Characterizing the Interaction Between Routing and MAC Protocols in Ad-hoc Networks

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Abstract: We empirically study the effect of mobility on the performance of protocols designed for wireless ad-hoc networks. An important objective is to study the interaction of the Routing and MAC layer protocols under different mobility parameters. We use three basic mobility models: grid mobility model, random waypoint model, and exponential correlated random model. The performance of protocols is measured in terms of (i) latency, (ii) throughput, (iii) number of packets received, (iv) long term fairness and (v) number of control packets at the MAC and routing layer level. Three different commonly studied routing protocols are used: AODV, DSR and LAR1. Similarly three well known MAC protocols are used: MACA, 802.11 and CSMA. Our main contribution is simulation based experiments coupled with *rigorous statistical analysis* to characterize the *interaction* of MAC layer protocols with routing layer protocols in ad-hoc networks. From the results, we can conclude the following:

- No single MAC or Routing protocol dominated the other protocols in their class. Probably more interestingly, no MAC/Routing protocol combination was better than other combinations over all scenarios and response variables.
- In general, it is not meaningful to speak about a MAC or a routing protocol in isolation. Presence of interaction leads to trade-offs between the amount of control packets generated by each layer. The results raise the possibility of improving the performance of a particular MAC layer protocol by using a cleverly designed routing protocol or vice-versa.

Thus in order to improve the performance of a communication network, it is important to study *the entire protocol stack* as *a single algorithmic construct*; optimizing individual layers in the seven layer OSI stack will not yield performance improvements beyond a point. A methodological contribution of this paper is the use of statistical methods such as *analysis of variance* (ANOVA), to characterize the interaction between the protocols, mobility patterns and speed. Such methods allow us to analyze complicated experiments with large input space in a systematic manner.

1 Introduction

Design of mobile ad-hoc networks is currently an extremely active area of research. Mobile ad-hoc networks lack a fixed infrastructure in the form of wireline, or base stations to support the communication. Interest in ad-hoc networks for mobile communications has also resulted in a special interest group for Mobile, Ad-hoc Networking within the Internet Engineering Task Force (IETF). Mobile ad-hoc networks impose specific requirements on the design of communication protocols at all levels of the protocols stack. Many MAC layer and routing layer protocols have been proposed and designed for ad-hoc networks. These protocols need to fulfill a multitude of design and functional requirements, including, *(i) High throughput; (ii) Low average latency; (iii) Heterogeneous traffic (e.g. data, voice, and video); (iv) Preservation of packet order; and (v) Support for priority traffic.* (See [RS96, Ra96, Ba98].) As ad-hoc networks lack fixed infrastructure in the form of base stations, fulfilling the above stated functional requirements becomes all the more difficult.

A commonly known group of MAC protocols is based on the carrier sense multiple access (CSMA) paradigm. The idea behind this paradigm is to reserve transmission channel at the originator (source) by carrier sensing. Until recently CSMA based protocols supported only single channel communication, but now, multiple channel extensions have been proposed [NZD99]. Many protocols have been proposed to avoid the hidden terminal problems. Two notable examples are the MACA [Ka90] and MACAW [BD+94] protocols. MACA introduced a reservation system achieved with exchange of an RTS/CTS (Request To Send/Clear To Send) pair of control packets. MACAW also recognizes the importance of congestion, and exchange of knowledge about congestion level among entities participating in communication. An advanced back-off mechanism was proposed to spread information about congestion. Furthermore, the basic RTS/CTS/DATA reservation schema has become an RTS/CTS/DS/DATA/ACK schema with significantly improved performance. In these protocols message originators reserve reception area at the sink by exchange of RTS/CTS control messages. This is in contrast to CSMA where reservation was done at originators. This powerful method has a drawback of introducing small control packets into the network that later collide with other data, control, or routing packets. IEEE 802.11 MAC standard [OP] was designed with a reservation system similar to MACA or MACAW in mind. 802.11 has also improved fairness characteristics, however, in [LNB98] authors point out deficiencies in the fairness of this protocol, as well. Detailed discussion of these protocols is omitted due to lack of space and can be found in [Ra96, BD+94, 802.11].

The role of routing protocols for mobile/ad-hoc networks is to find the shortest path from the source to the sink of a data transmission. The quality of these protocols is measured by the number of hops that data packets need to reach its destination. Routing protocols fall in one of the two categories: *proactive*, or *reactive*. Reactive routing protocols are also referred to as *on-demand*. Proactive protocols attempt to maintain routes to all destinations at all times, regardless of whether they are needed. Into the second category belong routing protocols which try to establish a route to the recipient when it is needed – on-demand. Example of such a protocol is DSR [JM96] where information about possible routes is done by flooding the network with routing packets. Methods based on *distance vectors* have been proposed – DSDV and AODV [PR99]. DSDV is derived from the classical distributed Bellman-Ford algorithm. TORA is an example of a *distributed* on-demand routing algorithm. This protocol has an advantage of localizing algorithmic reaction whenever possible. Route optimality in this protocol is considered of secondary importance. A comprehensive survey of various routing protocols can be found in [RS96]. Performance comparison of various routing protocols for ad-hoc networks can be found in [BM+98].

In this paper, we consider three well known routing protocols: (i) Dynamic Source Routing Protocols (DSR) [JM96], (ii) Ad-hoc On-demand Distance Vector Routing (AODV) [PR99] and (iii) Location-Aided Routing (LAR) Scheme 1 [KV98]. Similarly we consider three well known MAC layer protocols: (i) CSMA/CA, (ii) MACA and (iii) 802.11. Due to lack of space detailed description of these protocols is omitted but can be found in the complete version of this paper.

Many mobility models for ad-hoc networks simulations have been proposed. These include the *random waypoint* model [JM96], *random mobility model* [ZD97], and *exponential correlated random model (ECRM)* [RS98]. The first two specify movement for individual nodes, whereas the ECR model is a group mobility model. It specifies movement of a group of nodes in a correlated way. This model provides a more realistic model for node movement. A more sophisticated model is the *Reference Point Group Mobility (RPGM)* model [HG+99]. See [HG+99, BCSW98, RS96, RS98] for a comprehensive discussion of other mobility models.

2 Our Contributions

We conduct a comprehensive simulation based experimental analysis to characterize the interaction between MAC and routing protocols in mobile ad-hoc networks. Our work is motivated by the earlier work by Balakrishnan et.al. [BS+97, KKB00] and the recent results by Royer et.al. [DPR00, DP+, RLP00] that note the interplay between Routing and MAC protocols. In [DPR00], the authors conclude by saying – *"This observation also emphasizes the critical need for studying interactions between protocol layers when designing wireless network protocols"*.

This paper aims to undertake precisely such a study. We employ three different mobility models: (i) grid mobility model that simulates movement of nodes in a town with grid architecture, (ii) the random waypoint mobility model that approximates mobility in square area but the directionality and duration is random, and (iii) the exponential correlated random mobility model [RS98] that approximates movement of groups of nodes in a square area. The models are all qualitatively different. At one extreme is the random waypoint movement model with no predictable movement, while on the other extreme is the ECR model where points form clusters and these clusters move in fairly deterministic fashion. The grid mobility model is somewhere in the middle.

Apart from mobility patterns, we study the effect of speeds and injection rates of packets on the system performance. Thus our input variables are:

1. **Routing protocols:** AODV, DSR, LAR1. These are denoted by $R_i,\ 1 \leq i \leq 3$. The set of routing protocols will be denoted by R. The routing protocols were chosen keeping in mind the recommendations made by [DPR00, JL+00] after undertaking a detailed experimental study of recent routing protocols.

2. **Speed of Nodes:** 10m/s, 20m/s and 40m/s.[1] These are denoted by $S_j,\ 1 \leq j \leq 3$. The set of all speeds will be denoted by S.

3. **MAC protocols:** 802.11, CSMA and MACA. These are denoted by $M_k,\ 1 \leq k \leq 3$. The set of MAC protocols will be denoted by M. Again the choice of these protocols is based on the study in [RLP00, WS+97].

4. **Injection rates:** low (0.05 second), medium (0.025 second) and high (0.0125 second). The injection rates are denoted by $I_l,\ 1 \leq l \leq 3$. The set of injection rates will be denoted by I.

