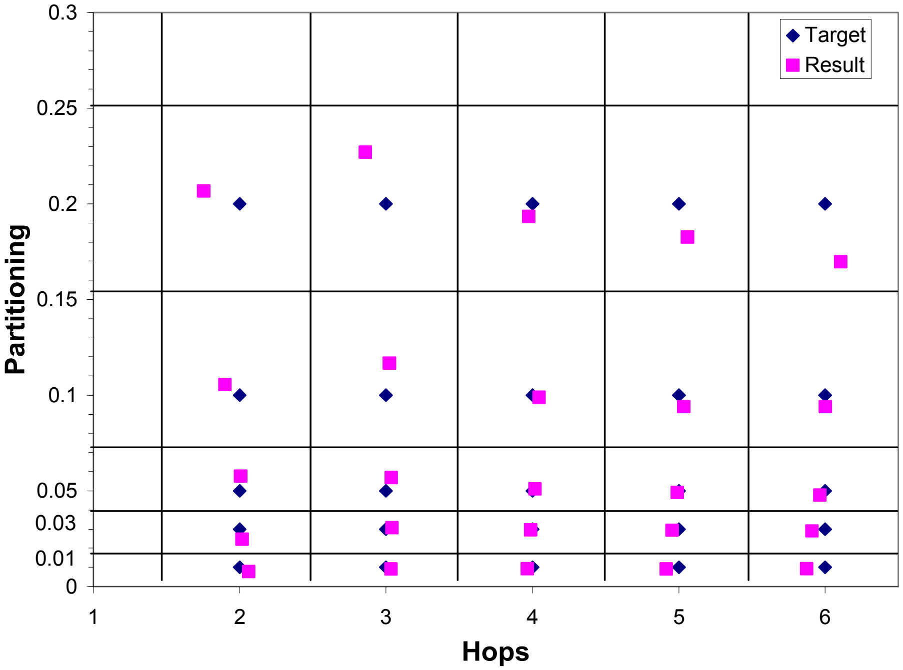

Fig. 7. Plot of A_{sp}Hops and ANP for both the target values and the resulting simulated values for square simulation areas using our original model (Equation 3 and Equation 4).

area. Initially we created models with number of nodes, area, speed, and pause time. However, the p-values for the speed and pause time predictors were statistically insignificant at $\alpha = 0.05$. We, therefore, removed node speed and node pause time from our initial models and refit. The resulting models are:

$$\begin{aligned}\ln(\text{ANP}) = & - 1.9439 - 3.1156 \ln(\text{nodes}) \\ & + 3.4639 \ln(\text{area}) \end{aligned} \tag{9}$$

and

$$\begin{aligned}\ln(\text{A}_{sp}\text{Hops}) = & - 0.3264 - 0.0802 \ln(\text{nodes}) \\ & + 0.5623 \ln(\text{area}), \end{aligned} \tag{10}$$

where $nodes$ is the number of nodes and $area$ is the R^2 simulation area. Equations 9 and 10 enable a researcher to input a desired level of A_{sp}Hops and ANP, and then solve for the number of nodes and the simulation area for a 1×2 aspect ratio. The solved equations are:

$$Nodes = e^{0.025} \times ANP^{-0.381} \times A_{sp}Hops^{2.35} \tag{11}$$

and

$$Area = e^{0.584} \times ANP^{-0.0544} \times A_{sp}Hops^{2.114}. \tag{12}$$

For example, to generate a scenario in which the average network partitioning is approximately 5% and the average shortest-path hop count is approximately 4, the number of nodes should be $e^{0.025} \times 0.05^{-0.381} \times 4^{2.35} \approx 83.4$, and the R^2 area of the simulation should be $e^{0.584} \times 0.05^{-0.0544} \times 4^{2.114} \approx 39.5$.

These results confirm our results presented in [7], in which we showed a network with 83 nodes and an area of 40 R^2 would have an average shortest-path hop count of approximately 4 and an average network partitioning of approximately 5%. We checked the accuracy of our results for 5% ANP and 4 A_{sp}Hops for a 1×2 rectangle with simulation. Specifically, we generated 25 scenarios with 83 nodes, an area of 39.4 R^2, and different values for node speed and node pause time (see Table VIII). For each scenario, we generated 200 independent snapshots within the scenario (or 5,000 snapshots) and then computed the shortest-path hop count and network partitioning for each snapshot. We then averaged over these 5,000 snapshots to estimate the resulting A_{sp}Hops and ANP for a scenario with 83 nodes and area 39.4 R^2. The resulting ANP was 0.062 and the resulting A_{sp}Hops was 4.07, which are close to the target values of 0.05 and 4, respectively.

We repeated this accuracy check for a total of 25 combinations of A_{sp}Hops and ANP, which are shown in Table IX. For each combination of A_{sp}Hops and ANP, we used Equations 11 and 12 to compute the number of nodes and simulation area needed to obtain the specified values of A_{sp}Hops and ANP. We then generated 5,000 independent snapshots of networks with these values for number of nodes and simulation area, using various values for node speed and node pause time (see Table VIII). Finally, we estimated the resulting A_{sp}Hops and ANP by averaging over the 5,000 snapshots. The results are presented in Figure 8. In general, the resulting values of A_{sp}Hops and ANP are close to the target values. The accuracy is best for target values of A_{sp}Hops greater than 4 or ANP less than 5%.

