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

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## ABSTRACT

We empirically study the effect of mobility and interaction between various input parameters 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 various quality of service measures including (i) latency, (ii) throughput, (iii) number of packets received and (iv) long term fairness. Three different commonly studied routing protocols are used: AODV, DSR and LAR scheme 1. 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* between the above stated parameters. Such methods allow us to analyze complicated experiments with large input space in a systematic manner. From our results, we conclude the following:

- No single MAC or routing protocol dominated the other protocols in their class. More interestingly, no MAC/routing protocol combination was better than other combinations over all mobility models 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.

## Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*; I.6.6 [**Simulation and Modeling**]: Simulation Output Analysis; C.2.0 [**Computer-Communication Networks**]: General—*Data communications*

## General Terms

Performance, Design, Experimentation

## Keywords

Ad Hoc Networks, Performance Analysis, Statistical Analysis

## 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, adhoc 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 [25, 2].) As adhoc networks lack fixed infrastructure in the form of base stations,

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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 [18]. Many protocols have been proposed to avoid the hidden terminal problems. Two notable examples are the MACA [14] and MACAW [5] 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 [19] was designed with a reservation system similar to MACA or MACAW in mind. 802.11 has also improved fairness characteristics, however, in [17] authors point out deficiencies in the fairness of this protocol, as well. Detailed discussion of these protocols is omitted here but can be found in [5, 26, 19].

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 most common metric for assessing the quality of these protocols is the number of hops data packets take to reach the destination, though, other metrics based on traffic, contention, available power at transceivers etc. have also been proposed. Routing protocols fall in one of the two categories: *proactive* and *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.

An example of pro-active protocol is DSDV [20]. On the contrary, reactive routing protocols are trying to minimize the number of routing table updates by spawning broadcast mechanism on need-to-know basis. AODV [21] and DSR [6] belong to the reactive category of routing protocols.

Recently, many researchers advocated use of the Global Positioning System (GPS) in efficient routing. Based on GPS coordinates in LAR scheme 1[1] and scheme 2 [16] the authors compute a zone within which the destination node is believed to be located. This approach decreases routing overhead and communication complexity. The forwarding scheme of LAR is similar to DSR, however, the intermediate nodes are allowed to forward route request packets only to neighbors in the zone.

In this paper, we consider three well known routing protocols: (i) Dynamic Source Routing Protocols (DSR) [6], (ii) Ad-hoc On-demand Distance Vector Routing (AODV) [21] and (iii) Location-Aided Routing (LAR) Scheme 1 [16]. Similarly we consider three well known MAC layer protocols: (i) CSMA/CA, (ii) MACA and (iii) 802.11. Many mobility models for ad-hoc networks simulations have been proposed. These include the *random waypoint* model [6], *random mobility model* [28], and *exponential correlated random model (ECRM)*[2] [25]. 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 [11]. See [11, 3, 24, 25] 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, routing protocols, nodes' speed and injection rates in mobile ad-hoc networks. Our work is motivated by the earlier work by Balakrishnan et.al. [2, 15] and the recent results by Royer et.al. [9, 8, 22] that note the interplay between Routing and MAC protocols. In [8], 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 [25] 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 MAC, routing protocol, nodes' speed and injection rates of packets on the system performance. More details on the input variables are listed in Table 6.

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 and (iv) Long term fairness[3] of the protocols, i.e. the proportional allocation of resources given to each active connection and Each of the input parameters and the performance measures considered here have been used in one of the earlier experimental studies [9, 6, 16, 22, 25]. We briefly comment on the parameters chosen in [9, 22] since the two studies are closest to the one in this paper. The authors consider two parameters that are 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 typically kept at 2. Instead we vary (i) the injection rate, (ii) movement models and (iii) speed of nodes. Based on the discussion in [9], 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*. We use four input variables, each with three different levels, which results in total number of $3^4 = 81$ scenarios. We ran each scenario 10 times to get a reasonable sample size for statistical analysis. This resulted in 810 runs. We constructed 3 basic ex-

[1]We use LAR scheme 1 and LAR1 interchangeably.

[2]We use ECRM and ECR Model interchangeably.

[3]Later, any reference to fairness implies long term fairness.

periments: each corresponding to one of the mobility models. For each of these mobility models, we have 81 scenarios and 810 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; also, 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 [22, 8, 9, 6].

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 the use of *statistical methods* to characterize the interaction between the *protocols, injection rates* and *speed*[4]. 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 [2, 15, 22, 9, 8]. In [15], the authors considered TCP/IP protocol and devised an elegant snoop protocol that conceptually sits between the transport layer and the network layer to overcome this problem. They 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 [22] 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 [22][5] in the following ways:

1. In [22], 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 [22], 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.

