Minimal Standards for Rigorous MANET Routing Protocol Evaluation*

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***Abstract*—**
Mobile Ad Hoc Network (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 routing protocols. For example, in scenarios with a low average hop count, little routing is needed, and poor protocols will 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 will appear unsuccessful.

We surveyed articles published at the MobiHoc Conference (2000-2005) and found that many of them used simulation scenarios with an average shortest-path hop count less than 2, and some of them used simulation scenarios that had more than 90% of the node pairs partitioned (on average). Thus, many of the simulation scenarios described in published MobiHoc articles are inadequate to provide a rigorous evaluation of a routing protocol.

This paper makes three contributions. First, we propose *minimal standards* to qualify a simulation scenario to be used for rigorous protocol evaluation, based on the scenario's average shortest-path hop count and its amount of network partitioning. Second, we describe several scenarios that meet our minimal standards; these scenarios can be used to rigorously test MANET routing protocols. Third, we describe an easy-to-implement method that researchers can use to produce additional simulation scenarios that meet the standards we propose.

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

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. These challenges include 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 evaluation of these protocols. 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 usefulness of a scenario in assessing the performance of routing protocols. Appropriate choices for these parameters have long been the subject of debate. Some researchers [2], [8] state that they have developed scenarios that are free of network partitioning[1]. Since no routing protocol is able to route between pairs of nodes that are partitioned, most protocols, even good ones, perform poorly in scenarios that have a large amount of partitioning.

While the amount of network partitioning needs to be small, the average shortest-path hop count[2] needs to be reasonably large, in order for a scenario to provide a rigorous test of a protocol. A scenario with an average shortest-path hop of 1 or 2 is a scenario in which many packets are only sent between neighbors; in other words, the protocol's routing capability is not rigorously tested. Most protocols, even poor ones, will perform well in scenarios that have low average shortest-path hop counts.

Some routing protocols [16] are designed to function in specialized environments, where the usual requirements regarding hop counts and partitioning do not apply. For example, delay-tolerant routing protocols (e.g., [5], [13], [14], [15]) that ferry data from one region to another, relying on mobility to deliver packets, require very sparse networks to test storage and delivery mechanisms. Most protocols, however, are designed to function in environments where routes generally exist between communicating nodes, and in which these routes often involve several hops. For these protocols,

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

[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-B for details.

it is important that scenarios be designed to have little partitioning and reasonably high average hop counts.

In this paper, we propose minimal standards for rigorous MANET protocol evaluation based on average shortest-path hop count and the amount of network partitioning. We argue that it is reasonable to require the average shortest-path hop count to be at least 4, and to require that (on average) no more than 5% of node pairs be partitioned. We present a method by which simulation scenarios that meet these standards may be constructed. Of course, other values for these standards may also be reasonable; thus, researchers should feel free to adapt our method to construct scenarios that are consistent with any values that they believe to be appropriate in a given situation.

This paper is organized as follows. Section II describes the metrics we use to measure the effectiveness of simulation scenarios, and defines our minimal standards. Section III presents a survey of scenarios that have recently been used in published MANET research. Section IV describes our method for generating effective scenarios, and Section V presents our recommendations and conclusions.

II. MANET Scenario Metrics

To sufficiently exercise a MANET routing protocol, we need packets to have the opportunity to be delivered to the appropriate destinations and we need a destination to be several hops from the source. In this section, we consider one metric that is needed to give packets the opportunity for delivery (i.e., low network partitioning) and 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). First, we precisely define the two metrics, average shortest-path hop count and network partitioning, that form the basis of our standards. We also describe how we estimated these values for various scenarios using simulation. Lastly, we define and justify the values for our minimal standards.

A. 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. As an example, Figure 1 presents a snapshot in time of a network with six nodes. 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. Thus, the degree of partitioning in this network at this point in time is $5/15 = 33.3\%$.

To calculate the degree of network partitioning, we construct a connectivity matrix [9], [12] that compares each node to each other node. The connectivity matrix contains a 1 for each node pair for which a path exists and a 0 for each node pair without a path. Figure 2 presents the connectivity matrix for Figure 1. This matrix shows that node five is

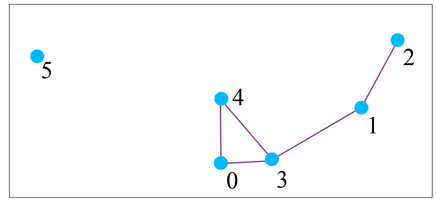

Fig. 1. Network with six nodes at a certain point in time. The lines represent communication links between two nodes.

partitioned from all of the other nodes. The degree of partitioning is the proportion of entries in the connectivity matrix that are 0.

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

Fig. 2. Connectivity matrix for the simulation scenario in Figure 1.

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,

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

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

B. 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. For example, in Figure 1, the hop count between node 0 and node 2 is three.

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. The shortest-path hop count between two nodes 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 [9] which stores the shortest path between two nodes in the matrix. Figure 3 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 this network 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., $34/20 = 1.7$.