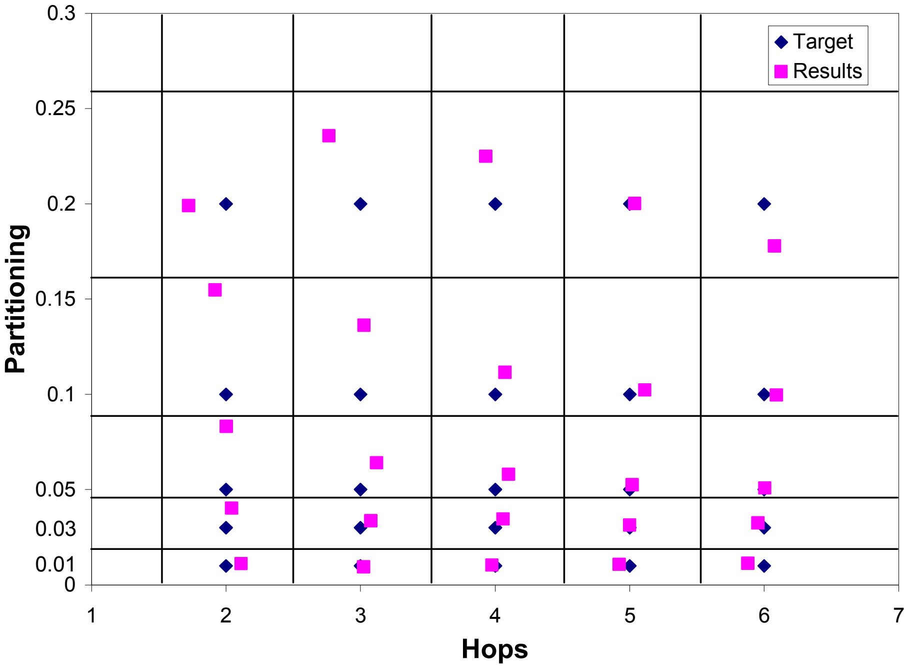

Fig. 8. Plot of A_{sp}Hops and ANP for both the target values and the resulting simulated values for 1×2 aspect ratio simulation areas using our recommended model (Equation 11 and Equation 12).

<u>1×3 Simulation Areas:</u> The results for the 1×3 aspect ratio study were similar to the results for the 1×2 aspect ratio study. Specifically, we found that node speed and node pause time were not statistically significant for A_{sp}Hops and ANP for a 1×3 aspect ratio simulation area. We, therefore,

removed node speed and node pause time from our initial models and refit. The resulting models are:

$$\begin{aligned}\ln(\text{ANP}) = &- 1.2178 - 3.14696\ln(\text{nodes})\\ &+ 3.3705\ln(\text{area})\end{aligned} \tag{13}$$

and

$$\begin{aligned}\ln(\text{A}_{sp}\text{Hops}) = &- 0.3051 - 0.0455\ln(\text{nodes})\\ &+ 0.5364\ln(\text{area}),\end{aligned} \tag{14}$$

where $nodes$ is the number of nodes and $area$ is the R^2 simulation area. Equations 13 and 14 enable a researcher to input a desired level of A$_{sp}$Hops and ANP, and then solve for the number of nodes and the simulation area for a 1×3 aspect ratio. The solved equations are:

$$Nodes = e^{0.245} \times ANP^{-0.350} \times A_{sp}Hops^{2.197} \tag{15}$$

and

$$Area = e^{0.590} \times ANP^{-0.030} \times A_{sp}Hops^{2.051}. \tag{16}$$

For example, to generate a scenario in which the average network partitioning is approximately 5% and the average shortest-path hop count is approximately 4, the number of nodes should be $e^{0.245} \times 0.05^{-0.35} \times 4^{2.197} \approx 76.6$, and the R^2 area of the simulation should be $e^{0.59} \times 0.05^{-0.03} \times 4^{2.051} \approx 33.8$. These results confirm our results presented in [7], in which we showed a network with 75 nodes and an area of 33 R^2 would have an average shortest-path hop count of approximately 4 and an average network partitioning of approximately 5%. We checked the accuracy of our results for 5% ANP and 4 A$_{sp}$Hops for a 1×3 rectangle with simulation. Specifically, we generated 25 scenarios with 76 nodes, an area of 34 R^2, and different values for node speed and node pause time (see Table VIII). For each scenario, we generated 200 independent snapshots within the scenario, and then averaged over these 5,000 snapshots to estimate the resulting A$_{sp}$Hops and ANP. The resulting ANP was 0.060 and the resulting A$_{sp}$Hops was 4.15, which are close to the target values of 0.05 and 4, respectively.