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

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

## 2.1 Summary of Experiment Specific Results

We first summarize results specific to each experiment.

***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 true at higher speeds which is consistent with the earlier experimental studies [9, 6, 16, 22, 25]. 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.

## 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 [9, 22].

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) **Fairness:** 2 kinds of 2-way interactions – Routing protocol/MAC-protocol and MAC-protocol/Injection Rate are significant.
2. **ECR 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) **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 except the interaction between router and nodes' speed.
   (c) **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. 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 show varying performance for various 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.

# 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) conceptually shows absence of interaction between the injection rate and speed of nodes.[6]

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) conceptually 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; it is the combination of the variables that is important. 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.**

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 pro-

[6]There is no real data plotted for Figure 2. It is shown just for illustrative purpose.

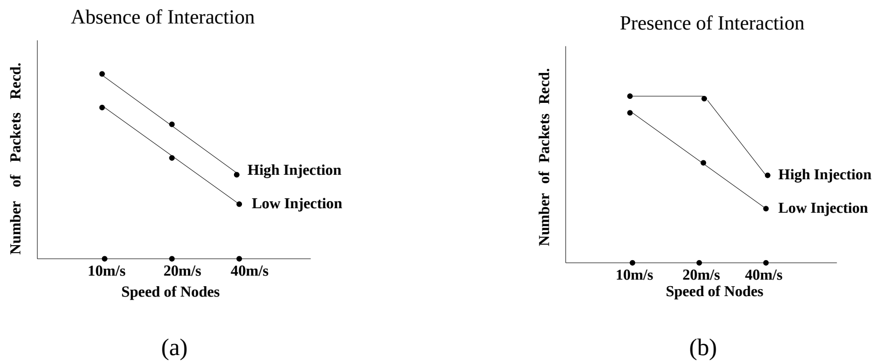



**Figure 2: Interaction levels between Injection Rate and Speed of Nodes**

| 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.**

tocol at a given layer in the protocol stack varies significantly depending upon the 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 unchanged when we change the value of the other. Algorithmic interaction can be more subtle. First, the change in a response variable is a result of the complicated causal dependencies between the two 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:** Intuitively, it is clear that the specific routes chosen by the routing protocol affects the performance of the underlying MAC protocols. In this section, we try to understand this effect further. First note that although the routing paths need not have common nodes, they might be close enough so as to cause MAC protocols at near by transceivers to interact. 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 under the radio propagation model. 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 all 1,000 packets per connection and the latency was 0.017 seconds. (B) Illustrates a situation when the routing protocol found a really bad route. Out of 1000 packets, the upper connection received only 2 packets and the lower connection received 993 packets. 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 0.028s and for the lower connection 0.0175s.

**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. In this example we consider two routing protocols: AODV and DSR and two MAC protocols: MACA and 802.11. Interestingly, quantifying CSMA interaction is somewhat harder 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 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 which has the same range. Figure 3(c) 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 as shown in Section 6. We have also plotted a spatial distribution of these 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-interfering paths. The other plots are omitted but 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.

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 [15, 22], 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.

## 4.1 Measures of Performance

The independent (input) variables are (i) Routing protocol, (ii) MAC protocol, (iii) Nodes' speed, (iv) Injection interval (rate) for the packets and (v) Network topology (dynamically changing over time). The following 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) Ratio of number of packets received to number of packets injected in percentage points, (iii) Throughput in bits/second (bps) and (iv) Fairness: Assignment of resources to each of the two connections.

Average number of packets received, latency, and throughput is simply measured as arithmetic mean over 10 independent runs (20 samples, i.e., 10 runs times two connections). We compute fairness as a ratio of allocation of resources between the two connections. Let $p_i$ be the number of packets received at destination $i$, $q = (p_1/p_2) - 1$ if $p_2 \leq p_1$ and $q = (p_2/p_1) - 1$ if $p_1 < p_2$. Average fairness is $\sum_{i=1}^{10} \hat{q}_i$, where $\hat{q}_i$ is $q$ with maximum value 5 and normalized into $\langle 1, 2 \rangle$ interval for the $i$th run of the protocol. This means that for the average fairness computation we disregard the information about allocation of resources to a specific connection.[7]

## 4.2 Mobility Models

**Grid Mobility Model:** The setup of this experiment is a grid network of $7 \times 7$ 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.

[7]Any deviation from 1 represents inequitable allocation of resources.

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.

**Random Waypoint model:** The setup of this experiment is again a grid network of $7 \times 7$ 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).