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

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 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

$$\mathrm{A}_{sp}\mathrm{Hops} = \frac{\sum_{i=1}^{T} hops_i}{\sum_{i=1}^{T} paths_i}, \qquad (2)$$

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

C. *Minimal Standards*

Our *standard for hops* is that the average shortest-path hop count (A_{sp}Hops) should be at least 4 hops. In scenarios with A_{sp}Hops of 3 hops or less, there are at most 2 intermediate nodes on average between source and destination. A minimum value of 4 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, our standard for hops is that the average shortest-path hop count be at least 4 hops.

Our *standard for partitioning* is that the average network partitioning (ANP) should be at most 5%. The value of ANP puts an upper bound on the expected delivery ratio, i.e., the highest expected delivery ratio is 100% – ANP. To illustrate this upper bound, we measured the delivery ratio of the Location Aided Routing (LAR) [6] protocol on NS-2.1b7a [11]. 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.

Figure 4 presents the delivery ratio plotted against ANP. When ANP = 5%, the delivery ratio is less than 95%; when ANP = 10%, the delivery ratio is less than 90%. We conclude that delivery failures occur when network partitioning is present, and many of these failures do not reflect on protocol performance. While it is unrealistic to insist on no network partitioning [4], we believe that it is desirable to keep the average amount of network partitioning low in order to rigorously evaluate a protocol. Thus, our standard for partitioning is that the average network partitioning be less than 5%.

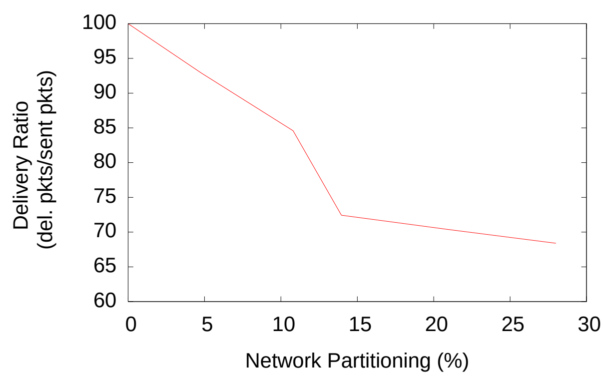

Fig. 4. Delivery ratio vs. network partitioning. Various simulation areas were used to obtain different percentages of partitioning. Fixed parameters were 100 nodes, 0.075 R/s average node speed and 2 second node pause time. 95% confidence intervals are shown.

We believe that the minimal standards we propose are reasonable in most situations. Of course, there may be other standards that are reasonable for a given situation. In Section IV, we present a method to generate simulation scenarios that meet our minimal standards; this method can be modified to produce scenarios that meet any standards that are considered appropriate for the situation at hand.

III. Current State of MANET Simulation

We conducted a survey [7] 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 to analyze MANETs; 114 of the 151 MobiHoc papers published (75.5%) reported simulation studies.

A. Mobility Models

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. Unfortunately, only 50 of the 114 published MobiHoc simulation papers (43.9%) identified the mobility model that was used. Figure 5 shows the distribution of the mobility models used in these 50 papers. 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). For this reason, we used the RWM for our analysis in this paper. Specifically, we used a steady-state version of the RWM [10] 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.

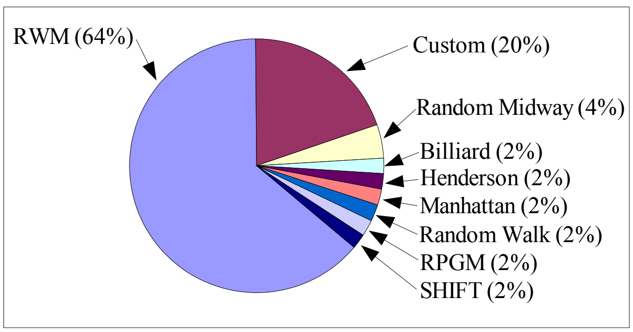

Fig. 5. Mobility model usage from our MobiHoc survey.

B. MobiHoc MANET Scenarios

There are five main simulation parameters in the steady-state RWM [10]: the number of nodes, which directly affects the number of possible data packet sources; 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, which describe the movement of the nodes.

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. As we will describe in Section III-C, the transmission range is the fundamental unit of distance in the description of simulation scenarios.

Only 48 of the 114 papers in our survey of published MANET protocol simulation MobiHoc papers provided the number of nodes, the dimensions of the simulation area, and the transmission range that were used in their simulations. There were a total of 59 scenarios described in these papers, and Table I presents the parameters used in each of them. There is a wide range of values; in fact, except for #36, #37, and #38, no two of the scenarios are exactly alike. The number of nodes varies from 10 to 1000, the simulation areas vary from 25 m $\times$ 25 m to 5000 m $\times$ 5000 m, and the transmission range varies from 3 m to 1061 m. There is also a wide variety of shapes used; while the majority of simulation areas are square, some scenarios have widths and heights that differ substantially from each other.

