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Key Factor and Interaction for Network Performance in Mobile Ad Hoc Networks

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Abstract—In this paper, we present a comprehensive statistical experiment and identify the key factors and interactions that impact network performance over mobile ad hoc networks. We use the design of experiments software named Design-Ease to establish the mathematical model for analyzing the set of simulation results from ns2. A variety of important parameters for network performance including routing protocol, node density, node speed, traffic load and pause time are considered to capture the vital factors and interactions for network performance by measuring the packet delivery ratio, average delay, discovery time and recovery time in which latter two are the crucial metrics for ad hoc self-organising performance measurement. With the simulation and analysis results, we conclude the key factors and interactions which influence the specific network performance and suggest which aspects the designers should focus on for improving the given network performance.

I. INTRODUCTION

An ad-hoc wireless network [1] is a collection of mobile terminals (e.g. handheld devices, mobile phones, laptops, etc.) that communicate through multi-hop connections without the aid of established infrastructure. This technology has recently become commercially viable and an attractive candidate to fulfill the ever growing demand for mobile devices to communicate anytime and anywhere without a central installation [1]. Due to its characteristics, efficient methods of networking mobile nodes have become a key research area.

Following the tremendous amount of routing protocols developed for solving the networking problem in mobile ad hoc network, there is also much work [1][2][3] done for evaluating and analyzing these protocols in recent years. One of the main goals of these works is to find out, among the scenario parameters (e.g. traffic load, pause time, node density, etc.) and the routing mechanism itself, which factors and interactions have the key impact on the network performance in term of the different performance metrics (e.g. packet delivery ratio, routing overhead, delay). However, most of these works were focus on the qualitative analysis and there is little work to provide the exact data for the contribution of the above parameters to the network performance with formal scientific approaches.

In order to achieve the full potential of collecting data in the simulation, a well designed formal mathematical analysis methodology is crucial. In this paper, we use a formal mathematical methodology for the quantitative analysis to extract all the information presented in the simulation results, and identify the dominant factors and interactions which we should focus on for improving the given network performance.

In this work, we used Design of Experiments (DOE) software called *Design-Ease* [5], with analysis of variance (ANOVA), which is widely used statistical software for finding out the significant factors and interactions. The main previous works using these approaches in ad hoc area could be found in [6] [7] [8]. In [6] and [7], the authors used ANOVA [9] statistical technique to characterize the effect of interaction between routing protocols and MAC protocols. Although different injection rates and network topology have been selected for simulation, there is no analysis for the effects of these parameters on the network performance. Also, there is no exact numerical data for the contribution of each factor and interaction. Vadde, et al. [8] considered QoS architecture, routing protocol, MAC protocol, offered load and mobility as factors using DOE software and indicated their contribution. However, their analysis was focused on protocols and QoS architectures, and also, the self-organising performance was not considered. Our statistical analysis focuses on the network level and includes all the important factors for the routing performance evaluation. In addition, we also consider these factors and interactions' effects on the self-organising performance (e.g. discovery time, recovery time) which is the important mobile ad hoc networks.

The rest of the paper is organised as follows. In Section II, we firstly introduce the simulation platform and parameters selected, and then present the design of statistical analysis. Section III presents and discusses the results of our statistical analysis. In section IV, we present our conclusions, and outline our further work.

II. SIMULATION PLATFORM AND STATISTICAL ANALYSIS

2.1 Simulation platform

The simulation was carried out in ns-2 network simulator [9] and the traffic and mobility models used here are similar to

Mobility model		Traffic model	
Simulation Area	1500m x 300m, 2400m x 480m	Sending rate of data packets	4 packets/s
Transmission Range	250m	CBR Traffic	10, 20, 30 connections
Interference Range	500m	Size of data packet	512 bytes
Bandwidth	2Mbps		
Simulation Time	900 s		
Pause Time	0,30,60,120,300,600,900 s		
Number of Nodes	50		
Node maximum Speed	1,5,10,20 (m/s)		
Routing Protocols	AODV, DSR		
Movement pattern	Random Waypoint Way		

Table 1. Simulation model specification

previously work done [1][2][3] for performance evaluation of ad hoc routing protocols. Two primary routing protocols, AODV and DSR, were chosen for the routing protocols.