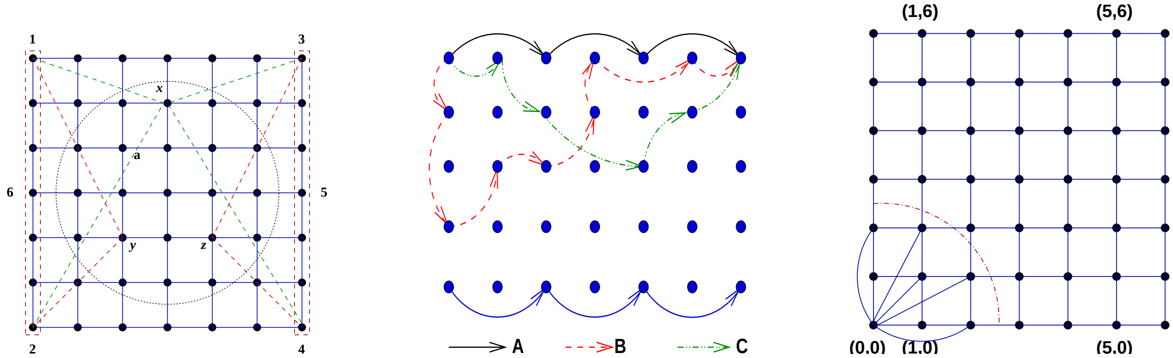
**ECR Model:** The setup of this experiment is an area of $600 \times 600$ meters onto which we uniformly randomly position 49 nodes. Let the nodes be numbered from 0 to 48 in the order they are positioned onto the grid. We divide the nodes into four groups. Nodes belonging to the class $0 \equiv k \pmod 4$ 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 $(r, \alpha)$ of a group at time $t$, (ii) $\tau$ is a time constant that regulates the rate of change, (iii) $\sigma$ 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 $\gamma_i$ 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.

Network topology is characterized as a simple distribution of node's degrees (radio radius = 250m) at a given time during simulation. The distribution is not averaged but derived from mobility pattern of a single run. By providing distributions for various simulation times we provide insight into the evolution of network's topology over time.

# 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 this study, 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.




(a) (b) (c)

**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.**

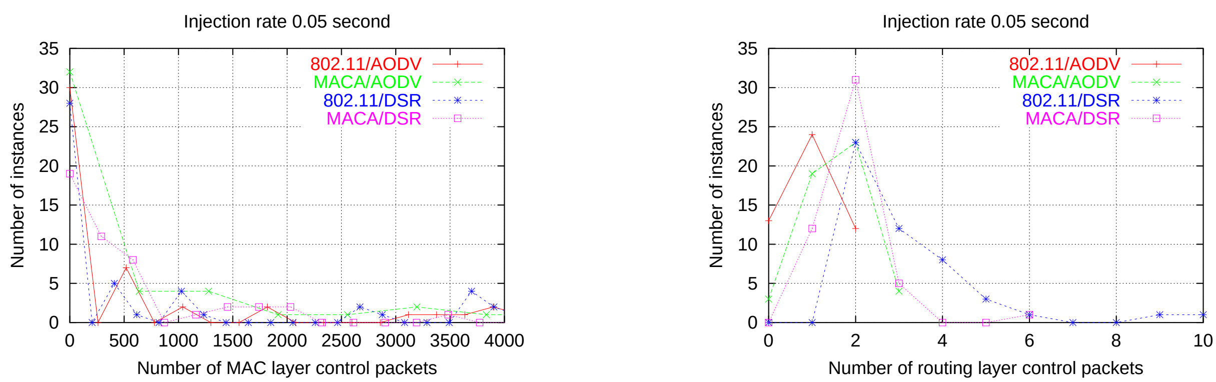



**Figure 4: Figure showing the MAC and routing overhead packet distribution for Example 2. The overhead is plotted as number of nodes with a given number of routing or MAC layer packets. For example, the right hand figure shows that for the combination of 802.11 and AODV there were 31 nodes that produced two routing control packets, and that there was no node that would produce 4 routing control packets. 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.**

## 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 for each mobility model.

**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).[8] 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 [10, 23]. Given that we have four factors, we use a four factor ANOVA.

**Mathematical Model:** The appropriate mathematical model for a

[8] 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 nonlinear 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.