Our evaluation criteria consists of following basic metrics: (i) *Latency:* Average end to end delay for each packet as measured in seconds, and includes all possible delays caused by buffering during route discovery, latency, queuing and backoffs, (ii) Total number of packets received (and in some cases packet delivery fraction) (iii) *Throughput:* The total number of unique data packets received in bits/second, (iv) Long term fairness of the protocols, i.e. the proportional allocation of resources given to each active connection and (v) *Control Overhead:* The number of control packets used by MAC and routing layers. Each of the input parameters and the performance measures considered here is used in one of the earlier experimental studies [DPR00, DP+, BM+98, KV98, RLP00, RS98]. We briefly comment on the parameters chosen in [DPR00, RLP00] since the two studies are closest to the one in this paper. The authors consider two parameters that we have not varied in this simulation: (i) Pause time in movement models and (ii) total number of connections. In our case the pause time is always 0 and the number of connections have always been kept constant. On the other hand, we vary (i) the injection rate, (ii) the movement models and (iii) speeds. These paramters are kept constant in [DPR00, RLP00]. Based on the discussion in [DPR00], a pause time of zero and our injection rates which start at .05 second and up imply that our scenarios might be considered “stressful”. Most of our results agree with their general findings in this regime.

Each combination of the input variable corresponds to a *scenario*. The total number of scenarios considered is $3^4 = 81$. We ran each scenario 10 times to get a reasonable sample size for statistical analysis. This resulted in 1620 runs. We constructed 3 basic experiments: each corresponding to one of the mobility models. For each of these mobility models, we have 81 scenarios and 1620 runs. In our experiments, we make two important observations. (i) All parameters considered here are *important* and cannot be *ignored*. Specifically, the results show that two and three way interactions are quite common; moreover, the interacting variables differ for different response variables (performance measure). Thus omitting any of these parameters is not likely to yield meaningful conclusions. (ii) The variation in parameters represents realistic possibilities. Other closely related studies have also considered similar parameters. See [RLP00, DPR00, DP+].

Given the large number of variables involved i.e. MAC, router, injection rate, nodes' speed, mobility and several levels of each variables, it is hard to derive any meaningful conclusions by merely studying plots and tables.

In order to effectively deal with the combinatorial explosion, and to draw conclusions with certain level of precision and confidence, we resort to well known techniques in statistics that can simultaneously and effectively handle such data sets. We setup a *factorial experimental design* and measure the response of 3 important response variables (output metrics). We use analysis of variance (ANOVA) to perform statistical analysis. A methodological contribution of this paper is to use *statistical methods* to characterize the interaction between the *protocols, mobility patterns* and *speed*[2]. Even though it is widely believed that these parameters interact in affecting the performance measure, to our knowledge a formal study such as the one undertaken in this paper has not been previously done. The simple statistical methods used here for analysis of network/protocol performance modeling are of independent interest and can be used in several other contexts.

While intuitively it is clear that different levels in the protocol stack should affect each other in most cases; to the best of our knowledge a thorough understanding of this interaction is lacking. The only related references in this direction that we are aware are [BS+97, KKB00, RLP00, DPR00, DP+]. In [KKB00], the authors were specifically

[1] m/s stands for meters per second.

[2] The statistical techniques used in this paper are well known and routine; but to our knownledge have not been previously applied in our setting.

considering TCP/IP protocol and have devised an elegant snoop protocol that conceptually sits between the transport layer and the network layer to overcome this problem. It also point out how short term fairness of the MAC can affect the TCP/IP performance which in turn can affect the overall performance of the communication system. In [RLP00] the authors considered performance of routing and the effect of MAC layers on routing protocols. Our results can be viewed as furthering the study initiated in [RLP00][3] in the following ways:

1. In [RLP00], the authors consider a multitude of routing and MAC protocols as considered here. But the authors did not consider simultaneously the effect of injection rates, spatial location of connections and mobility models in characterizing the interaction. As our results show each of these parameters play a significant role in characterizing interaction.

2. Statistical methods to characterize and quantify interactions between protocols have not been considered prior to this paper. Moreover, we characterize the interaction not only between the MAC and Routing protocols but also between other input parameters and show that in many cases are significant.

3. In [RLP00], the authors *leave open the question of characterizing the interplay between On Demand Routing protocols and MAC protocols.* This paper takes the first step in this direction and considers AODV and DSR (both of which are on demand routing protocols). Our findings show that these protocols exhibit different levels of variations due to MAC protocols.

4. Finally, the paper not only aims to study the effects of MAC layer on routing layer but also studies the effect of routing layer on the MAC layer. The results show that the interaction is both ways: routing layers affect MAC layers and MAC layers affect routing layers.

2.1 Summary of Experiment Specific Results

We first summarize results specific to each experiment. Due to lack of space, we have chosen to elaborate on the Grid mobility model for statistical analysis (Section 5) and have chosen ECR model to discuss model specific empirical results (Section 6). Nevertheless the overall conclusions of the statistical analysis are summarized in Figure 1. Details for the statistical and empirical analysis of the other models can be obtained from the authors.

Experiment 1: Grid mobility model. CSMA and MACA did not perform well. For MACA, this was accompanied with an extreme increase in MAC layer control packets generated. Interaction between MAC and routing layer protocols is quite apparent. Control packets at the routing layer in many cases failed to deliver the route to the source. This was especially apparent at higher speeds and agrees with the earlier experimental studies [DPR00, DP+, BM+98, KV98, RLP00, RS98]. This caused the data packets to spend inordinate amounts of time in the node buffers and their subsequent removal due to time outs. Number of control packets for 802.11 was also extremely high and varied under different routing protocols. Yet it is fair to say that it performed substantially better than CSMA and MACA at low speeds. As for the routing protocols, AODV performed better than DSR, or LAR scheme 1 – demonstrating an advantage of distributed routing (AODV) information handling over centralized (DSR).

Experiment 2: Random waypoint model. This experiment illustrated the difference as measured by response variables between models in which movement of nodes is correlated in some way versus models in which the node movement is by and large random. The temporal variance of individual node degrees and connectivity is quite high. As a result the performance parameters exhibit the worst behavior under this movement model as compared to other movement models. CSMA and MACA performed poorly. Performance of 802.11 depended on the routing protocol used, and performed best with AODV.

Experiment 3: Exponential correlated random model. ECRM represents a mobility model that keeps relative distances of nodes within a group roughly constant. Moreover, the nodal degree and connectivity characteristics of nodes within a group stay roughly the same and this feature positively influences performance. Performance of 802.11 with this model is very good, and performance of MACA shows significant improvement over the random waypoint model. Performance of CSMA is again very poor. The correlated movement of nodes within a group facilitated routing and decreased the number of control packets at the MAC as well as the routing layer.

[3] We are not aware of other such studies in the literature.

1. **Grid Mobility Model**
   (a) **Latency:** Significant 3 way interaction – Routing protocols, Transceiver (node) speeds and the MAC protocols interact significantly.
   (b) **Number of packets received:** Significant 4-way interaction – Routing protocols, Transceiver (node) speed, Injection rate and the MAC protocols interact significantly.
   (c) **Long term Fairness:** 2 kinds of 2-way interactions – Routing protocol/MAC-protocol and MAC-protocol/Injection Rate are significant.
2. **ECRM Mobility Model**
   (a) **Latency:** Significant 3 way interaction – Routing protocols, Transceiver (node) speeds and the MAC protocols interact significantly.
   (b) **Number of packets received:** All 2-way interactions *except* Routing protocol/Injection rate and Routing Protocol/Transceiver Speed are significant.
   (c) **Long term Fairness:** Only Routing protocols and MAC protocols interact. All other interactions are completely insignificant.
3. **Random Waypoint Mobility Model**
   (a) **Latency:** Unlike the first two mobility models, there is no 3-way interaction when latency is used as the response measure. Among 2-way interactions, the only significant ones are MAC protocols/injection rate, Routing protocols/Transceiver speed and Routing protocols/MAC-protocol.
   (b) **Number of packets received: All** 2-way interactions are significant.
   (c) **Long term Fairness:** The only 2-way interactions that are significant are MAC protocol/Injection rate and Routing protocol/MAC protocols.