A. Physical layer and MAC layer

At the physical layer, we chose Lucent's WaveLAN [10] radio model with a 250m nominal transmission range. The model employed the tworayround propagation model which uses signal attenuation as $1/r^2$ at near distances and $1/r^4$ at far distances. The channel capacity was set to 2 Mbps. At the MAC layer, the IEEE 802.11 DCF (distributed coordination function) MAC protocol was employed. In this medium access control protocol, the data packet is sent out to a neighbour node after the handshaking with request-to-send/clear-to-send (RTS/CTS) exchanges. An acknowledgement packet will be sent back to the sender after receiving the data packet.

B. Mobility model

The mobility model is based on a network with 50 wireless nodes with transmission range of 250m in a rectangular space of size 1500 m × 300 m and 2400 m × 480 m. The random waypoint mobility model was initially employed. Simulations were run for 900 simulated seconds and seven pause times in the (0, 30, 60, 120, 300, 600, 900 second) were chosen to reflect the degree of motion of network. Here, a pause time of 0 means constant movement by all nodes, and pause time of 900 corresponds to no motion [2]. For our experiments, we used four maximum speeds 1 m/s, 5 m/s, 10 m/s and 20 m/s. In the random waypoint mobility model, each node chooses a uniformly distributed velocity over between 0 and maximum speed, moves towards a destination with a uniform random distribution over the area. After the node reaches the proposed position, it waits there for a pause time, and then repeats the above behaviour.

C. Traffic model

The traffic source and destination were randomly chosen from all the nodes in the area. We experimented the network with 10, 20, 30 CBR (constant bit rate) connections. Every source generated the CBR sources at the given rate. The sending rate of data packets we selected here is 4 packets per second at 2 Mbps channel. The size of data packet is fixed at 512 byte.

2.2 Design of statistical analysis

In order to extract the useful information from the numerous simulation data from the simulation carried out in the above simulation correctly and achieve the full potential of collecting data in the simulation, a well designed formal

mathematical analysis methodology is vital. Depending on the nature of our raw data from ns2, we use software named *Design-Ease* with ANOVA technique, one of the formal experimental designs, which is usually be used for the experiments which produce numerical data [11]. Using this tool is a way of identifying not only the effects of input factors separately but their interaction effects.

Figure 1 shows the model we use here for our statistical design. For the input variables of our statistical analysis, we selected five factors which are widely considered as the most important parameters in influencing the network performance of mobile ad hoc networks. We here choose node speed and pause time as the parameters for movement patterns, traffic load as the parameter for communication model, routing protocol as the parameter for routing mechanisms and node density as the parameter for the network topology. For the output variables, packet delivery ratio and average delay, as the most two important factors for the network performance measurement; and discovery time & recovery time as two metrics of ad hoc self-organisation performance which is crucial for such network, are chosen.

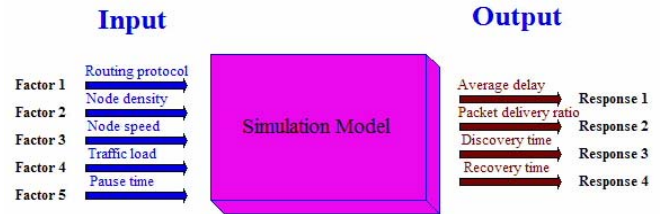


Figure 1. Model of statistical analysis

As one of the input factors, routing protocol has two level including AODV and DSR. Two simulation areas listed in table 1 yield two levels of node density. The different node speed and pause time we selected in table 1 yield 4 and 7 different levels, respectively. For traffic load, we considered three levels from 10 connections to 30 connections. These results in $2 \times 2 \times 4 \times 7 \times 3 = 336$ samples for our analysis. A mathematical model for a five factors ANOVA would be as follows:

$$\begin{aligned}
Y_{ijklmn} = & \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \mu_m + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\alpha\delta)_{il} + (\alpha\mu)_{im} \\
& + (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\beta\mu)_{jm} + (\gamma\delta)_{kl} + (\gamma\mu)_{km} + (\delta\mu)_{lm} + (\alpha\beta\gamma)_{ijk} + (\alpha\beta\delta)_{ijl} \\
& + (\alpha\beta\mu)_{ijm} + (\alpha\gamma\delta)_{ikl} + (\alpha\gamma\mu)_{ikm} + (\alpha\delta\mu)_{ilm} + (\beta\gamma\delta)_{jkl} + (\beta\gamma\mu)_{jkm} + (\beta\delta\mu)_{jlm} \\
& + (\gamma\delta\mu)_{klm} + (\alpha\beta\gamma\delta)_{ijkl} + (\alpha\beta\gamma\mu)_{ijkm} + (\alpha\beta\delta\mu)_{ijlm} + (\alpha\gamma\delta\mu)_{iklm} + (\beta\gamma\delta\mu)_{jklm} \\
& + (\alpha\beta\gamma\delta\mu)_{ijklm} + \epsilon_{ijklmn}
\end{aligned}$$