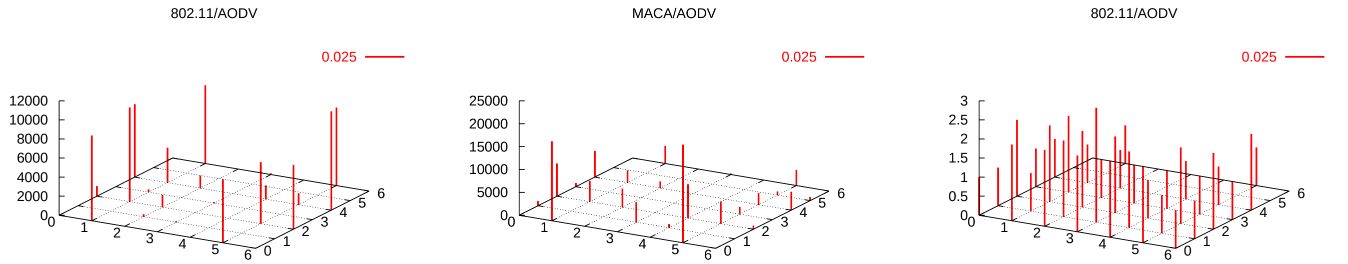



**Figure 5: Figure showing the spatial distribution of the control overhead for Example 2. The network is as shown in Figure 3 (c). All the plots are for injection rate of 0.025 seconds. Left: Results for *MAC layer overhead* for (802.11,AODV). Center: Results for MAC layer overhead for (MACA,AODV) combination.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

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 which is 10 in our experiment.

3. $\alpha_i$ is the effect of routing protocol, $\beta_j$ is the effect of the speed of nodes, $\gamma_k$ is the effect of the MAC protocol and $\delta_l$ 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);

   (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, $\varepsilon_{ijklm}$ is the random error.

**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[9] and refer it by $SS(14)$, which stands for residual sum of squares for model number 14. The degrees of freedom[10] 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

[9]For a regression model, $Y_i = \alpha + \beta X_i + e_i$, the residuals are $e_i = Y_i - \alpha - \beta X_i$ and the residual sum of squares is $\sum_i (e_i)^2 = \sum_i (Y_i - \alpha - \beta X_i)^2$. Refer to [10] for more details. We use statistical package Splus to perform this analysis.

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

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. 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 based on the recommendations made by [9, 13] after undertaking a detailed experimental study of recent routing protocols.
4. **MAC protocols**: IEEE 802.11 DCF, 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 [22, 27].
5. The size of physical area simulated was $600 \times 600$ meters.
6. **Speed of nodes**: 10m/s, 20m/s and 40m/s.[a] These are denoted by $S_j,\ 1 \leq j \leq 3$. The set of all speeds will be denoted by $S$.
7. **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 $I$. 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 at 40,960 bits per second.
8. 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
9. **Simulator used:** GlomoSim [7].
10. The transmission range of transceiver was 250 meters.
11. The simulation time was 100 seconds.
12. Hardware used in all cases was a Linux PC with 512MB of RAM memory, and Pentium III 500MHz microprocessor.

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

**Figure 6: Parameters used in the Experiments.**

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 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:

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

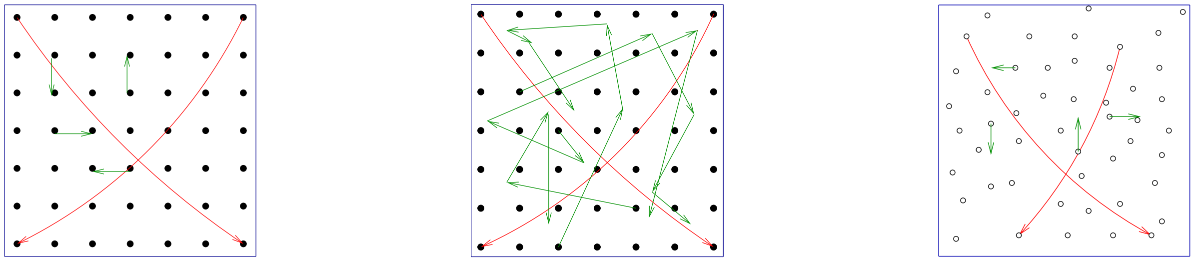
where $SS(a)$ is the sum of squares residuals for model $a$ and $SS(b)$ is the sum of squares residuals for model $b$. Similarly $DF(a)$ is the degrees of freedom for model $a$ and $DF(b)$ is the degrees of freedom for model $b$. The $SS_{full}$ is the sum of squares residuals for the full model (largest model) i.e. the model with all the four interaction terms. $DF_{full}$ is the degrees of freedom for the full model. Due to lack of space we give details only on Grid model.