Figure 1: **Brief Summary of Statistical Results on Interactions Between Various Input Variables.**

2.2 Broad Conclusions and Implications

1. The performance of the network varies widely with varying mobility models, packet injection rates and speeds; and can in fact be characterized as fair to poor depending on the specific situation. No single MAC or routing protocol, as well as, no single MAC/routing protocol combination dominated the other protocols in their respective class across various measures of performance. Nevertheless, in general, it appears that the combination of AODV and 802.11 is typically better than other combination of routing and MAC protocols. This is in agreement with the results of [DPR00, RLP00].

2. MAC layer protocols *interact* with routing layer protocols. This concept which is formalized in Section 3 and 5 implies that in general it is not meaningful to speak about a MAC or a routing protocol in isolation. See Figure 1 for a summary of results on interactions. Such interactions lead to trade-offs between the amount of control packets generated by each layer. More interestingly, the results raise the possibility of improving the performance of a particular MAC layer protocol by using a cleverly designed routing protocol or vice-versa.

3. Routing protocols with distributed knowledge about routes are more suitable for networks with mobility. This is seen by comparing the performance of AODV with DSR or LAR scheme 1. In DSR and LAR scheme 1, information about a computed path is being stored in the route query control packet.

4. MAC layer protocols have varying performance with varying mobility models. It is not only speed that influences the performance but also node degree and connectivity of the dynamic network that affects the protocol performance.

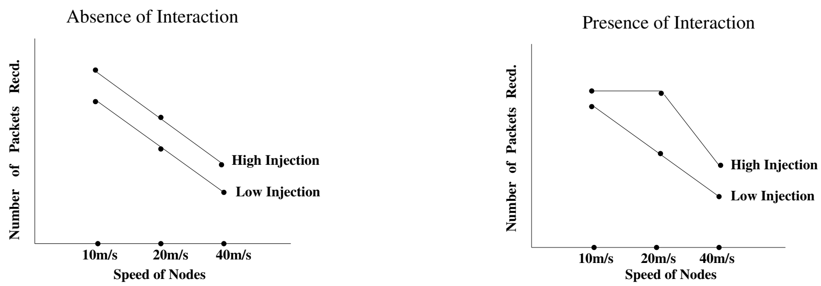

Figure 2: Interaction levels between Injection Rate and Speed of Nodes

3 Characterizing Interaction

An important research question we study is whether the four factors i.e. routing protocol, nodes' speed, MAC protocol and injection rate interact with each other in a significant way. Of particular interest is to characterize the interaction between the MAC and the routing protocols.

Variable Interaction. Statistically, interaction between two factors is said to exist when effect of a factor on the response variable can be modified by another factor in a significant way. Alternatively, in the presence of interaction, the mean differences between the levels of one factor are not constant across levels of the other factor. We illustrate this by a simple example. Suppose we want to know if injection rate and speed of nodes interact in affecting the number of packets received. The dependent or response variable is the *number of packets received*. The Independent variables (factors) are *injection rate and speed of nodes*. The goal is to test if there is interaction between injection rate and speed of nodes.

Our main concern is *not* if the number of packets received differs between different speed levels or whether the number of packets received differs between low and high injection rates. Our main concern is to determine if one injection rate performs relatively better (in terms of number of packets received) than the other for different speed levels. In other words, is there interaction between injection rate and the speed of nodes. If the difference between the mean number of packets received is the same for all speed levels for both injection rates, there is no interaction between injection rate and nodes' speed. Figure 2(a) shows absence of interaction between the injection rate and speed of nodes.

However, if the mean difference in number of packets received for different speed levels is significantly different for high injection rates versus low injection rate, an interaction between injection rate and speed of nodes is said to exist. Figure 2(b) shows the presence of interaction between the injection rate and speed of nodes. Table 1 illustrates the concept via the data collected from our simulations. The first three rows of the table show that the difference between the mean value of packets received at high and low injection rates is very different for the three speed levels. The F-test which is explained later finds this difference to be statistically significant and hence we conclude that speed and injection rates interact when number of packets is used as the response variable. In other words, one cannot explain the variation in number of packets by considering each of these parameters individually; some of the variation is due to the combination of the variables. The second part of Table 1 shows the mean value of latency. The difference in the mean value of latency at high and low injection rates is insignificant according to the F-test at different speed levels which implies that there is no interaction between speed and injection rates when latency is used as the response variable.

Algorithmic Interaction. The interaction discussed above is between two variables and is measured w.r.t. a response variable (e.g. latency). We call this the variable-variable interaction. In the context of communication networks, we also have another kind of interaction – algorithmic interaction. Such an interaction exists between two protocols (algorithms) operating at individual transceiver nodes of a communication network. Here we use the word *interaction* to mean that the behavior (semantics) of a protocol at a given layer in the protocol stack varies significantly due to two different protocols above or below it in the protocol stack. Note that in contrast, speed and injection rates are variables and the value of one remains changed when we change the value of the other. Algorithmic interaction can be more subtle. First, the change in a response variable now is a result of the complicated causal dependencies between the two

Speed	Low Inj	High Inj	Diff in High-Low Inj.
Mean Number of Packets Recd.			
10m/s	28.17	12.52	15.65
20m/s	18.51	8.39	10.12
40m/s	11.12	4.74	6.38
Mean Value of Latency			
10m/s	0.61	0.81	0.20
20m/s	1.21	1.28	0.07
40m/s	2.02	1.91	0.11

Table 1: This table shows the mean value of the response variable for high-low injection rates and different speed of the nodes. The interaction is found to be significant in case of response variable **number of packets received** but insignificant in case of **latency**.

protocols A and B that mutually affect each other. Second, some of the effects of this interaction might be measurable while other effects might not be directly measurable. For instance, in case of routing protocols although the routing paths need not have common nodes, they might cause interaction between two MAC protocols operating at distinct transceivers that are not neighbors as a result of long range effects. These effects can typically be produced through intermediate sequence of routing paths. To make matters more complicated a routing protocol at a given node interacts with a routing protocol at another node. Thus we have interaction between: (i) two routing/MAC protocols running at two distinct and not necessarily adjacent nodes and (ii) a MAC and a routing protocol running at the same or distinct nodes. We illustrate this via our simulation experiments.

Example 1: Consider the following setting illustrated in Figure 3(a). We have shown three paths from 1 to 2 and similarly three paths from 3 to 4. The paths $1-6-2$ and $3-5-4$ are completely non-interfering. Paths $1-x-2$ and $3-x-4$ share the node x and thus clearly interfere. The paths $1-y-2$ and $3-z-4$ are interesting. These paths do not share nodes but influence each other in that y and z cannot simultaneously transmit. This is due to the fact that under the radio propagation model, nodes y and z can not simultaneously transmit. Figure 3 (b) shows a simple grid. We have two connections, both running from left to right. One connection is at the top of the grid and the other connection is at the bottom of the grid. (A) An example of a situation when the routing protocol found the shortest path. Thus, there was no interaction between the two paths shown with the actual hops. The MAC layer transmitted 1,000 packets per connection and the latency was 0.017s. (B) Illustrates a situation when the routing protocol found a route that is really bad. The packets received were 2 for the upper connection and 993 for the lower connection. The latency was 0.17s for the upper connection and 0.014s for the lower connection. (C) This shows situation that lies in between the previous two situations. Packets received for the upper and lower connections were 425 and 983 respectively. The latency for the upper connection was 0.028 seconds and for the lower connection 0.0175 seconds.