Most importantly, a significant number of these scenarios are inadequate for protocol testing under the minimal standards we propose. For each scenario, we computed the average network partitioning (ANP) and the average number of shortest-path hops (A_{sp}Hops) by using the steady-state RWM to generate 100 independent realizations of each scenario. As shown in Table I, only eight of the 59 scenarios (13.56%) meet our minimal standards of 5% or less network partitioning and 4 or more hops on average. Several of the scenarios fail to meet any reasonable standard. For example, scenario #30 was generated to guarantee a completely connected topology, however this resulted in an A_{sp}Hops of only 1.47. Scenario #57 is simulating a dense network, but it is so dense every node is within one-hop of every other node. Several other scenarios have average hop counts less than 2. In these scenarios, little routing is needed for communication. As mentioned previously, some research investigations involve protocols that are intended for use in specialized environments for which our standards do not apply. For example, scenario #11 in Table I is for a ferry-based routing protocol which requires a sparse network [14], hence a large percentage of partitioning. Our standards, however, are relevant to most routing protocols that are investigated.

C. Using Transmission Range as the Unit of Distance

When distances are measured in absolute units, such as meters, it is impossible 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 $\times$ 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 provide considerably more stress to a routing 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 $\times$ 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$\times$5 R area and a node speed 0.25 R/s. Table II presents an example to show that a simulation scenario with a 80 m $\times$ 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$\times$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

TABLE I

INPUT PARAMETERS, AVERAGE NETWORK PARTITIONING, AND AVERAGE SHORTEST-PATH HOP COUNTS FROM 59 PUBLISHED MANET SCENARIOS IN THE PROCEEDINGS OF THE MOBIHOC CONFERENCE, 2000-2005, SORTED BY NUMBER OF NODES.

No.	Nodes	Area (m x m)	Range (m)	ANP %	A_{sp} Hops
1	10	1000 x 1000	100	94.6	1.00
2	20	350 x 350	100	7.5	2.18
3	20	1000 x 750	250	6.5	2.27
4	24	800 x 1200	250	10.3	2.49
5	25	200 x 200	100	0.0	1.35
6	25	900 x 900	250	4.3	2.28
7	30	350 x 350	100	2.2	2.21
8	36	3000 x 3000	1061	0.3	1.76
9	40	350 x 350	100	0.6	2.13
10	40	900 x 900	250	1.0	2.18
11	40	5000 x 5000	250	98.6	1.19
12	50	40 x 40	10	0.7	2.43
13	50	350 x 350	100	0.2	2.10
14	50	500 x 500	100	5.9	3.05
15	50	1500 x 300	250	0.2	2.29
16	50	1500 x 300	275	0.1	2.10
17	50	1000 x 1000	250	0.9	2.42
18	50	1000 x 1000	100	85.1	2.74
19	60	350 x 350	100	0.1	2.07
20	70	25 x 25	10	0.0	1.57
21	70	350 x 350	100	0.0	2.06
22	80	350 x 350	100	0.0	2.05
23	90	350 x 350	100	0.0	2.04
24	100	100 x 100	20	0.4	2.87
25	100	350 x 350	100	0.0	2.03
26	100	300 x 1500	250	0.0	2.21
27	100	400 x 400	100	0.0	2.29
28	100	1200 x 1200	250	0.4	2.75
29	100	500 x 500	100	0.6	2.89
30	100	575 x 575	250	0.0	1.47
31	100	575 x 575	125	0.1	2.62
32	100	650 x 650	67	40.5	5.80
33	100	1000 x 1000	250	0.0	2.28
34	100	1000 x 1000	150	3.9	4.03
35	100	1000 x 1000	50	98.0	1.79
36	100	1000 x 1000	100	44.3	5.96
37	100	1000 x 1000	100	44.3	5.96
38	100	1000 x 1000	100	44.3	5.96
39	100	2200 x 600	275	0.2	3.01
40	100	2000 x 600	250	0.4	3.07
41	100	150 x 1500	250	0.0	2.15
42	100	3000 x 900	250	5.8	4.77
43	110	350 x 350	100	0.0	2.03
44	120	2500 x 1000	250	2.0	4.14
45	200	100 x 100	40	0.0	1.55
46	200	500 x 500	70	0.7	3.96
47	200	1700 x 1700	250	0.4	3.76
48	200	1981.7 x 1981.7	250	1.6	4.46
49	225	100 x 100	20	0.0	2.73
50	225	600 x 600	100	0.1	3.27
51	400	100 x 100	20	0.0	2.67
52	400	800 x 800	100	0.1	4.23
53	500	3000 x 3000	67	99.6	1.83
54	600	3000 x 3000	250	1.1	6.33
55	625	1000 x 1000	100	0.2	5.22
56	1,000	40 x 40	3	0.4	6.88
57	1,000	81.6 x 81.6	300	0.0	1.00
58	1,000	100 x 100	10	0.0	5.03
59	1,000	500 x 500	20	20.3	14.36

all distances in terms of an arbitrary transmission range R. Our results are valid for any choice of transmission range.