As before, we repeated this accuracy check for a total of 25 combinations of A$_{sp}$Hops and ANP, which are shown in Table IX. For each combination of A$_{sp}$Hops and ANP, we used Equations 15 and 16 to compute the number of nodes and simulation area needed to obtain the specified values of A$_{sp}$Hops and ANP. We then generated 5,000 independent snapshots of networks, using various values for node speed and node pause time (see Table VIII), and estimated the resulting A$_{sp}$Hops and ANP by averaging over the 5,000 snapshots. The results are presented in Figure 9. In general, the resulting values of A$_{sp}$Hops and ANP are close to the target values. The accuracy is best for target values of A$_{sp}$Hops greater than 4 or ANP less than 5%.

1 × 4 Simulation Areas: The results for the 1×4 aspect ratio study were similar to the results for the 1×2 and 1×3 aspect ratio studies. Specifically, we found that node speed and node pause time were not statistically significant for A$_{sp}$Hops and ANP for a 1×4 aspect ratio simulation area. We, therefore, removed node speed and node pause time from our initial models and refit. The resulting models are:

$$\begin{aligned}\ln(\text{ANP}) = &- 0.55665 - 3.2157\ln(\text{nodes})\\ &+ 3.3385\ln(\text{area})\end{aligned} \tag{17}$$

and

$$\begin{aligned}\ln(\text{A}_{sp}\text{Hops}) = &- 0.2850 - 0.0161\ln(\text{nodes})\\ &+ 0.5149\ln(\text{area}),\end{aligned} \tag{18}$$

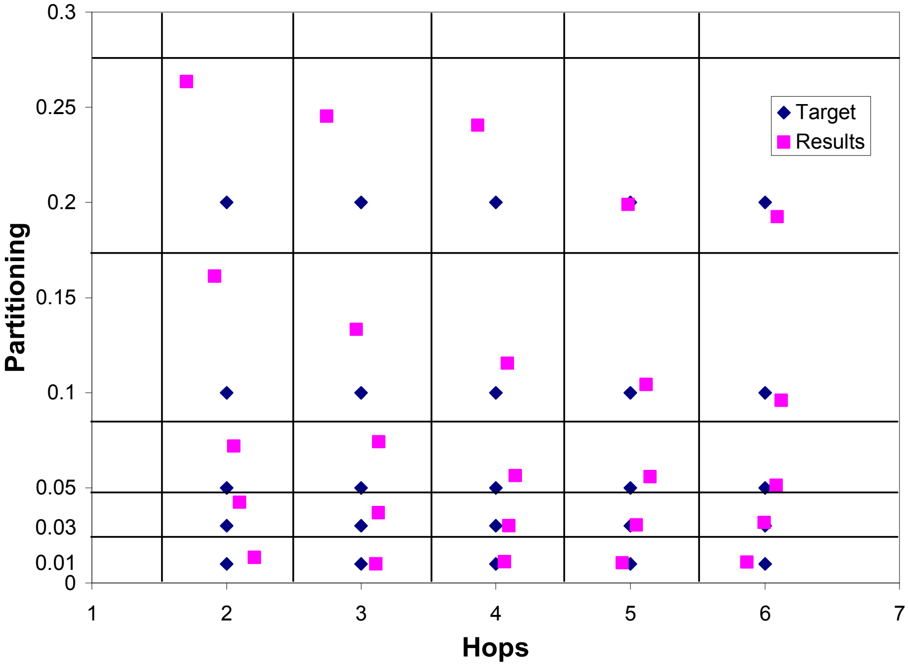

Fig. 9. Plot of A$_{sp}$Hops and ANP for both the target values and the resulting simulated values for 1×3 aspect ratio simulation areas using our recommended model (Equation 15 and Equation 16).

where $nodes$ is the number of nodes and $area$ is the R^2 simulation area. The solved equations are:

$$Nodes = e^{0.415} \times ANP^{-0.321} \times A_{sp}Hops^{2.08} \tag{19}$$

and

$$Area = e^{0.566} \times ANP^{-0.01} \times A_{sp}Hops^{2.01}. \tag{20}$$

For example, to generate a scenario in which the average network partitioning is approximately 5% and the average shortest-path hop count is approximately 4, the number of nodes should be $e^{0.415} \times 0.05^{-0.321} \times 4^{2.08} \approx 70.8$, and the R^2 area of the simulation should be $e^{0.566} \times 0.05^{-0.01} \times 4^{2.01} \approx 29.4$. These results confirm our results presented in [7], in which we showed a network with 70 nodes and an area of 28 R^2 would have an average shortest-path hop count of approximately 4 and an average network partitioning of approximately 5%.

As before, we checked the accuracy of our results for 5% ANP and 4 A$_{sp}$Hops for a 1×4 rectangle with simulation. We averaged the results over 5,000 snapshots, to estimate the resulting A$_{sp}$Hops and ANP for a scenario with 71 nodes and an area of 29.1 R^2. The resulting ANP was 0.046 and the resulting A$_{sp}$Hops was 3.99, which are close to the target values of 0.05 and 4, respectively.

As before, we repeated this accuracy check for a total of 25 combinations of A$_{sp}$Hops and ANP, which are shown in Table IX. For each combination of A$_{sp}$Hops and ANP, we used Equations 19 and 20 to compute the number of nodes and simulation area needed. We then generated 5,000 independent snapshots of networks, using various values for node speed and node pause time (see Table VIII), and estimated the resulting A$_{sp}$Hops and ANP. The results are presented in Figure 10. In general, the resulting values of A$_{sp}$Hops and ANP are close to the target values. The accuracy is best for target values of A$_{sp}$Hops greater than 4 or ANP less than 5%.