## 5.2 Grid Mobility Model Results (Experiment 1)

*Performance measure: Latency.* Table 2 shows ANOVA results for the Grid Mobility model. Columns 4-6 show the interaction results when latency is used as the performance measure. We start with an initial model of 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 $0.65$ (insignificant at any confidence level) 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 was 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.

| 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 | $92.28^*$ | $7.3 \times 10^7$ | 801 | $3.35^*$ |
| 2 | 2-way | $[RS][RM][RI][SM][SI]$ | 80071 | 1591 | 2.9 | 283870 | 1591 | $347.24^*$ | $6.8 \times 10^7$ | 781 | $4.63^*$ |
| 3 | 2-way | $[RS][RM][RI][SM][MI]$ | 79705 | 1591 | 1.07 | 166571 | 1591 | $4.87^*$ | $6.7 \times 10^7$ | 781 | 2.47 |
| 4 | 2-way | $[RS][RM][RI][SI][MI]$ | 82480 | 1591 | $14.98^*$ | 189797 | 1591 | $72.66^*$ | $6.7 \times 10^7$ | 781 | 2.34 |
| 5 | 2-way | $[RS][RM][SM][SI][MI]$ | 79541 | 1591 | 0.24 | 172840 | 1591 | $23.16^*$ | $6.6 \times 10^7$ | 781 | 0.60 |
| 6 | 2-way | $[RS][RI][SM][SI][MI]$ | 83689 | 1591 | $21.05^*$ | 199212 | 1591 | $100.14^*$ | $6.9 \times 10^7$ | 781 | $8.80^*$ |
| 7 | 2-way | $[RM][RI][SM][SI][MI]$ | 79857 | 1591 | 1.83 | 166835 | 1591 | $5.64^*$ | $6.6 \times 10^7$ | 781 | 1.29 |
| 8 | All 2-way | $[RS][RM][RI][SM][SI][MI]$ | 79492 | 1587 | 1.41 | 164903 | 1587 | $9.69^*$ | $6.6 \times 10^7$ | 777 | 1.06 |
| 9 | 3-way | $[RSM][RSI][RMI]$ | 77310 | 1563 | 0.17 | 156619 | 1563 | $26.67^*$ | $6.3 \times 10^7$ | 753 | 0.62 |
| 10 | 3-way | $[RSM][RSI][SMI]$ | 77512 | 1563 | 0.68 | 140957 | 1563 | $3.81^*$ | $6.3 \times 10^7$ | 753 | 0.64 |
| 11 | 3-way | $[RSM][RMI][SMI]$ | 77377 | 1563 | 0.34 | 141359 | 1563 | $4.40^*$ | $6.4 \times 10^7$ | 753 | 1.06 |
| 12 | 3-way | $[RSI][RMI][SMI]$ | 79012 | 1563 | $4.44^*$ | 140992 | 1563 | $3.86^*$ | $6.4 \times 10^7$ | 753 | 1.93 |
| 13 | All 3-way | $[RSM][RSI][RMI][SMI]$ | 77240 | 1555 | 0.65 | 138342 | 1555 | $4.76^*$ | $6.3 \times 10^7$ | 745 | 0.80 |
| 14 | All 4-way | $[RSMI]$ | 76718 | 1539 | | 131816 | 1539 | | $6.2 \times 10^7$ | 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 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 fairness is calculated by taking the ratio of packets received for the two connections. Hence 10 runs (20 samples from 2 connections) lead to only 10 actual measurements for fairness. $*$ shows that the $F$-test is significant at 99$\%$ confidence level.**



(a) (b) (c)

**Figure 7: (a) Grid mobility and (b) Random Waypoint Models. We position 49 nodes onto a $7 \times 7$ grid. The nodes are numbered from the top left corner in row wise 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 $600 \times 600$ meters area. The nodes are numbered in the order their random position is computed. The start movement depends on assignment of the four groups.**

*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: Fairness.* The last three columns of Table 2 show 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 samples instead of 20 for each of the 81 scenarios mentioned above.[11] 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.

## 6. 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 [2] 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. In a companion paper [4] we characterize the interaction between the parameters studied here in a static radio network. The study is undertaken for two reasons: (i) it helps us understand the effect of mobility, (ii) in a static network we can control the degree and connectivity parameters more effectively; we observed that these parameters play an important role in protocol performance.

The statistical analysis 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.

It is worth noting that ANOVA is a statistical tool to qualitatively measure the interaction between different input variables. As such it presumes correctness of the data being produced by simulations for statistical testing. Errors in implementing a protocol may result in spurious interactions and invalid conclusions. Nevertheless, the method does provide a way to compare two simulators or comparing the results from simulations with real field tests.

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.

[11] 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.

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