TABLE II

SIMULATION SCENARIO PARAMETERS EXPRESSED IN METERS, AND IN UNITS OF THE TRANSMISSION RANGE (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

IV. SCENARIOS FOR RIGOROUS EVALUATION

In this section, we first show that when nodes move according to the random waypoint model, speed and pause time have relatively little effect on the average shortest-path hop count and the average network partitioning. We then describe a variety of scenarios that meet our standards of A_{sp}Hops $\geq$ 4 hops and ANP $\leq 5\%$. Lastly, we present a method which researchers can use to construct other simulation scenarios that meet our minimal standards.

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. We computed values of A_{sp}Hops and ANP for 36 different combinations of speed and pause time, and three combinations of number

TABLE III

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		

TABLE IV

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

of nodes, width, and height, for a total of 108 scenarios in all. Table III presents the parameter values used in these scenarios.

Table IV 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. For example, in the 150-node scenarios, partitioning ranged from 0.36% to 0.90% and A_{sp}Hops ranged from 3.50 to 3.57 hops. We conclude that node speed and pause time do not greatly affect ANP or A_{sp}Hops for the scenarios (see Table III) that we tested.

B. *Constructing Some Simulation Scenarios*

In this section, we consider how to construct scenarios that meet both our standard for hops (A_{sp}Hops ≥ 4 hops) and our standard for average network partitioning (ANP $\leq 5\%$). Imagine a fixed number of nodes tightly packed in a small square simulation area, 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.

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 4 hops. If, at that point, ANP is still less than 5%, this simulation scenario will meet our minimal standards; in fact, this scenario will be the smallest simulation area that meets our minimal standards for the given number of nodes. Now, suppose that ANP is less than 5% and imagine expanding the simulation area still further. At some point, ANP will reach 5%; the resulting simulation scenario will be the largest simulation area that meets our minimal standards for the given number of nodes. If one expands the simulation area further, ANP $> 5\%$ which does not meet our standard for partitioning.

For the results presented in the rest of this section, we calculated A_{sp}Hops and ANP for several combinations of number of nodes and simulation area width and height. For each combination, we based our calculations 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 minimal standards. Figure 6 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 6, 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 6 illustrates that areas less than about 7.05 R×7.05 R ($\approx$49 R^2) have A_{sp}Hops < 4 hops; in other words, these simulation areas are too small to meet our standard for hops. Areas greater than about 8.2 R×8.2 R ($\approx$67 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 minimal standards.

We note that if the number of nodes is too small, then no simulation scenario will meet our minimal standards. Figure 7 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 minimal standards.

The smallest number of nodes that can be used to meet our minimal standards in a square scenario is about 95. Figure 8 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 our

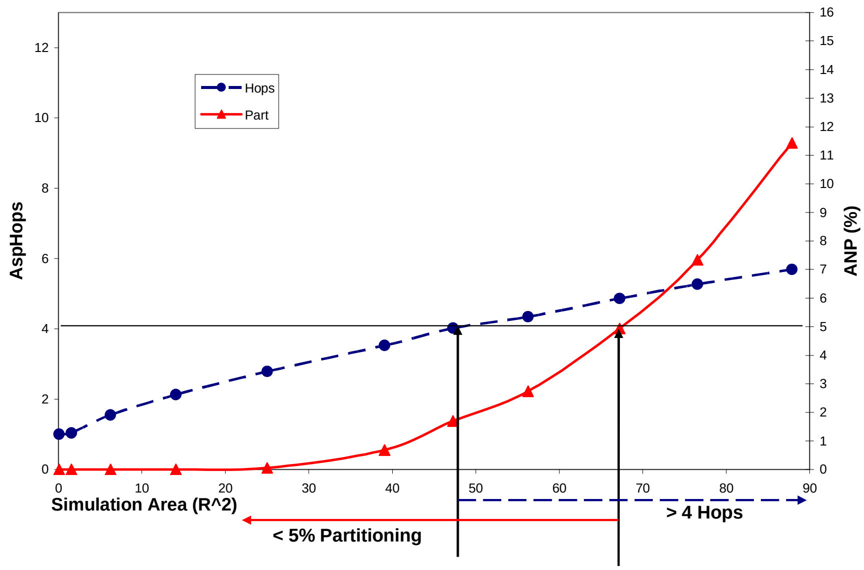

Fig. 6. For square scenarios of 150 nodes, the dashed curve plots A_{sp}Hops versus simulation area. Areas for which the curve is above the horizontal line meet our standard for hops (A_{sp}Hops ≥ 4 hops). The solid curve plots ANP versus simulation area. Areas for which the curve is below the horizontal line meet our standard for partitioning (ANP $\leq 5\%$). Therefore, for a square scenario of 150 nodes, simulation areas between about 49 R^2 and 67 R^2 meet our minimal standards for both A_{sp}Hops and ANP. These results assume a steady-state RWM with node speed 0.25 R/s and pause time 10 s.