Example 2: We show the interaction between MAC and routing layer. The interaction is measured by the variation in the number of control packets generated by each layer. We used two routing protocols: AODV and DSR. The MAC protocols used were MACA and 802.11. Interestingly, quantifying CSMA interaction is somewhat harder to measure since it does not generate any control packets per se. We could have used the number of back-offs as a proxy variable though. For illustrative purposes, the experiments were done on a *static grid*. This is done since it allows us to show a spatial distribution of control packets and thus argue about long range interactions. The network is shown in Figure 3(c). There is a transmitter at each grid point and each transmitter has the same range. Figure shows the range for one of the transmitter via a dotted quarter circle. There are two connections. The first connection starts at node $(1, 0)$ and ends at node $(1, 6)$. The second connection starts at node $(5, 0)$ and ends at node $(5, 6)$. We consider four combinations obtained by using MACA and 802.11 as MAC protocols and AODV and DSR as routing protocols. Figure 4 shows two different types of plots one for each combination (8 plots in total). The quantities plotted are: (i) distribution of MAC overhead packets and (ii) distribution of Routing overhead packets. From the figures it is clear that the different combination yield different levels of overhead. This phenomenon becomes more pronounced in the presence of mobility; the aim of the exmaple is to explain the basic idea. We have also plotted a spatial distribution of these control packets depicting the control packets produced at each node. Figure 5 shows examples of MAC/routing overhead for three different (MAC, Routing) protocol combination. The square grid is represented in the (X, Y)-plane and the the height of the bars denotes the average number of MAC/Routing control packets generated over 10 runs at each transceiver. Interestingly, as the figures show, the routing protocol tries to discover non-interferring paths. The other plots are omitted due to lack of space and can be obtained from the authors. The results clearly demonstrate protocol level interaction. They also show that the spatial distribution of the overhead packets vary; this aspect is harder to demonstrate for dynamic networks. This includes the number of overhead packets and the paths used to move the packets.

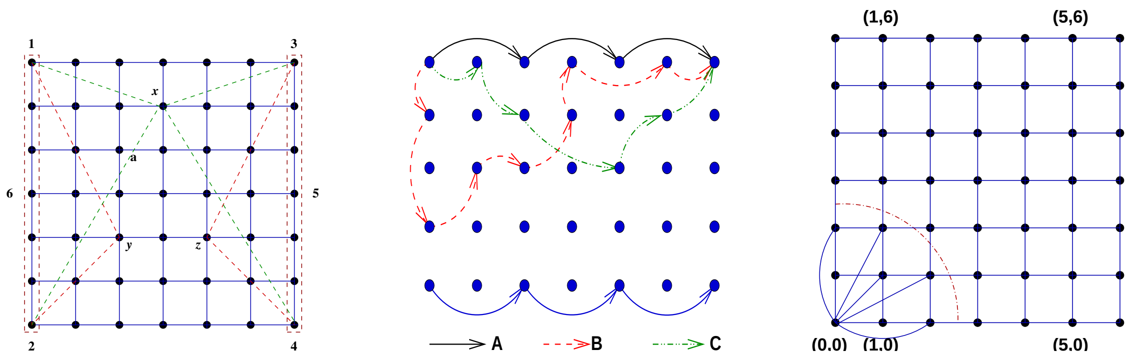

Figure 3: (a) and (b): Illustration of Example 1. (a) Illustrating schematically the effect of routing paths on MAC layer protocols. (b) Figure illustrating the different paths used by a routing protocol. (c) Set up for Experiment 2. The first figure schematically illustrates the connectivity of the graph. For clarity only the edges incident on the node $(0, 0)$ are shown. The dotted arc shows the transceiver's radio range.

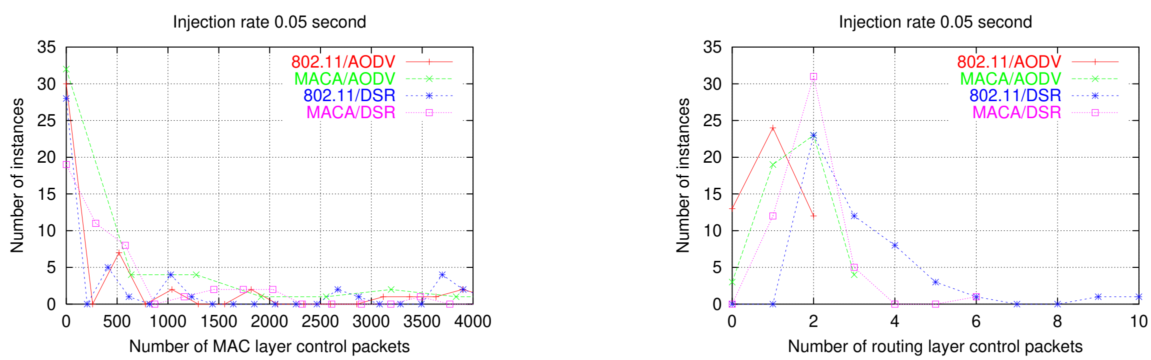

Figure 4: Figure showing the MAC and routing overhead packet distribution for Example 2. The network is as shown in Figure 3 (c). Each figure consists of four plots: one for each MAC/routing protocol combination. The left plot shows the MAC overhead packet distribution, the right plot shows the routing overhead packet distribution.

The results show that the routing protocol can significantly affect the MAC layer protocols and vice-versa. The paths taken by the routing protocol, induce a virtual network by exciting the MAC protocols at particular nodes. Conversely, contention at the MAC layer can cause a routing protocol to respond by initiating new route queries and routing table updates. Combined with the results of [KKB00, RLP00], our results show that discussion about the performance of a MAC or a routing layer cannot typically be carried out without putting it in context of the other protocols in the stack. Moreover given the randomized nature of the protocols and constant movement of transceivers in an ad-hoc environment makes the problem of engineering these protocols significantly harder.

4 Experimental Setup

We first describe the details of the parameters used. The overview of the parameters can be found in Figure 6.

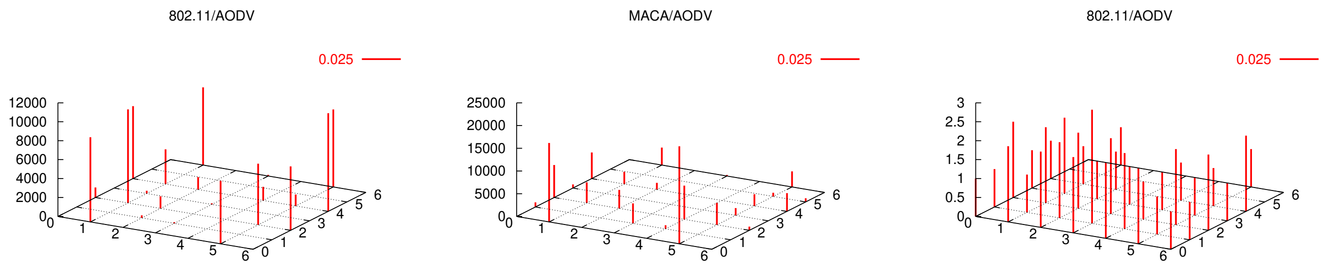

Figure 5: Figure showing the spatial distribution of the control overhead for Example 2. The network is as shown in Figure 3 (c). All the plots are for injection rate of 0.025 seconds. Left: Results for MAC layer overhead for (802.11,AODV). Center: Results for MAC layer overhead for (MACA,AODV) combination. Although the number of MAC overhead packets appears low, it is because the percentage of packets delivered using this combination is substatially lower than what is delivered using (802.11,AODV) combination. Right: Results for Routing layer overhead for (802.11, AODV) combination.

4.1 Measures of Performance

The independent (input) variables are the routing protocol, MAC protocol, nodes' speed and the injection interval for the packets. The following five pieces of information (also called the dependent variable) were collected: (i) Latency: Average end to end delay for each packet as measured in seconds, (ii) Total number of packets received, (iii) Throughput in bits/second, (iv) Adjusted number of control packets at MAC layer level per 1,000 data packets.[4] (v) Total number of control packets at routing layer level.

4.2 Measuring average Latency, Throughput and Fairness

Apart from latency and packets received that are plotted for each connection (recall for most part we deal with two connections), we also report the average behavior of the protocols. We briefly describe the method used to calculate this. Average throughput and average latency is simply the average over 20 runs of each protocol over the two connections (10 for each connection). For fairness, let $r = p_1/p_2$ denote the ratio of packets received for a given run of the protocol for the two connections. Then $|r-1|$ denotes the deviation of the protocol from perfectly equitable allocation.[5] Average fairness is $\sum_{i=1}^{i=10} r_i$, where r_i is the above stated ratio for the ith run of the protocol.