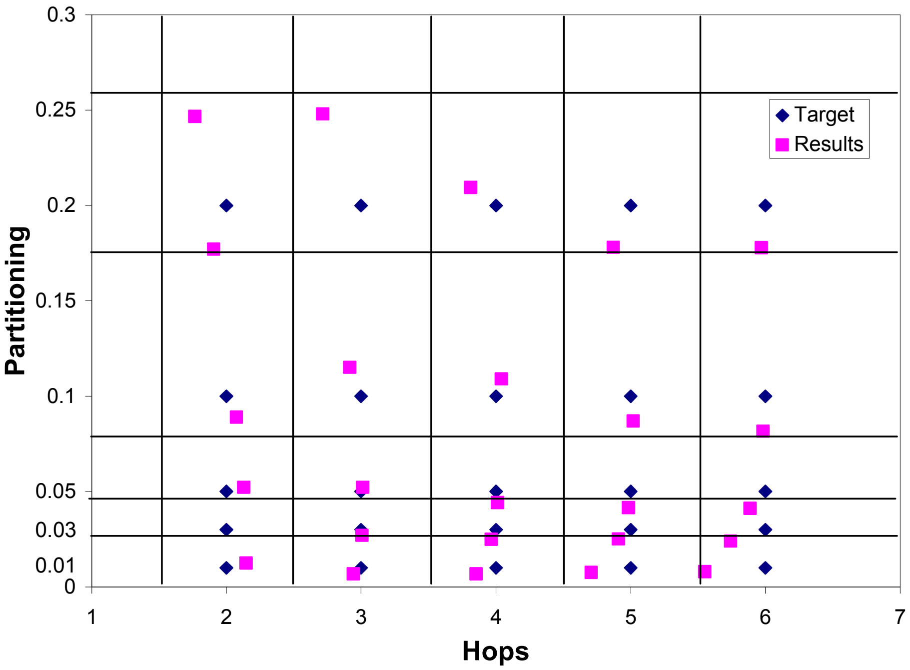

Fig. 10. Plot of A_{sp}Hops and ANP for both the target values and the resulting simulated values for 1×4 aspect ratio simulation areas using our recommended model (Equation 19 and Equation 20).

V. SCENARIOS WITH STANDARDS

We note that all our equations in Section IV will output the simulation area and number of nodes that approciamtely meet the inputs for A_{sp}Hops and ANP. Instead, the researcher may prefer to consider the range of scenarios that have A_{sp}Hops greater than a minimal value and aANP smaller than a maximum value. We explore a range of scenarios tha thave A_{sp}Hops greater than a minimal value and ANP smaller than a maximum value in this section.

Imagine a fixed number of nodes in a small square simulation area, such that the number of nodes is larger than the minimum needed to meet our standards. Imagine that these nodes are tightly packed, so that all nodes are within a single transmission range. This configuration will have no partitioning (ANP = 0), since every node will be within one hop of every other node. However, A_{sp}Hops will be equal to 1 hop, which does not meet our standard for hops (Standard 1).

To increase A_{sp}Hops, imagine gradually expanding the simulation area, retaining its square shape. As the area increases, both A_{sp}Hops and ANP will increase. At some point, the value of A_{sp}Hops will reach the researcher's desired value for A_{sp}Hops (suppose x hops). If, at that point, ANP is still less than the desired degree of network partitioning (suppose $y\%$), then this simulation scenario will meet our two standards (A_{sp}Hops $\geq x$ hops and ANP $\leq y\%$); in fact, this scenario will be the smallest simulation area that meets our two standards for the given number of nodes. Now, suppose that ANP is less than $y\%$ and imagine expanding the simulation area still further. At some point, ANP will reach $y\%$; the resulting simulation scenario will be the largest simulation area that meets our two standards for the given number of nodes. If one expands the simulation area further ANP will be greater than $y\%$. In summary, given a target value of A_{sp}Hops, a target value of ANP, and enough nodes, there will be a range for the simulation area size that meets our two standards. Furthermore, some standard metrics are impossible. For example, Figure 5 shows that a scenario with 50 nodes and at least 4 A_{sp}Hop is not possible. Thus, for a given aspect ratio, a minimum number of nodes is needed to ensure our two standards can be met. We investigate this result further in Section V-B.

In the rest of this section, we first justify the standard metrics that we have chosen in our own research. We note, however, that any value a researcher finds appropriate for either metric could be used. Then, given differnt value for number of nodes, we consider the minimum and maximum simulation area sizes needed to meet our two standards with our chosen targets for square and rectangular simulation areas.

A. Our Chosen Targets

In scenarios with A_{sp}Hops of 3 hops or less, there are at most 2 intermediate nodes on average between source and destination. Four hops for A_{sp}Hops ensures that there are at least 3 intermediate nodes on average, which increases the frequency with which packets are routed beyond immediate neighbors. Thus, we have chosen an average of 4 shortest-path hops as the standard in our research. Again, however, any value a researcher finds appropriate for average shortest-path hops could be used.