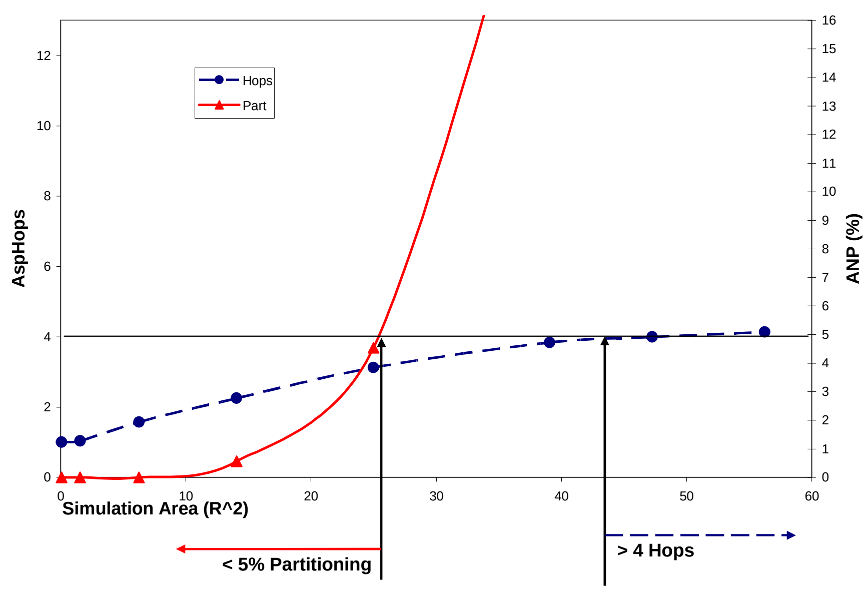

Fig. 7. For square scenarios of 50 nodes, the dashed curve plots A_{sp}Hops versus simulation area. Areas for which the curve is above the horizontal line meet our standard for hops (A_{sp}Hops ≥ 4 hops). The solid curve plots ANP versus simulation area. Areas for which the curve is below the horizontal line meet our standard for partitioning (ANP $\leq 5\%$). Therefore, for a square scenario of 50 nodes, there is no area that meets our minimal standards for both A_{sp}Hops and ANP. These results assume a steady-state RWM with node speed 0.25 R/s and pause time 10 s.

standard for hops (A_{sp}Hops $\geq$ 4 hops) and our standard for partitioning (ANP $\leq$ 5%). Smaller simulation areas with 95 nodes will fail to meet our standard for hops, and larger simulation areas with 95 nodes will fail to meet our standard for

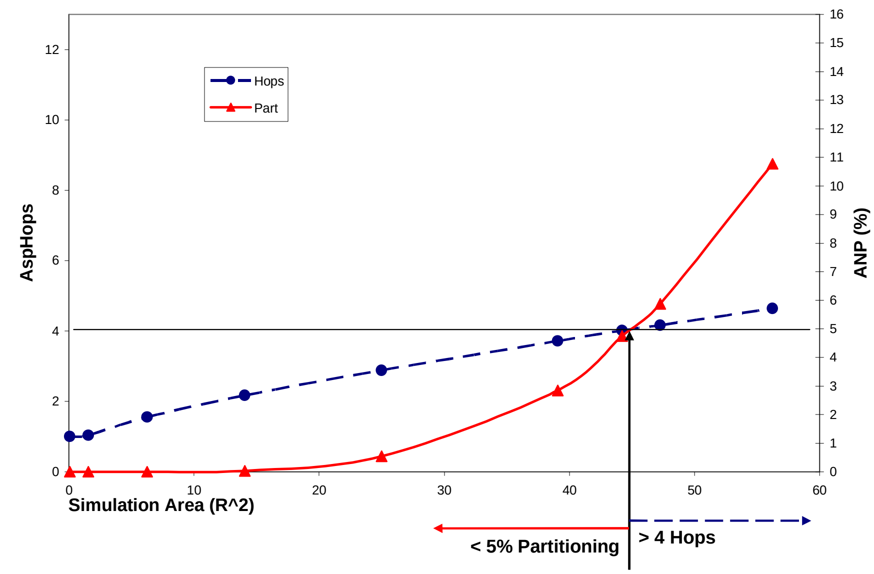

Fig. 8. For square scenarios of 95 nodes, the dashed curve plots A_{sp}Hops versus simulation area. Areas for which the curve is above the horizontal line meet our standard for hops (A_{sp}Hops ≥ 4 hops). The solid curve plots ANP versus simulation area. Areas for which the curve is below the horizontal line meet our standard for partitioning (ANP $\leq 5\%$). Therefore, for a square scenario of 95 nodes, our minimal standards for both A_{sp}Hops and ANP are just barely met in a simulation area of about 44 R^2. These results assume a steady-state RWM with node speed 0.25 R/s and pause time 10 s.

partitioning.

To estimate the minimum and maximum simulation areas that will meet our minimal standards for various numbers of nodes in square scenarios, we repeated the procedure used to create Figures 6–8. For each number of nodes, we constructed simulation scenarios with the simulation widths and heights increasing in increments of 0.05 R. 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 V 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 found that meets our standard for partitioning (ANP $\leq 5\%$).

Table V can be used to generate other square scenarios that meet our minimal standards for rigorous MANET routing protocol evaluation. First, choose a number of nodes for the simulation scenarios from Table V (e.g., 125 or 200 nodes). Then, choose a simulation area between the minimum and maximum areas presented in Table V for the chosen number of nodes. Finally, calculate the scenario width (w) and height (h) as $w = h = \sqrt{area}$. In most cases, the resulting scenario will meet our minimal standards for rigorous protocol testing. In a few cases, the resulting scenario may not quite meet our minimal standards for rigorous protocol testing; these few cases occur because of approximations due to simulation, and because we ignore the relatively small effects that exist from node speed and pause time.