Here, y_{ijklmn} is the network performance variable (e.g. average delay, discovery time, etc.), i, j, k, l and m mean the i th routing protocol, j th node density, k th node speed, l th traffic load, m th pause time, respectively, and n is the size of sample, which is 336 in our analysis. $\alpha_i, \beta_j, \gamma_k, \delta_l, \mu_m$ are the individual effects of routing protocol, node density, node speed, traffic load and pause time, respectively. u is the overall mean and e is the random error. The remaining items are the two-factor, three-factor, four-factor and five-factor interactions. For example, $(\alpha\gamma)_{ik}$ present the interaction between routing protocol and node speed, and $(\alpha\beta\mu)_{ijkm}$ presents the interaction between routing protocol, node density, node speed and pause time.

III. ANALYSIS RESULTS AND DISCUSSION

Table 2 is the effects table for the average delay, packet delivery ratio, discovery time and recovery time. Here, the first column lists the input variables and their interactions. As mentioned in last section, we have 5 individual input factors, which yield ten 2-way interactions, ten 3-way interactions, five 4-way interactions and one 5-way interactions. The column 2-5 named percentage contribution provides the data for the contribution of individual factor and interaction to a variety of response variables.

A. Average delay

The second column in table 2 shows the effects list for the average delay which is one of the response variables we selected. From the table, we can find that traffic load (D), routing protocol (A) and routing protocol and traffic load interaction (AD) contribute more than 79% to the average delay of network. Among these three terms, network traffic's contribution is over 50% and is critical for the network delay performance. The visual contribution of factors and interactions can be found in figure 2. Traffic load, routing protocol, their interaction and other 6 significant factors and interactions whose contribution are over 1%, accounting for over 91% of contribution to the average delay, were selected for ANOVA table.

In the ANOVA table, the most interesting value for us is the F value which presents the factors and interactions which are statistically significant. As the same conclusion from the effects table, ANOVA table also indicates that network traffic (D), routing protocol (A) and their interaction domain the average delay.

Based on the results shown in the table 2, 3 and figure 2, we can conclude that traffic and routing protocol are two main factors which domain the average delay. The impact of topology (node density) property and mobility properties are not the primary for the network delay. This suggests that in order to improve the network's delay performance, traffic control in the network and the selection of suitable routing protocol are crucial.

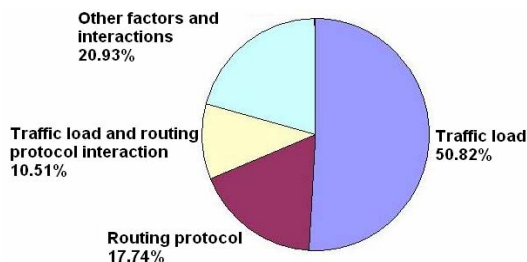


Figure 2. Chart for the contribution of factor and interaction to average delay

Term	Contribution to average delay (%)	Contribution to packet delivery ratio (%)	Contribution to discovery time (%)	Contribution to recovery time (%)
A	17.7372	1.558909	0.015902	12.40752
B	0.040763	15.34613	17.25388	32.53205
C	1.6985	2.298441	3.442207	0.878189
D	50.8166	66.80518	0.141949	3.478473
E	2.21348	0.299869	20.89531	5.551869
AB	0.002513	0.18756	0.191418	11.99301
AC	0.934689	0.47106	0.706689	0.424411
AD	10.5069	1.39677	0.176938	1.247945
AE	1.23958	0.219138	5.199072	3.641206
BC	0.038785	0.023363	3.935892	1.452737
BD	4.3452	0.980358	0.427464	0.074681
BE	1.49717	0.694059	20.75084	3.994151
CD	0.653232	0.928542	0.672785	0.911902
CE	1.20866	1.904444	6.087202	2.40963
DE	0.612451	0.725972	0.694343	1.131669
ABC	0.013108	0.003479	0.467706	0.087168
ABD	0.912725	0.13638	0.037372	0.85503
ABE	0.30522	0.095198	5.180038	2.32406
ACD	0.462234	0.285085	0.033575	0.261672
ACE	0.656989	0.218978	0.960949	0.945756
ADE	0.43056	0.165343	0.082065	0.509732
BCD	0.183666	0.151563	0.586445	0.3333
BCE	0.607115	2.395213	5.990859	2.822057
BDE	0.516889	0.812069	0.80346	1.324067
CDE	0.703478	0.849744	1.682359	1.759812
ABCD	0.048882	0.014225	0.037757	0.522964
ABCE	0.24758	0.058084	1.022929	1.203501
ABDE	0.136209	0.072393	0.071103	0.476187
ACDE	0.399285	0.203112	0.394727	1.194283
BCDE	0.562225	0.632343	1.694701	1.973
ABCDE	0.268011	0.066994	0.362067	1.277971