4.3 Mobility Models

Grid Mobility Model: The setup of this experiment is a grid network of 7×7 nodes. The grid unit is 100 meters. There are 49 nodes that are positioned on the grid. See Figure 7(a). The mobility model follows movement in an area with grid architecture, i.e., nodes at (i, j) move only to one of the 8 adjacent grid sites. If a node reaches a boundary, it is reflected back and continues to move with the same speed. Let the node IDs range from 0 to 48; the IDs are assigned row wise starting from the top and from left to right.

The movement of the nodes is described quite simply. Let $0 \leq k \leq 48$. Nodes belonging to the equivalence class $0 \equiv k (\bmod 4)$ start moving to the South, nodes belonging to the class $1 \equiv k (\bmod 4)$ start moving to the North, nodes belonging to the class $2 \equiv k (\bmod 4)$ start moving to the East and nodes belonging to the class $3 \equiv k (\bmod 4)$ start moving to the West. When a node reaches the end of the grid, movement of the node is reversed. This is essentially reflecting the boundary condition as opposed to periodic boundary condition used in many other contexts. We run the simulation with three different node speeds: 10 m/s, 20 m/s, 40 m/s.

[4] We adjusted the number of control packets at the MAC layer level to the number of data packets injected. This means that the number of control packets was divided by a factor of two at the injection rate of 0.05 second, by a factor of four at the injection rate of 0.025 second, and by a factor of eight at the injection rate of 0.0125 second.

[5] We take the absolute value since the ratio could be greater than or less than 1 depending on which particular connection got more resources.

1. **Network Topology:** We describe the experiment specific topologies in respective sections.
2. **Number of connections:** We use two connections.
3. **Routing protocols** : AODV, DSR, LAR scheme 1.
4. Movement of nodes at 10 m/s, 20 m/s, 40 m/s.
5. The initial packet size was 256 bytes, the initial number of packets was 2,000, and the initial injection interval was 0.05 second. Each time the injection interval was reduced by a factor of 2, we also reduced the packet size by a factor of 2 but increased the number of packets by a factor of 2. For example, if the injection interval was halved to 0.025 seconds then the new packet size was 128 bytes and the new number of packets was 4,000. This allowed us to keep the injection at input nodes constant in terms of bits per second.
6. The bandwidth for each channel was set to 1Mbit. Other radio propagation model details are as follows: (i) Propagation path-loss model: two ray (ii) Channel bandwidth: 1 Mb (iii) Channel frequency: 2.4 GHz (iv) Topography: Line-of-sight (v) Radio type: Accnoise (vi) Network protocol: IP (vii) Connection type: TCP
7. **Simulator used:** GlomoSim.
8. The transmission range of transceiver was 250 meters.
9. The simulation time was 100 seconds.
10. Hardware used in all cases was a Linux PC with 512MB of RAM memory, and Pentium III 500MHz microprocessor.

Figure 6: Parameters used in the Experiments.

Random Waypoint model: The setup of this experiment is again a grid network of 7×7 nodes. The grid unit is 100 meters. There are 49 nodes (numbered 0 to 48) that are positioned on the grid. In this model nodes move from the current position to a new randomly generated position at a predetermined speed. After reaching the new destination a new random position is computed. There are no stop-overs, i.e., nodes start moving immediately to a new destination. This setup is depicted in Figure 7(b).

ECRM Model: The setup of this experiment is an area of 600×600 meters onto which we uniformly randomly position 49 nodes. Let the nodes be numbered from 0 to 48 in the order they are positioned onto the grid. We divide the nodes into four groups. Nodes belonging to the class $0 \equiv k \pmod 4$ form the first group, nodes belonging to the class $1 \equiv k \pmod 4$ form the second group, nodes belonging to the class $2 \equiv k \pmod 4$ form the third group, and nodes belonging to the class $3 \equiv k \pmod 4$ form the fourth group. The setup is shown in Figure 7(c). The four groups follow the exponential correlated random model described by an equation of the form $\mathbf{x}(t+1) = \mathbf{x}(t)e^{(-1/\tau)} + s \cdot \sigma \cdot r \cdot \sqrt{1 - e^{(-2/\tau)}}$ where: (i) $\mathbf{x}(t)$ is the position (r, α) of a group at time t, (ii) τ is a time constant that regulates the rate of change, (iii) σ is the variance that regulates the variance of change, (iv) s is the velocity of the group, and (v) r is gaussian random variable. Let γ_i be the orientation of the velocity vector s for the i-th group. The orientation is assigned as follows: the first group - south, the second group - north, the third group - east, the fourth group - west. Should a node reach boundaries of the area its orientation is reversed. After all nodes' orientation is reversed, the group starts moving to the opposite direction.

5 Statistical Analysis

We set up a statistical experiment to evaluate the performance of the following four factors; the MAC protocol, routing protocol, the injection rate and the speed at which the nodes are moving in the network. Each of these four factors (variables) have three levels (values the variables take). The variables and their levels are given in Section 2.

In our analysis, we analyze, if the four factors, interact in their effect on the performance measure. We perform three different analysis, one for each performance measure to observe the interaction among factors. We perform a different set of experiments for each of the mobility models. Our general implications are summarized in Figure 1.

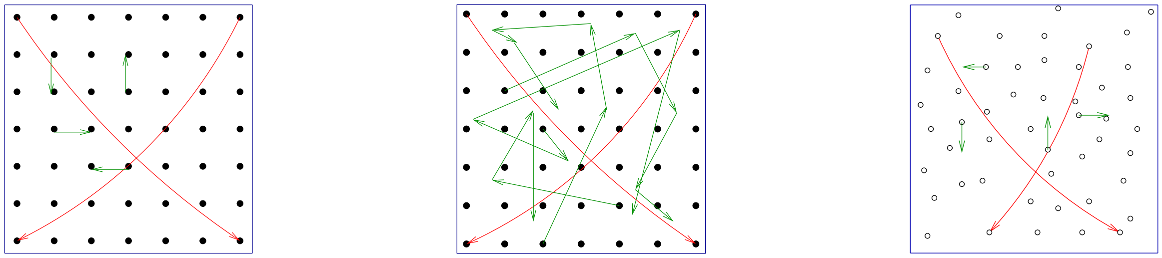

Figure 7: (a) Grid mobility and (b) Random Waypoint Models. We position 49 nodes onto a 7×7 grid. The nodes are numbered from the top left corner in rowwise order. The figure gives an example for four chosen nodes. Movement for other nodes is not shown. There are two connections: the first one from the top left corner to the bottom right corner, and the second one from the top right corner to the bottom left corner. (c) Exponential correlated random mobility. We position 49 nodes uniformly onto a 600×600 meters area. The nodes are numbered in the order their random position is computed. The start movement depends on assignment of the four groups.

5.1 Experimental Setup for the Statistical Analysis

Each set of experiment utilizes three different combinations of MAC, router, injection rate and the speed; thus yielding $3^4 = 81$ different scenarios. Our performance matrix consists of three measures i.e. latency, number of packets received and the long term fairness.

Approach: We first construct a matrix of 4 dummy variables. For each factor we create a dummy variable. This variable takes a value 1, 2 and 3 for the three levels of the factor. For example, the dummy variable for MAC protocol, takes a value 1 whenever 802.11 is being used to calculate the performance matrix, value 2 whenever CSMA protocol is being used and value 3 whenever MACA is being used to calculate the performance matrix. For the router variable, the dummy takes a value of 1 whenever AODV protocol is being used and value 2 whenever DSR is being used and value 3 whenever LAR1 is being used to calculate the performance matrix. Similar dummies are created for the injection rate and the speed variables. To detect interactions between the factors, we use a statistical technique known as the *analysis of variance* (ANOVA).[6] ANOVA is used to study the sources of variation, importance of different factors and their interrelations. It is a useful technique for explaining the cause of variation in response variable when different factors are used. The statistical details discussed below are routine and are provided for the convenience of the reader. For more details on the techniques used in this analysis, refer to [GH96, Ron90]. Given that we have four factors, we use a four factor ANOVA.