TABLE V

APPROXIMATE MINIMUM AND MAXIMUM SIMULATION AREAS FOR SQUARE SCENARIOS FOR VARIOUS NUMBERS OF NODES. FIXED PARAMETERS WERE 0.25 R/S NODE SPEED AND 10 SECOND NODE PAUSE TIME.

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: While a majority of studies (e.g., 49 of the 59 MobiHoc scenarios in Table I) use square simulation areas, rectangular areas are sometimes used as well. We repeated our estimation of minimum and maximum simulation areas for a given number of nodes in rectangular scenarios with aspect ratios[3] of 1×2, 1×3, and 1×4. For a given number of nodes in a given aspect ratio, we constructed several simulation scenarios with the

[3]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.

shorter side of the simulation area increasing in increments of 0.025 R. For each of these 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 VI 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 our standard for hops (A_{sp}Hops $\geq$ 4 hops), and the maximum area is the largest simulation area found that meets our standard for partitioning (ANP $\leq 5\%$).

TABLE VI

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 SECOND 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 minimal standards. In Table VI, the smallest number of nodes listed for each aspect ratio is the smallest number of nodes that can be used to meet our minimal standards in that aspect ratio. Specifically, the smallest number of nodes that can be used to meet our minimal standards in a 1×2, 1×3, and 1×4 aspect ratio is about 85, 75, and 70 nodes, respectively. Note that as the aspect ratio goes from 1×1 to 1×4, the smallest number of nodes required to meet our minimal standards decreases.

Table VI can be used to generate other rectangular scenarios that meet our minimal standards for rigorous MANET routing protocol evaluation. First, choose an aspect ratio and a number of nodes for that aspect ratio from Table VI (e.g., 125 nodes in a 1×3 rectangle). Then, choose a simulation area between the appropriate minimum and maximum areas presented in Table VI. Finally, calculate the scenario width (w) as $w = \sqrt{area/ar}$ and the scenario height (h) as $h = ar \times w$, where ar is the $1 \times ar$ aspect ratio. As with a square scenario, the resulting rectangular scenario will meet our minimal standards for rigorous protocol testing in most cases. In a few cases, the resulting scenario may not quite meet our minimal standards due to simulation approximations and the relatively small effects of node speed and pause time.

C. Constructing Additional Simulation Scenarios

To construct simulation scenarios that meet our standards for a number of nodes not reported in Tables V and VI, we can interpolate the tabulated results along an appropriately fitted curve. Figure 9 presents the results for square scenarios. There are two curves in Figure 9, both of which are fit by least squares, and each of which plots simulation area versus number of nodes. The lower curve is fitted to the minimum simulation areas shown in Table V; this lower curve provides, for each number of nodes, a good approximation of the minimum square simulation area that meets our standard for hops (A_{sp}Hops $\geq$ 4 hops). The upper curve is fitted to the maximum simulation areas shown in Table V; this upper curve provides, for each number of nodes, a good approximation to the maximum simulation square area that meets our standard for partitioning (ANP $\leq 5\%$). Figures 10, 11, and 12 present analogous results for 1×2, 1×3, and 1×4 scenarios, respectively.

The curves in Figures 9–12 can be used to generate other scenarios that meet our minimal standards for rigorous MANET routing protocol evaluation. Specifics are presented below for each of the aspect ratios we studied:

Square area: Choose a number of nodes n, where $n \geq 95$. Then choose an area that satisfies the inequality

$$10.15 \ln n - 1.74 < \text{Area} < 0.41n + 6.01. \quad (3)$$

1×2 aspect ratio: Choose a number of nodes n, where $n \geq 85$. Then choose an area that satisfies the inequality

$$9.29 \ln n - 3.12 < \text{Area} < 0.41n + 3.03. \quad (4)$$

1×3 aspect ratio: Choose a number of nodes n, where $n \geq 75$. Then choose an area that satisfies the inequality

$$6.02 \ln n + 5.75 < \text{Area} < 0.39n + 4.09. \quad (5)$$

1×4 aspect ratio: Choose a number of nodes n, where $n \geq 70$. Then choose an area that satisfies the inequality