To determine a value for average network partitioning (ANP), we measured the delivery ratio of the Location Aided Routing (LAR) [5] protocol on NS-2.1b7a [12] using the steady-state Random Waypoint Model (RWM) [9]. We tested several scenarios with values of ANP ranging from 0 to 28% in 100 node scenarios. Each scenario had 20 source and destination nodes, with constant bit rate traffic of four packets per second from each source for 100 seconds. From the simulation data, we conclude that delivery failures occur when network partitioning is present, and many of these failures do not reflect on the performance of generic MANET routing protocols. While it is unrealistic to insist on no network partitioning [4], we desired to keep the average amount of network partitioning low in order to rigorously evaluate our MANET routing protocols. While any low level of ANP that a researcher finds appropriate could be used, we chose ANP $< 5\%$ as the standard in our research.

In Section V-B, we describe a variety of scenarios that meet both our standard for hops (A_{sp}Hops ≥ 4 hops) and our standard for average network partitioning (ANP $\leq 5\%$). In other words, the scenarios presented in the next section meet our standards with the standard targets that we have chosen (i.e., A_{sp}Hops ≥ 4 hops and ANP $\leq 5\%$); however, our models in Section IV can be used to construct other scenarios that meet Standard 1 and Standard 2 with any target value for each metric that a researcher finds appropriate.

B. Our Standard Simulation Scenarios

For the results presented in this section, we calculated the combinations of number of nodes and simulation area width and height using the area and node equations from Section IV. We based our results on 500 independent realizations of the scenario using the steady-state RWM.

Square Simulation Scenarios: We now present numerous simulation scenarios with square areas that meet our two standards with our chosen targets. Figure 11 presents results for a 150-node square simulation area using the RWM with node speed 0.25 R/s and pause time 10 s. There are two curves in Figure 11, one of which plots simulation area versus A_{sp}Hops and one of which plots simulation area versus ANP. The solid horizontal line represents both our standard for hops (A_{sp}Hops ≥ 4 hops) and our standard for partitioning (ANP $\leq 5\%$). Figure 11 illustrates that areas less than about 7.05 R×7.05 R ($\approx 49\,\mathrm{R}^2$) have A_{sp}Hops < 4 hops; in other words, these simulation areas are too small to meet our standard for hops. Areas greater than about 8.2 R×8.2 R ($\approx 67\,\mathrm{R}^2$) have ANP $> 5\%$; in other words, these simulation areas are too large to meet our standard for partitioning. Finally, areas between approximately 49 R^2 and 67 R^2 have A_{sp}Hops ≥ 4 hops and ANP $< 5\%$; simulation scenarios with areas between these two values will, in most cases, meet our two standards.

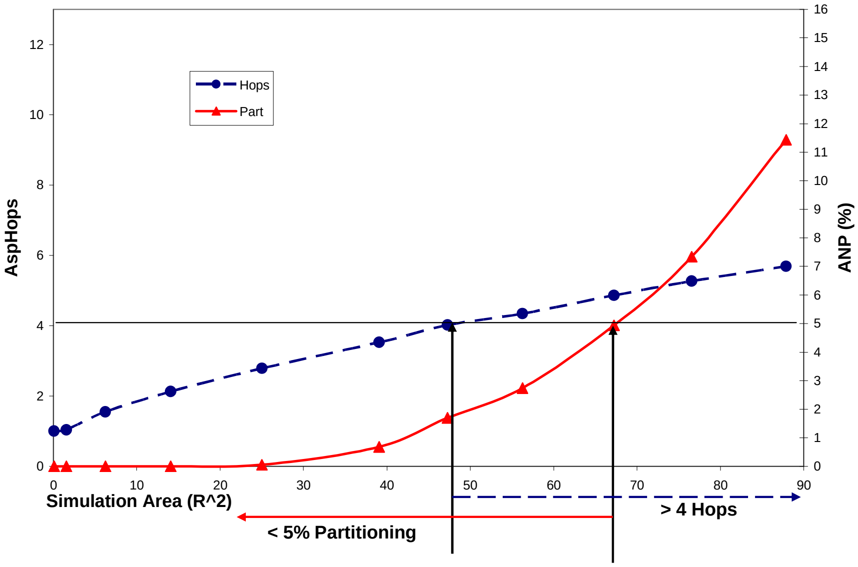

Fig. 11. For 150 node square scenarios, the dashed curve plots A_{sp}Hops versus simulation area. Areas for which the curve is above the horizontal line meet our hops standard (≥ 4 hops). The solid curve plots ANP versus area. Areas for which the curve is below the horizontal line meet our ANP standard ($\leq 5\%$). Therefore, for a square 150 node scenario, simulation areas between 49 R^2 and 67 R^2 meet our two standards. The results assume a steady-state RWM, node speed 0.25 R/s, and pause time 10 s.

We note that if the number of nodes is too small, then no simulation scenario will meet our two standards. Figure 12 presents results for a 50-node square scenario. In order to meet our standard for partitioning, the simulation area must be less than about 27 R^2. However, in order to meet our standard for hops, the simulation area must be greater than $43\,R^2$. Therefore, no square scenario with 50 nodes will meet our two standards.