Mathematical Model: The appropriate mathematical model for a four factor ANOVA is as follows:

$$y_{ijklm} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\alpha\delta)_{il} + (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\gamma\delta)_{kl}$$
$$+(\alpha\beta\gamma)_{ijk} + (\alpha\beta\delta)_{ijl} + (\alpha\gamma\delta)_{ikl} + (\beta\gamma\delta)_{jkl} + (\alpha\beta\gamma\delta)_{ijkl} + \varepsilon_{ijklm}$$

where

1. y_{ijklm} is the measurement of the performance variable (e.g. latency) for the i^{th} routing protocol, j^{th} speed, k^{th} MAC protocol and l^{th} injection rate.

2. m is the number of runs/samples which is 20 in our experiment.

3. α_i is the effect of routing protocol, β_j is the effect of the speed of nodes, γ_k is the effect of the MAC protocol and δ_l is the effect of the injection rate on the performance measures.

4. The **two way interaction terms** measure the interaction present between pairs of variables (x, y) and are as follows:

   (a) $(\alpha\beta)_{ij}$: (routing protocol, speed of the nodes);

[6] ANOVA is a linear model. There are alternatives available to ANOVA which can handle much more complex statistical problems. **Bayesian inference Using Gibbs Sampling** is one such nono-linear method which performs Bayesian analysis of complex statistical models using Markov chain Monte Carlo (MCMC) methods. ANOVA suffices for the purposes of the conclusions that we aim at drawing in this paper.

(b) $(\alpha\gamma)_{ik}$: (routing protocol, MAC protocol);
(c) $(\alpha\delta)_{il}$: (routing protocol, injection rates);
(d) $(\beta\gamma)_{jk}$, (nodes' speed, MAC protocol);
(e) $(\beta\delta)_{jl}$: (nodes' speed, injection rates);
(f) $(\gamma\delta)_{kl}$, (MAC protocols, injection rate).

5. The **three way interaction terms** measure the interaction present between triples of variables (x, y, z) and are as follows:
   (a) $(\alpha\beta\gamma)_{ijk}$: (routing protocol, nodes' speed, MAC protocol);
   (b) $(\alpha\beta\delta)_{ijl}$: (routing protocol, nodes' speed, injection rates);
   (c) $(\alpha\gamma\delta)_{ikl}$: (routing protocol, MAC protocol, injection rates);
   (d) $(\beta\gamma\delta)_{jkl}$: (nodes' speed, MAC protocol, injection rates).
6. The **four way interaction term** $(\alpha\beta\gamma\delta)_{ijkl}$ measures the four way interaction: (routing protocol, nodes' speed, MAC protocol, injection rate).
7. Finally, ε_{ijklm} is the random error.

A scenario is a particular combination of MAC protocol, routing protocol, nodes' speed and injection rate. For example, CSMA, AODV, 10m/s and low injection rate would form one scenario. For each scenario we generate 20 runs/samples for the analysis.

Model Selection and Interpretation: The model selection method considered here is called the *stepwise method.* This method assumes an initial model and then adds or deletes terms based on their significance to arrive at the final model. *Forward selection* is a technique in which terms are added to an initial small model and *backward elimination* is a technique in which terms are deleted from an initial large model. Our analysis uses the method of *backward elimination* where each term is checked for significance and eliminated if found to be insignificant. Our initial model is the largest possible model which contains all the four factor effects. We then eliminate terms from the initial model to eventually find the smallest model that fits the data. The reason for trying to find the smallest possible model is to eliminate factors and terms that are not important in explaining the response variable. After eliminating redundant factors, it becomes simpler to explain the response variable with the remaining factors. The smaller models can normally provide more powerful interpretations

To test four way interaction between the MAC, routing protocol, nodes' speed and injection rates in effecting the response variable, we perform the four factor ANOVA using the above mathematical model. This is also called the *full/saturated* model since it contains all 1-way, 2-way, 3-way and 4-way interactions. After running this model, we calculate the residual sum of squares[7] and refer it by $SS(14)$, which stands for residual sum of squares for model number 14. The degrees of freedom[8] is referred by $DF(14)$. Now we drop the 4-way interaction term i.e. $(\alpha\beta\gamma\delta)_{ijkl}$ and rerun the ANOVA model. The resultant model has now only have 1-way, 2-way and 3-way interaction terms. From this model, we can calculate the residual sum of squares for model 13, i.e. $SS(13)$ and degrees of freedom for model 13, $DF(13)$. We now compare model 14 with model 13 to find out if the 4-way interaction is significant. If the F-statistic turns out to be insignificant, we can say that 3-way interaction model i.e. model number 13 can explain the response variable as well as model 14. This implies that model 14 can be dropped off without loosing any information. Next we test for each term in model 13 and check which ones are significant. Any term that is not important in affecting the response variable can then be dropped off. This is achieved by dropping each 3-way term one at a time and then comparing the resulting model with model 13. In our tables, model 9 to 12 are being compared with model number 13. If the F-statistic is significant after dropping off the term, it implies that the term that was dropped off played a significant role and hence should not have been dropped. After checking 3-way interactions, we compare *all 2-way* interaction model (model 8) with *all 3-way* interaction model to see if there is a smaller model that can fit the data as well as the 3-way interaction model. Just like the 3-way model, we then drop off one term at a time from model 8 and compare the new models with model 8 to find out which of the 2-way interactions are most significant; in the

[7] For a regression model, $Y_i = \alpha + \beta X_i + e_i$, the residual are $e_i = Y_i - \alpha - \beta X_i$ and the residual sum of squares is $\sum_i (e_i)^2 = \sum_i (Y_i - \alpha - \beta X_i)^2$

[8] The number of independent pieces of information that go into the estimate of a parameter is called the degrees of freedom.

Response Variable			Latency			Num. of Packets Recd.			Fairness		
No.	Interaction	Source	SS	DF	F-**test**	SS	DF	F-**test**	SS	DF	F-**test**
1	All 1-way	$[R][S][M][I]$	87879	1611	7.01^*	354609	1611	92.28^*	7.3×10^7	801	3.35^*
2	2-way	$[RS][RM][RI][SM][SI]$	80071	1591	2.9	283870	1591	347.24^*	6.8×10^7	781	4.63^*
3	2-way	$[RS][RM][RI][SM][MI]$	79705	1591	1.07	166571	1591	4.87^*	6.7×10^7	781	2.47
4	2-way	$[RS][RM][RI][SI][MI]$	82480	1591	14.98^*	189797	1591	72.66^*	6.7×10^7	781	2.34
5	2-way	$[RS][RM][SM][SI][MI]$	79541	1591	0.24	172840	1591	23.16^*	6.6×10^7	781	0.60
6	2-way	$[RS][RI][SM][SI][MI]$	83689	1591	21.05^*	199212	1591	100.14^*	6.9×10^7	781	8.80^*
7	2-way	$[RM][RI][SM][SI][MI]$	79857	1591	1.83	166835	1591	5.64^*	6.6×10^7	781	1.29
8	All 2-way	$[RS][RM][RI][SM][SI][MI]$	79492	1587	1.41	164903	1587	9.69^*	6.6×10^7	777	1.06
9	3-way	$[RSM][RSI][RMI]$	77310	1563	0.17	156619	1563	26.67^*	6.3×10^7	753	0.62
10	3-way	$[RSM][RSI][SMI]$	77512	1563	0.68	140957	1563	3.81^*	6.3×10^7	753	0.64
11	3-way	$[RSM][RMI][SMI]$	77377	1563	0.34	141359	1563	4.40^*	6.4×10^7	753	1.06
12	3-way	$[RSI][RMI][SMI]$	79012	1563	4.44^*	140992	1563	3.86^*	6.4×10^7	753	1.93
13	All 3-way	$[RSM][RSI][RMI][SMI]$	77240	1555	0.65	138342	1555	4.76^*	6.3×10^7	745	0.80
14	All 4-way	$[RSMI]$	76718	1539		131816	1539		6.2×10^7	729	

Table 2: ***(Experiment 1), Grid Mobility Model:*** This table shows results of four-factor ANOVA where the factors are the routing protocol, nodes' speed, MAC protocol and the injection rate. The *response variables or the performance measures are the* latency, number of packets received and long term fairness. Note that the degrees of freedom for the fairness measure is smaller than the other two measures. This is due to the fact that the long term fairness is calculated by taking the ratio of packets received for the two connections. Hence 20 runs/samples lead to only 10 actual measurements for fairness. $*$ shows that the F-test is significant at 99% confidence level.

tables, model 2-7 are being compared with model 8. We continue with the elimination process till we find the smallest possible model that explains the data.