$$4.33 \ln n + 8.67 < \text{Area} < 0.41n - 1.06. \quad (6)$$

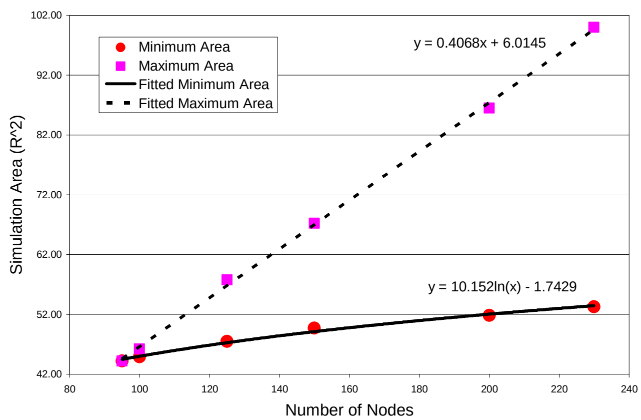

Fig. 9. For a square simulation area, the solid curve indicates the minimum simulation area that will meet our standard for hops (A_{sp}Hops ≥ 4 hops), and the dashed curve indicates the maximum simulation area that will meet our standard for partitioning (ANP $\leq 5\%$), for a given number of nodes. Square scenarios whose number of nodes and simulation area correspond to points between the two curves will meet both our minimal standards. Results assume the steady-state RWM with node speed 0.25 R/s and pause time 10 s.

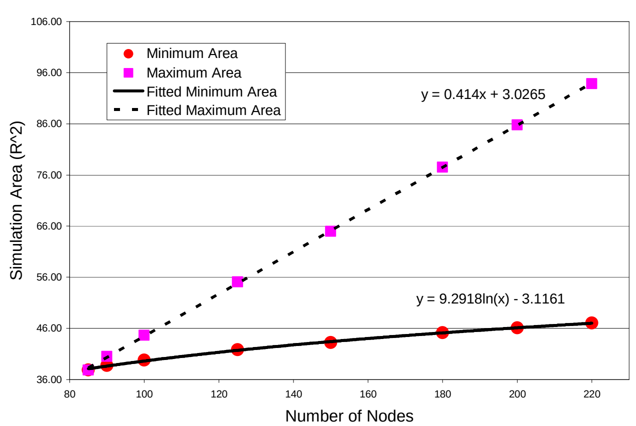

Fig. 10. For a rectangular simulation area with aspect ratio 1×2, the solid curve indicates the minimum simulation area that will meet our standard for hops (A_{sp}Hops ≥ 4 hops), and the dashed curve indicates the maximum simulation area that will meet our standard for partitioning (ANP $\leq 5\%$), for a given number of nodes. Scenarios with an aspect ratio of 1×2 whose number of nodes and simulation area correspond to points between the two curves will meet both our minimal standards. Results assume the steady-state RWM with node speed 0.25 R/s and pause time 10 s.

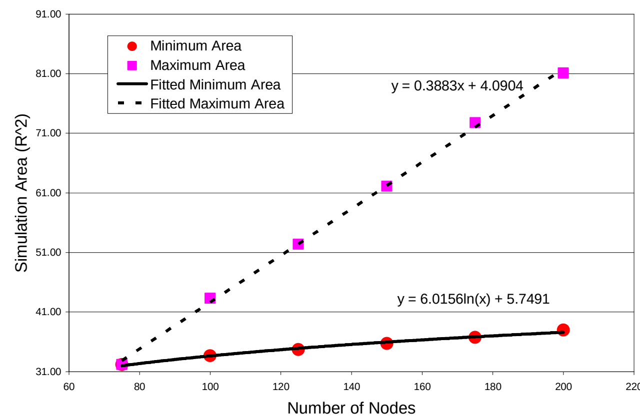

Fig. 11. For a rectangular simulation area with aspect ratio 1×3, the solid curve indicates the minimum simulation area that will meet our standard for hops (A_{sp}Hops ≥ 4 hops), and the dashed curve indicates the maximum simulation area that will meet our standard for partitioning (ANP $\leq 5\%$), for a given number of nodes. Scenarios with an aspect ratio of 1×3 whose number of nodes and simulation area correspond to points between the two curves will meet both our minimal standards. Results assume the steady-state RWM with node speed 0.25 R/s and pause time 10 s.

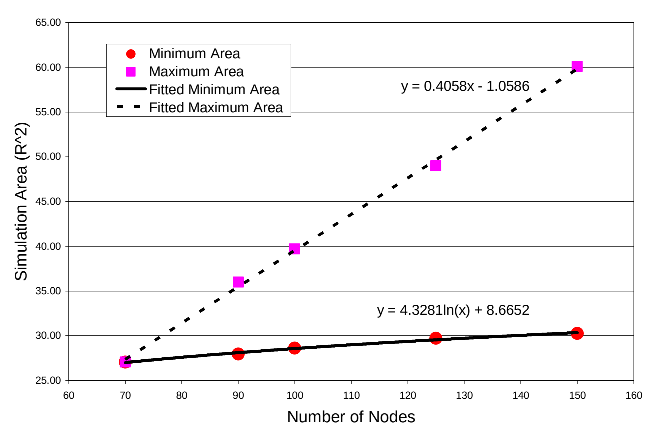

Fig. 12. For a rectangular simulation area with aspect ratio 1×4, the solid curve indicates the minimum simulation area that will meet our standard for hops (A_{sp}Hops ≥ 4 hops), and the dashed curve indicates the maximum simulation area that will meet our standard for partitioning (ANP $\leq 5\%$), for a given number of nodes. Scenarios with an aspect ratio of 1×4 whose number of nodes and simulation area correspond to points between the two curves will meet both our minimal standards. Results assume the steady-state RWM with node speed 0.25 R/s and pause time 10 s.