The smallest number of nodes that can be used to meet our two standards in a square scenario is about 95, which follows from our result from Section IV-A. Figure 13 presents results for a 95-node square scenario. An area of about 6.65 R×6.65 R ($\approx$ 44 R^2) just meets both standards, A_{sp}Hops ≥ 4 hops and ANP $\leq 5\%$. Smaller simulation areas with 95 nodes will fail to meet our hops standard, and larger simulation areas with 95 nodes will fail to meet our partitioning standard.

To estimate the minimum and maximum simulation areas that will meet our two standards for various numbers of nodes in square scenarios, we used Equations 7 and 8. We first set A_{sp}Hops = 4 and ANP = 5% as our targets, and then calculated the smallest number of nodes that will meet our standard targets. We then fixed A_{sp}Hops at 4, and decremented ANP from 5% to 0%, by increasing the simulation area in increments of 25 R^2. This process determined the minimum simulation area needed for larger numbers of nodes. We also fixed ANP at 5% and incremented A_{sp}Hops past 4, by increasing the simulation area in increments of 25 R^2. This process determined the maximum simulation area possible for larger numbers of nodes.

For each scenario, we generated 500 independent realizations of a steady-state RWM with node speed 0.25 R/s and pause time 10 s, from which we estimated A_{sp}Hops and ANP. Table X presents the results. For each number of nodes, the minimum area is the smallest simulation area found that meets our standard for hops (A_{sp}Hops ≥ 4 hops), and the maximum area is the largest simulation area

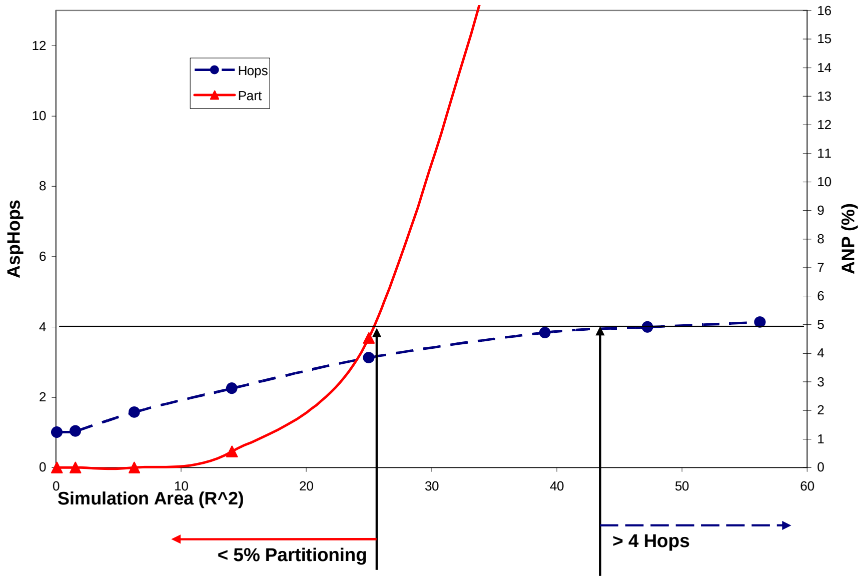

Fig. 12. For 50 node square scenarios, the dashed curve plots A_{sp}Hops versus simulation area. Areas for which the curve is above the horizontal line meet our hops standard (≥ 4 hops). The solid curve plots ANP versus area. Areas for which the curve is below the horizontal line meet our ANP standard ($\leq 5\%$). Therefore, for a square 50 node scenario, there is no area that meets both standards. These results assume a steady-state RWM, node speed 0.25 R/s, and pause time 10 s.

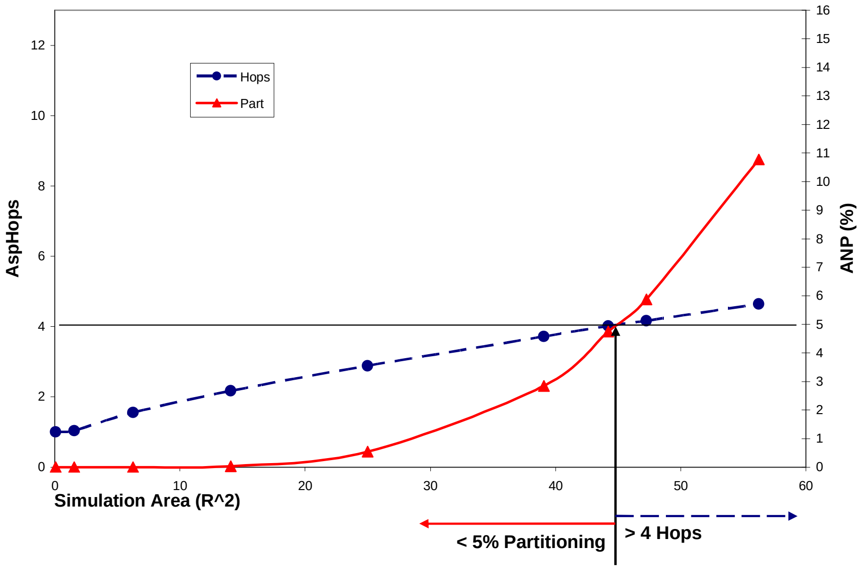

Fig. 13. For 95 node square scenarios, the dashed curve plots A_{sp}Hops versus simulation area. Areas for which the curve is above the horizontal line meet our hops standard (≥ 4 hops). The solid curve plots ANP versus area. Areas for which the curve is below the horizontal line meet our ANP standard ($\leq 5\%$). Therefore, for a square 95 node scenario, both standards are just met in a simulation area of about 44 R^2. These results assume steady-state RWM, node speed 0.25 R/s, and pause time 10 s.

found that meets our standard for partitioning ($\leq 5\%$).