NOTE: A: Routing protocol, B: Node density, C: Node speed, D: Traffic load, E: Pause time.

Table 2. Effects table for the average delay, packet delivery ratio, discovery time and recovery time

Source	Sum of Squares	Degree of Freedom	F Value
Model	430.5818	47	64.33887
A	83.64717	1	587.4446
B	0.192233	1	1.350028
C	8.009943	3	18.75097
D	239.6464	2	841.5049
E	10.43857	6	12.21815
AD	49.54971	2	173.991
AE	5.845727	6	6.842313
BD	20.49155	2	71.95491
BE	7.060503	6	8.264186
CE	5.699931	18	2.223887

Table 3. ANOVA table for the average delay

B. Packet delivery ratio

The third column in table 3 presents the effects list for the packet delivery ratio. Node density (B) and network traffic (D) drive the fraction of packets delivered. As the effects list for average delay, network traffic again becomes the most critical factor for the packet delivery ratio performance. There are 7 factors and interaction of factors which contribute over 1% to the packet delivery ratio, thus we consider them as significant terms and included in the ANOVA table.

Source	Sum of Squares	Degree of Freedom	F Value
Model	84098.99	60	58.39512
A	1413.927	1	58.90659
B	13918.91	1	579.8853
C	2084.681	3	28.95046
D	60592.15	2	1262.186
E	271.9805	6	1.888529
AD	1266.868	2	26.38993
BC	21.18988	3	0.294269
BE	629.5097	6	4.371074
CE	1727.327	18	3.997965

Table 4. ANOVA table for packet delivery ratio

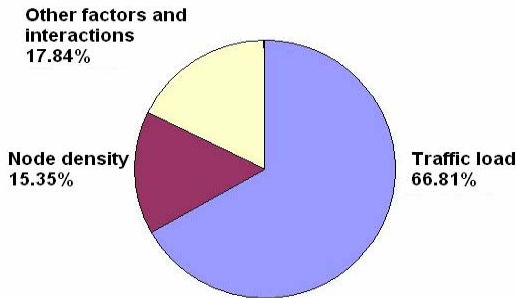


Figure 3. Chart for the contribution of factor and interaction to packet delivery ratio

As shown in the effects list, ANOVA table and chart, traffic load and node density demonstrate their importance to the packet delivery ratio. Also, packet delivery ratio is not sensitive to the mobility properties and routing mechanism used. For the given scenario, traffic control again becomes the primary factor to consider for improving the packet delivery ratio.

C. Discovery time

As one of the most important self-organising performance metrics for ad hoc networks, discovery time is defined as the amount of time a node needs to find a route to a destination node when there is no route entry in the source node to the destination node.

The effects list for discovery time shown in the fourth column in table 2, ANOVA table shown in table 5 and figure 4 indicate network density (B), pause time (E) and their interaction become the critical factors for the network performance of discovery time. This is because the scenario with dense nodes can benefit the discovery time quite a lot. Pause time and its interaction with node density are also important for the scenarios in which the source can not find the route to the destination with the initial topology.

Also note that node speed (C) and its interactions (BC, CE, BCE, CDE, ABCE) are contributed considerably 22% of contribution to the discovery time. This suggests that node speed is another important factor to the discovery time. The importance of node speed is due to the same reason of the importance of pause time.

The above tables and figures indicate the discovery time is quite sensitive to the mobility properties and network density, which we need to pay more attention for decreasing the discovery time.