The sum of squares, degrees of freedom and the F-*test* value for each of the models is shown in the Table 2. Interaction column shows which interactions are included in the model. Finally the F-*test* is calculated using the following statistic:

$$F = \frac{SS(a) - SS(b)/DF(a) - DF(b)}{SS_{full}/DF_{full}}$$

where $SS(a)$ is the sum of squares residuals for model a and $SS(b)$ is the sum of squares residuals for model b. Similarly $DF(a)$ is the degrees of freedom for model a and $DF(b)$ is the degrees of freedom for model b. The SS_{full} is the sum of squares residuals for the full model (largest model) i.e. the model with all the four interaction terms. DF_{full} is the degrees of freedom for the full model.

5.2 Grid Mobility Model Results (Experiment 1)

Performance measure: Latency. In Table 2, we show the results for the Grid Mobility model using latency as the performance measure. We start with an initial model with all the 4-way interactions and compare it with all 3-way interactions model. Model 14 is being compared with model 13. The F-statistic of 0.65 shows that the model 13 fits the data as well as model 14 so the four way interaction is not significant in affecting the latency measure. Similarly, we try to find all significant 3-way interactions by dropping each 3-way term one at a time. Looking at the F-test results of model numbers 9 to 12, we find model 12 to be the most significant. From that we conclude that the router, nodes' speed and the MAC protocol interact most significantly. Note that this was the combination that were dropped off from model 12. To find out if there is a smaller model that can fit the data as well as the 3-way interaction model, we further look at the 2-way interaction models. The F-test values conclude that the most significant interaction is between the router and MAC. The other most significant 2-way interaction is between nodes' speed and MAC. The rest are all insignificant. This shows that the 3-way interaction between the router, nodes' speed and the MAC are due to the 2-way interaction between router-MAC and speed-MAC. There is no interaction between router and nodes' speed as far as the effect on latency is concerned. Now we create a model with only the 2-way significant interaction terms and compare it with a model containing only the 3-way significant terms to find the smallest model that fits the data. If the F-test for these two models turns out to be significant, we conclude that these 3-way interactions cannot be explained by the 2-way model and hence cannot be dropped off. Our results find that to be true, implying that indeed the smallest possible model, is the 3-way [RSM] model.

Performance measure: Number of packets received. Columns 7, 8 and 9 in Table 2 show the ANOVA results for the response variable "packets received". The interpretation of the results is similar to the response variable "latency". The interaction results show significant 4-way interaction between the router, nodes' speed, MAC and the injection rate in explaining the number of packets received. The 4-way interaction automatically implies that there must be significant 2-way and 3-way interactions present too, although it does not imply that all smaller models will be significant. A closer look in our case, however shows that all smaller models with 3-way and 2-way interaction are significant. Among the 2-way interactions, F-test shows that the MAC and injection rates interact most significantly. The router and the MAC also interact very significantly. In 3-way interaction, it is the router, MAC and injection rate that interact most significantly. The 3-way interaction results are consistent with the 2-way results because they all point to interaction between router, speed and the injection rate in affecting the number of packets received. In this case, the smallest model has all four factors $[RSMI]$ interacting significantly.

Performance measure: Long Term Fairness. The last three columns of Table 2 shows the ANOVA results for various models using long term fairness as the performance measure. The initial setup for a four way interaction effect of the factors on the fairness measure is done as explained before. The only exception is that now we have 10 runs instead of 20 for each of the 81 scenarios mentioned above.[9] The results show that both 4-way and 3-way interactions are insignificant in affecting the fairness. Looking at the results of 2-way interactions between the factors, we find that the router and MAC protocol interact in the most significant way in affecting the fairness. The interaction between the MAC and injection rate is also significant but not to the extent of router and MAC interaction. In this case, the smallest model has only $[RM][MI]$ 2-way interaction terms.

Due to lack of space, it is not possible to show the details of the statistical tests on ECR and the random waypoint mobility model. Statistical results for the other two models can be obtained from the authors upon request. However, the summary of the results for all the three mobility models is shown in Figure 1.

6 Specific Results for ECR Model

We briefly explain specific results for one mobility model. We have chosen ECR model since we have already discussed some aspects of grid mobility model in the previous section. Due to lack of space the details on the other mobility models are omitted here but can be obtained from the authors.

ECRM represents a mobility model that keeps the relative distances of nodes within a group roughly constant. Let G_i be the i-th group in our setting, and let S_i be the set of nodes that belong to the group G_i. Then any two nodes $a, b \in S_i$ that have a common edge (a, b) at time t will also have a common edge with high probability, at time $t + k$, $k = \langle 0, ST\rangle$, ST is the simulation time. This fact facilitates routing and there are lower requirements on the MAC layer protocols as well. Interaction among the four groups influences the behavior to a much bigger extent.

We make the following observations. Many of these observations tend to agree with the conclusions in [DPR00, RLP00] qualitatively.

- CSMA and MACA do not perform well at all. Both CSMA and MACA are able to deliver no more than 20% of the total packets, the percentage drops with increased speeds and injection rates. In addition, MACA also produces huge number of MAC level control packets. They range between 70,000 and 100,000. This makes the behavior of MACA much less acceptable than CSMA.

- Our results show that in general the performance of the system falls significantly with increased speed for all MAC protocols. However (802.11,AODV) is still able to deliver 50% of the packets at high speeds (40 m/s) and injection rates (0.0125s).

- Figure 8(c) depicts the distribution of node degrees at three distinct times in the simulation. The node degrees do show a variation, but within limits. This allows routing and MAC protocols to perform much better than when the transceivers move using the random waypoint model.

- Figures 8(a) and (b) show the distributions of MAC and Routing level control packets for three different combinations. Due to the discussion above, the MAC layer protocol considered is always 802.11. The routing layer protocols used are AODV, DSR and LAR1 respectively.

[9] This is due to the fact that fairness measure is calculated by taking a ratio of the number of packets received for the two connections.

- Figrues 9(a), (b) and (c) show the performance of protocols in terms of three response variables; Latency, % packets received and long term fairness. The results make an interesting point: in contrast to recent efforts to improve the fairness of MAC protocols [LNB98], the results show that routing layer can make a considerable impact on the fairness characteristics of these protocols.

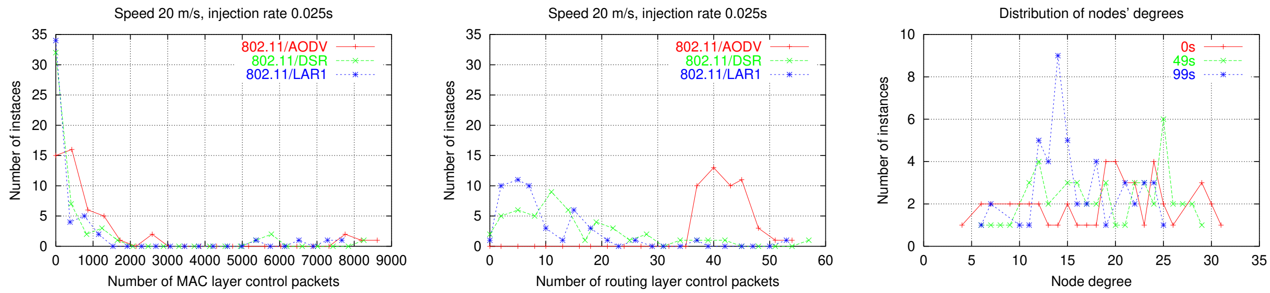

Figure 8: **(ECR mobility, 802.11, and AODV, DSR, LAR scheme 1.)** From left: (a) Distribution of MAC layer control packets, (b) Distribution of routing layer control packets, (c) Distribution of node degrees at three different simulation times.