TABLE X

Approximate min. and max. simulation areas for square scenarios for numbers of nodes (n). Fixed parameters were speed 0.25 R/s and pause time 10 s.

n	**Minimum Area**	**Maximum Area**
95	6.65 R×6.65 R	6.65 R×6.65 R
100	6.70 R×6.70 R	6.80 R×6.80 R
125	6.90 R×6.90 R	7.60 R×7.60 R
150	7.05 R×7.05 R	8.20 R×8.20 R
200	7.20 R×7.20 R	9.30 R×9.30 R
230	7.30 R×7.30 R	10.00 R×10.00 R

Rectangular Simulation Scenarios: We repeated our estimation of minimum and maximum simulation areas for a given number of nodes in rectangular scenarios with aspect ratios of 1×2, 1×3, and 1×4, using our equations for each aspect ratio from Section IV. For each of these scenarios, we generated 500 independent realizations of a steady-state RWM with node speed 0.25 R/s and pause time 10 s, from which we estimated A$_{sp}$Hops and ANP. Table XI presents the results. For a given number of nodes and a given aspect ratio, the minimum area is the smallest simulation area found that meets Standard 1 with our chosen target for hops (A$_{sp}$Hops ≥ 4 hops), and the maximum area is the largest simulation area found that meets Standard 2 with our chosen target for partitioning (ANP $\leq 5\%$).

TABLE XI

Approximate minimum and maximum simulation areas for rectangular scenarios for various numbers of nodes. Fixed parameters were 0.25 R/s node speed and 10 s node pause time.

n	**Aspect Ratio**	**Minimum Area**	**Maximum Area**
85	1×2	4.35 R×8.7 R	4.35 R×8.70 R
90	1×2	4.40 R×8.8 R	4.50 R×9.00 R
100	1×2	4.475 R×8.95 R	4.725 R×9.45 R
125	1×2	4.575 R×9.15 R	5.25 R×10.5 R
150	1×2	4.65 R×9.3 R	5.70 R×11.4 R
180	1×2	4.75 R×9.5 R	6.225 R×12.45 R
200	1×2	4.80 R×9.6 R	6.55 R×13.1 R
220	1×2	4.85 R×9.7 R	6.85 R×13.7 R
75	1×3	3.275 R×9.825 R	3.275 R×9.825 R
100	1×3	3.35 R×10.05 R	3.80 R×11.4 R
125	1×3	3.40 R×10.2 R	4.175 R×12.525 R
150	1×3	3.45 R×10.35 R	4.55 R×13.65 R
175	1×3	3.50 R×10.5 R	4.925 R×14.775 R
200	1×3	3.55 R×10.65 R	5.20 R×15.6 R
70	1×4	2.60 R×10.4 R	2.60 R×10.4 R
90	1×4	2.65 R×10.6 R	2.975 R×11.9 R
100	1×4	2.675 R×10.7 R	3.15 R×12.6 R
125	1×4	2.725 R×10.9 R	3.50 R×14.0 R
150	1×4	2.75 R×11.0 R	3.875 R×15.5 R

As mentioned previously, if the number of nodes is too small, then no simulation scenario will meet our two standards with our chosen targets (A$_{sp}$Hops ≥ 4 hops and ANP $\leq 5\%$). In Table XI, the smallest number of nodes listed for each aspect ratio is the smallest number of nodes that can be used to meet our two standards in that aspect ratio. Specifically, the smallest number of nodes that can be used to meet our two standards in a 1×2, 1×3, and 1×4 aspect ratio is about 85, 75, and 70 nodes, respectively. (These results follow the results from Seciont IV-B.) Note that as the aspect ratio goes from 1×1 to 1×4, the smallest number of nodes required to meet our two standards decreases.

VI. RECOMMENDATIONS AND CONCLUSIONS

In order to ensure that scenarios provide an effective platform for testing generic MANET routing protocols, we recommend using the average shortest-path hop count and the average amount of network partitioning to characterize simulation scenarios. To calculate A_{sp}Hops, build the multi-hop connectivity matrix at regular intervals throughout the simulation. The value of A_{sp}Hops is found by averaging all non-zero entries in all evaluations of the multi-hop connectivity matrix (Equation 1). To calculate ANP, evaluate the connectivity matrix at regular intervals throughout the simulation. The value of ANP is the proportion of entries in all evaluations of the multi-hop connectivity matrix that are equal to 0 (Equation 2).

Conclusion #1: We presented algorithms that enable investigators to specify desired values for ANP and A_{sp}Hops, then construct a simulation scenario that meets these target values to a close approximation. Our specific conclusions for this work follow.