Source	Sum of Squares	Degree of Freedom	F Value
Model	23584.84	157	15.38198
B	4369.235	1	447.3881
C	871.6771	3	29.75181
E	5291.361	6	90.30155
AE	1316.572	6	22.46841
BC	996.6938	3	34.01884
BE	5254.777	6	89.67721
CE	1541.474	18	8.768855
ABE	1311.751	6	22.38615
BCE	1517.077	18	8.630069
CDE	426.0273	36	1.211753
ABCE	259.0384	18	1.47357
BCDE	429.1525	36	1.220642

Table 5. ANOVA table for discovery time

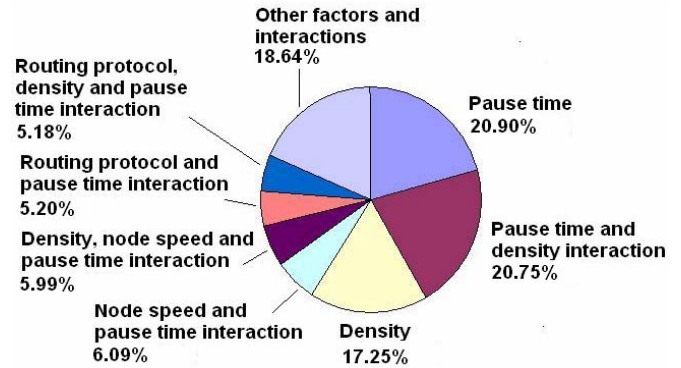


Figure 4. Chart for the contribution of factor and interaction to discovery time

D. Recovery time

Recovery time we used for measuring the ad hoc self-organising performance is defined as the amount of time a node needs to re-build a new route to a destination node when the source node receives the route error information saying that the current route breaks.

The fifth column in table 3, table 6 and figure 5 show the effects list, ANOVA table and factor's contribution to recovery time. It could be found that routing protocols, node density and their interaction contribute over 12%, 32% and 11%, respectively. With the similar situation as discovery time, node density is important for the response time when the existing route fails to get the destination. The chance to get a replaced route for denser network is bigger. Also, the recovery mechanisms in the routing protocols have the great impact on the response time for the route re-establishment.

Source	Sum of Squares	Degree of Freedom	F Value
Model	1680.514	256	4.604543
A	222.4844	1	156.0572
B	583.3456	1	409.176
D	62.37394	2	21.87547
E	99.55288	6	11.63823
AB	215.0516	1	150.8436
AD	22.37741	2	7.848092
AE	65.29198	6	7.632957
BC	26.04962	3	6.09066
BE	71.62078	6	8.372825
CE	43.20807	18	1.683746
DE	20.29242	12	1.186142
ABE	41.67368	6	4.87186
BCE	50.60348	18	1.971933
BDE	23.74239	12	1.387802
CDE	31.55592	36	0.614841
ABCE	21.58047	18	0.840955
ACDE	21.41518	36	0.417257
BCDE	35.37868	36	0.689324
ABCDE	22.91582	36	0.446496

Table 6. ANOVA table for recovery time

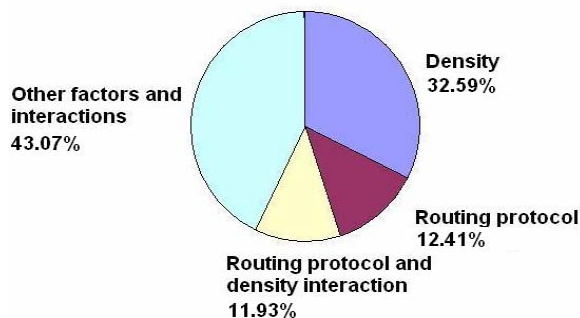


Figure 5. Chart for the contribution of factor and interaction to recovery time

IV. CONCLUSION AND FURTHER WORK

Considerable research has been done for evaluating and analyzing ad hoc routing protocols in recent years. Some qualitative analysis carried out for identifying the most important parameters/factors for the network performance, but there is little work done in network level towards the quantitative analysis using the formal statistical approaches. In this paper, we use design of experiment software called Design-ease for the quantitative analysis. With the simulation and analysis results, we show the key factors' and interactions'

contribute to a variety of network performance including average delay, packet delivery ratio, discovery time and recovery time, in which the latter two are the crucial performance metrics for ad hoc self-organising performance. We also suggest the possible solution and factors which should be focused on for improving the given network performance.

As part of our future work, we would like to decompose the individual routing protocol to set of mechanistic building blocks in term of which phase the mechanism used for, and then use the formal mathematical methodology to identify the key factors/phases for the routing performance. The results can be used as the guideline for the design of a programmable structure for better routing performance in the various application scenarios.

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