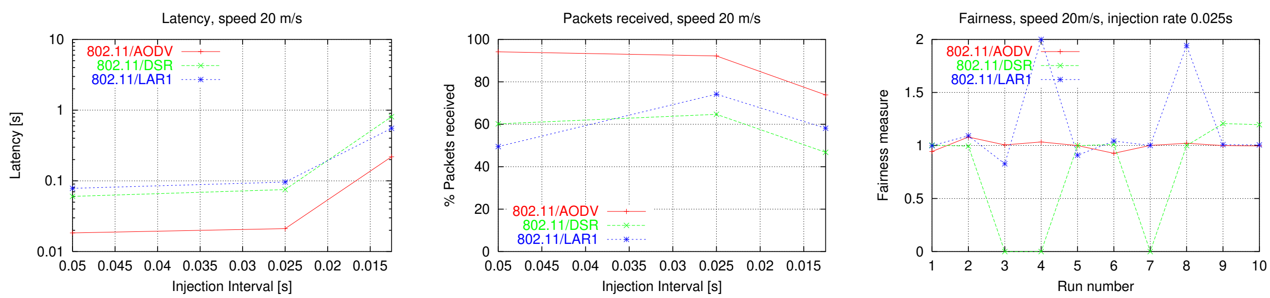

Figure 9: **(ECR mobility, 802.11, and AODV, DSR, LAR scheme 1.)** From left: (a) Latency, (b) Packets received, (c) Long term Fairness. The figures show the average simulation run with different seeds.

7 Concluding Remarks and Future Directions

We characterized the performance and interaction of well known Routing and MAC protocols in an ad-hoc network setting. Our results and those in [BS+97] on the design of snoop protocols suggest that optimizing the performance of the communication network by optimizing the performance of individual layers is not likely to work beyond a certain point. We need to *treat the entire stack as a single algorithmic construct* in order to improve the performance. The statistical analysis method used in this paper suggests an engineering approach to choose the right protocol combination for a given situation. Specifically, the analysis combined with the concept of recommendation systems can be used as an automated method for tuning and choosing a protocol combination if the network and traffic characteristics are known in advance. We are currently in the process of building such a kernel.

Another implication of the work is to design new dynamically adaptive protocols that can adapt to changing network and traffic characteristics in order to efficiently deliver information. Moreover, evaluation of such protocols as discussed above needs to be done in totality. For instance when we say overhead it should include both MAC and routing overhead (in fact should also include transport layer overhead but is beyond the scope of the current paper). Also, in order to draw meaningful and robust conclusions from the results of such complex experiments, it is almost essential to use statistical tools which are used extensively by other researchers in similar situations. As a next step, we plan to undertake a more comprehensive experimental study involving in addition to the MAC and routing protocols, various Transport protocols.

References

[802.11] Wireless LAN Medium Access Control (MAC) and Physical (PHY) Layer Specification. IEEE Standard 802.11, IEEE, June 1999.

[Ba98] H. Balakrishnan. Challenges in Reliable Data Transport Over Heterogeneous Wireless Networks. Ph.D. Thesis, Department of Computer Science, University of California at Berkeley, 1998.

[BCSW98] S. Basagni, I. Chlamtac, V. Syrotiuk, and B. Wood. A Distance Routing Effect Algorithm for Mobility (DREAM). *ACM/IEEE International Conference on Mobile Computing and Communication (MOBICIM98)*, pp. 76–84, 1998.

[BS+97] H. Balakrishnan, S. Seshan, E. Amir, R. Katz. Improving TCP/IP Performance over Wireless Networks. *Proc. 1st ACM Conf. on Mobile Computing and Networking*, Berkeley, CA, November 1995.

[BD+94] V. Bharghavan and A. Demers and S.Shenker and L. Zhang. MACAW: A Media Access Protocol for Wireless LANs. *Proc. 1994 SIGCOMM Conference,* London, UK, pages 212–225, 1994. citeseer.nj.nec.com/bharghavan94macaw.html

[BM+98] J. Broch, D. Maltz, D. Johnson, Y. Hu, and J. Jetcheva. Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols. *Proc. 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking,* ACM, Dallas, TX, October 1998.

[BT+99] L. Bajaj, M. Takai, R. Ahuja, K. Tang, R. Bagrodia, and M. Gerla. GloMoSim: A Scalable Network Simulation Environment. UCLA Computer Science Department Technical Report 990027, May 1999.

[DPR00] S. Das, C. Perkins, and E. Royer. Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks. *Proc. IEEE Conference on Computer Communications (INFOCOM),* Tel Aviv, Israel, March 2000, pp. 3-12.

[DP+] S. R. Das, C. E. Perkins, E. M. Royer and M. K. Marina. Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks. To appear in *IEEE Personal Communications Magazine, special issue on Mobile Ad Hoc Networks*, Feb 2001.

[GH96] G. Glass and K. D. Hopkins. *Statistical Methods in Education and Psychology*, 3rd ed., Allyn and Bacon, 1996.

[HG+99] X. Hong, G. P. M. Gerla, and C. Chiang. A group mobility model for -ad-hoc wireless networks. *2nd ACM International Workshop on Modeling and Simulation of Wireless and Mobile Systems (MSWiM'99)*, p.8, Aug. 1999.

[JM96] D. Johnson and D. Maltz. Dynamic Source Routing in Ad Hoc Wireless Networks. *Mobile Computing*, Tomasz Imielinski and Hank Korth, Eds. Chapter 5, pages 153-181, Kluwer Academic Publishers, 1996.

[JL+00] P. Johansson, T. Larsson, N. Hedman and B. Mielczarek. Routing Protocols for Mobile Ad hoc Networks: A Comparative Performance Analysis. *Proc. 5th ACM International Conf. on Mobile Computing and Networks, (MOBICOM),* pp. 195-206, 1999.

[Ka90] P. Karn. MACA - a new channel access method for packet radio. MACA - a new channel access method for packet radio ARRL/CRRL Amateur Radio 9th Computer Networking Conference 1990

[KKB00] C. Koksal, H. Kassab, and Hari Balakrishnan An Analysis of Short-Term Fairness in Wireless Media Access Protocols. *Proc. ACM SIGMETRICS*, June 2000. MIT-LCS-TR-807, May 2000.

[KV98] Y. Ko and N. Vaidya. Location-Aided Routing(LAR) in Mobile Ad Hoc Networks. *4th Annual International Conference on Mobile Computing and Networking (MOBICOM'98)*, October, 1998.

[LNB98] S. Lu, T. Nandagopal, and V. Bharghavan. A Wireless Fair Service Algorithm for Packet Cellular Networks. *ACM Mobicom'98*, Dallas, TX. October 1998.

[NZD99] A. Nasipuri, J. Zhuang and S. R. Das. A Multichannel CSMA MAC Protocol for Multihop Wireless Networks. *Proc. IEEE Wireless Communications and Networking Conference (WCNC),* Sept., 1999.

[OP] B. O'Hara and A. Petrick *802.11 Handbook, A Designer's Companion.* IEEE Press, 1999.

[PR99] C. E. Perkins and E. M. Royer. Ad-hoc On-Demand Distance Vector Routing. *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, pp. 90–100, New Orleans, LA, February 1999.

[RLP00] E. Royer, S. Lee and C. Perkins. The Effects of MAC Protocols on Ad hoc Network Communications. *Proc. IEEE Wireless Communications and Networking Conference,* Chicago, IL, September 2000.

[Ron90] R. Christensen. *Log-linear Models*, Springer Verlag, Chapter 4, 1990.

[RS96] S. Ramanathan and M. Steenstrup, A survey of routing techniques for mobile communication networks, *Mobile Networks and Applications*, 1-2, pp. 89-104, 1996.

[RS98] S. Ramanathan and M. Steenstrup, Hierarchically-organized, multihop mobile networks for multimedia support, *ACM/Baltzer Mobile Networks and Applications*, Vol. 3, No. 1, pp 101-119, 1998.

[Ra96] T.S. Rappaport. *Wireless Communications.* Prentice-Hall, 1996.

[WS+97] J. Weinmiller, M. Schlager, A. Festag and A. Wolisz Performance Study of Access Control in Wireless LANs - IEEE 802.11 DFWMAC and ETSI RES 10 Hiperlan. *Mobile Networks and Applications*, pp. 55-67, 2, (1997).

[ZD97] M. Zonoozi and P. Dassanayake. User mobility modeling and characterization of mobility patterns. *IEEE Trans. on Selected Areas in Communications*, pp. 1239–1252, Sept. 1997.