- **A.** Our models work when the target value of A_{sp}Hops is between 3 and 6 and the target value of ANP is between 1% and 20%.
- **B.** Node speed and node pause time have little impact on A_{sp}Hops and ANP, if speed is within the range 0.01-1.25 R/sec and pause time is less than 40 seconds.
- **C.** Equations 7 and 8 can be used to construct scenarios with square simulation areas that meet specified values for A_{sp}Hops and ANP.
- **D.** Equations 11 and 12 can be used to construct scenarios with simulation areas with 1×2 aspect ratios and specified values for A_{sp}Hops and ANP.
- **E.** Equations 15 and 16 can be used to construct scenarios with simulation areas with 1×3 aspect ratios and specified values for A_{sp}Hops and ANP.
- **F.** Equations 19 and 20 can be used to construct scenarios with simulation areas with 1×4 aspect ratios and specified values for A_{sp}Hops and ANP.

Conclusion #2: We note that both A_{sp}Hops and ANP measure long-run average behavior of the network. Thus, scenarios constructed by our method will exhibit approximately the target number of hops and approximately the target degree of network partitioning on the average over the long run. The shortest-path hop count and degree of network partitioning will vary around these averages when measured at specific time points, or when measured over short periods of time. This is appropriate, as one would not expect the average number of hops and degree of partitioning to be constant over time in a realistic network scenario.

Conclusion #3: For a given aspect ratio, there exists a smallest number of nodes that can be used to meet our two standards. The smallest number of nodes that can be used in a 1×1, 1×2, 1×3, and 1×4 simulation area for $\mathrm{A}_{sp}\mathrm{Hops} \geq 4$ hops and $\mathrm{ANP} \leq 5\%$ is approximately 95, 85, 75, and 70 nodes, respectively. As the aspect ratio goes from 1×1 to 1×4, the smallest number of nodes required to meet our standards decreases.

Conclusion #4: For a given aspect ratio and a given number of nodes, there exists a smallest simulation area that can be used to meet our standard for hops. For a given aspect ratio and a given number of nodes, there exists a largest simulation area that can be used to meet our partitioning standard.

The main contributions of this paper are (1) to highlight that we need standards to obtain rigorous evaluation of MANET protocols and to begin defining these standards, (2) to propose two standards that should be employed to ensure long routes are available and used in the evaluation of generic MANET routing protocols, (3) to provide algorithms that researchers can use to determine the number of nodes and area required to generate desired A_{sp}Hops and ANP levels and therefore construct scenarios that meet their standards (4) to illustrate our method that others can modify to generate scenarios that use a different mobility model, with different values for both the minimum average shortest-path hop count and the maximum amount of network partitioning.

Information on obtaining the code used in this study can be found at `http://toilers.mines.edu`.

Acknowledgment: We thank Jeff Boleng for the code used in parsing the mobility files.

REFERENCES

[1] T. Camp, J. Boleng, and V. Davies. A survey of mobility models for ad hoc network research. *Wireless Communications & Mobile Computing (WCMC)*, pages 483–502, 2002.

[2] B. N. Clark, C. J. Colbourn, and D. S. Johnson. Unit disk graphs. *Discrete Mathematics*, 86:165–177, 1990.

[3] Association for Computing Machinery. The ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc). URL: http://www.sigmobile.org/mobihoc. Page accessed Apr 1, 2006.

[4] J. Hähner, D. Dudkowski, P. Marrán, and K. Rothermel. A quantitative analysis of partitioning in mobile ad hoc networks. In *Proceedings of the Joint International Conference on Measurement and Modeling of Computer Systems*, pages 400–401, 2004.

[5] 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.

[6] S. Kurkowski, T. Camp, and M. Colagrosso. MANET simulation scenarios: The incredibles. *ACM Mobile Computing and Communications Review (MC2R)*, pages 50–61, October, 2005.

[7] S. Kurkowski, T. Camp, and W. Navidi. Standards for rigorous MANET routing protocol evaluation. *Proceedings of the 3rd IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS)*, 2006.

[8] L. Miller. Multihop connectivity of arbitrary networks. Technical report, Wireless Communication Technologies Group, National Institute of Standards and Technology (NIST), 2001.

[9] W. Navidi, T. Camp, and N. Bauer. Improving the accuracy of random waypoint simulations through steady-state initialization. In *Proceedings of the 15th International Conference on Modeling and Simulation (MS)*, pages 319–326, 2004.

[10] K. Pawlikowski. Do not trust all simulation studies of telecommunications networks. *International Conference on Information Networking (ICOIN)*, pages 899–908, 2003.

[11] K. Pawlikowski, J. Jeong, and R. Lee. On credibility of simulation studies of telecommunication networks. *IEEE Communications Magazine*, pages 132–139, 2001.

[12] The VINT Project. The network simulator - ns-2. URL: http://www.isi.edu/nsnam/ns/. Page accessed Apr 1, 2006.

[13] T. Rappaport, editor. *Wireless Communications - Principle and Practice*. Prentice-Hall, 1996.

[14] J.-P. Rodrigue. The notion of accessibility. URL: http://people.hofstra.edu/geotrans/eng/ch1en/meth1en/ ch1m2en.html Page accessed on December 8, 2005.