We summarize our method for generating simulation scenarios that rigorously evaluate a MANET routing protocol in the following seven-step process. Following these steps enables a researcher to develop scenarios that (in most cases) meet both our standard for hops (A_{sp}Hops ≥ 4 hops) and our standard for partitioning (ANP $\leq 5\%$). As mentioned, our minimal standards may not quite be met in a few cases; these few cases exist because of approximations due to simulation and curve fitting, and because we ignore the relatively small effects of node speed and pause time.

To construct a simulation scenario that meets both our standard for hops (A_{sp}Hops ≥ 4 hops) and our standard for partitioning (ANP $\leq 5\%$) for rigorous MANET routing protocol evaluation:

1) Choose a speed and a pause time for the nodes.
2) Choose a node transmission range (R).
3) Select an aspect ratio (ar) of 1, 2, 3, or 4 as $1 \times ar$.
4) Choose a number of nodes (n); n must be greater than the smallest number of nodes that can be used to meet our minimal standards in a given aspect ratio (i.e., $n \geq 95$ for $ar = 1$, $n \geq 85$ for $ar = 2$, $n \geq 75$ for $ar = 3$, and $n \geq 70$ for $ar = 4$).
5) Choose a simulation $area$ that satisfies the appropriate inequality (3)–(6) for the selected aspect ratio.
6) Calculate the scenario width (w) as $w = \sqrt{area/ar}$.
7) Calculate the scenario height (h) as $h = ar \times w$.

To verify our seven-step process, we generated several new scenarios. These new scenarios have 210 nodes (1×1), 190 nodes (1×2), 180 nodes (1×3), and 140 nodes (1×4). We fixed the node speed at 0.25 R/second and node pause time at 10 seconds, and calculated A_{sp}Hops and ANP for each scenario. Table VII presents the results. The results show successful application of our seven-step process. All the scenarios we generated meet our minimal standards for rigorous evaluation of MANET routing protocols.

TABLE VII

SEVERAL SIMULATION SCENARIOS GENERATED BY OUR SEVEN-STEP PROCESS. FIXED PARAMETERS WERE 0.25R/S NODE SPEED AND 10 SECOND NODE PAUSE TIME.

n	**ar**	**Area**	**w x h**	**ANP**	**A_{sp} Hops**
210	1×1	52.42	$7.24R \times 7.24R$	0.71	4.01
210	1×1	72.25	$8.50R \times 8.50R$	2.19	4.83
210	1×1	89.30	$9.45R \times 9.45R$	4.41	5.49
190	1×2	45.65	$4.78R \times 9.55R$	0.70	4.04
190	1×2	66.13	$5.75R \times 11.5R$	2.48	4.98
190	1×2	81.66	$6.39R \times 12.78R$	4.97	5.67
180	1×3	37.77	$3.55R \times 10.64R$	0.42	4.06
180	1×3	55.99	$4.32R \times 12.96R$	2.00	5.06
180	1×3	73.90	$4.96R \times 14.90R$	4.49	5.93
140	1×4	29.89	$2.73R \times 10.95R$	0.42	4.02
140	1×4	43.92	$3.31R \times 13.27R$	2.27	4.95
140	1×4	55.13	$3.70R \times 14.90R$	4.91	5.64

V. RECOMMENDATIONS AND CONCLUSIONS

In order to ensure that scenarios provide an effective platform for testing routing protocols, we recommend using the average amount of network partitioning and the average shortest-path hop count to characterize simulation scenarios. To calculate ANP, build the connectivity matrix at regular intervals throughout the simulation. The value of ANP is the proportion of entries in all evaluations of the connectivity matrix that are equal to 0 (Equation 1). To calculate A_{sp}Hops, evaluate 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 2). We recommend as minimal standards that the standard for hops be A_{sp}Hops ≥ 4 hops and the standard for partitioning be ANP $\leq 5\%$.

We reach the following conclusions:

Conclusion #1: Only eight of the 59 scenarios (13.56%) in the 2000-2005 MobiHoc conferences meet our minimal standards for rigorous MANET protocol evaluation.

Conclusion #2: Within each number of nodes and width/height combination that we tested, varying node speed and node pause time had little effect on ANP and A_{sp}Hops.

Conclusion #3: For a given aspect ratio, there exists a smallest number of nodes that can be used to meet our minimal standards. The smallest number of nodes that can be used in a 1×1, 1×2, 1×3, and 1×4 simulation area is about 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 minimal 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 standard for partitioning.

Conclusion #5: For a given aspect ratio and a given number of nodes (larger than the minimum number allowed), simulation scenarios with simulation areas that satisfy the appropriate inequality (3)–(6) will yield A_{sp}Hops ≥ 4 hops and ANP $\leq 5\%$ in most cases. In the few cases where these values are not quite attained, they will (in general) be very nearly attained.

Conclusion #6: Our seven-step process described in Section IV-C will develop a simulation scenario that meets our minimal standards for rigorous protocol evaluation in most cases. In the few cases where the minimal standards are not quite met, they will (in general) be very nearly met.

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

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