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Characterizing the Interaction Between Routing and MAC Protocols in Ad-hoc Networks [4,5]

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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) number of packets received and (iii) 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.

1 Introduction

Design of mobile ad-hoc networks (MANET) is currently an extremely active area of research. MANETs 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

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networking within the Internet Engineering Task Force (IETF). Such 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].) Since ad-hoc networks lack fixed infrastructure in the form of base stations, fulfilling the above stated functional requirements becomes all the more difficult.

MAC Protocols. 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 here but can be found in [Ra96, BD+94, 802.11].

Routing Protocols. 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 [PB94]. In DSDV each node maintains a routing table that lists all available destinations and routes to them. Each node periodically broadcasts the routing table to its neighbors which incorporate that information into their own tables. AODV [PR99] is an on-demand extension of DSDV. This protocol is trying to minimize the number of routing table updates by spawning broadcast mechanism on need-to-know basis. When a node needs to find a destination it broadcasts a route request packet. This packet is flooded throughout the network and each forwarding node stores the node address from which it came in their routing table. The route request packet either reaches the destination node or a forwarding node with an unexpired route to the destination. This node sends back a route reply packet which follows the reversed route to the source. This packet is also used to update routing tables of forwarding nodes. The source node is now ready to send data packets that follow the route to the destination provided by each forwarding node. DSR [JM96] implements a similar strategy to AODV. In this protocol, however, the full route to the destination is encoded into the route request/reply packet, and later stored at source and copied into data packets. Data packets thus contain a complete route to the destination in their headers, and do not rely on forwarding nodes to provide this information. The disadvantage is higher requirement on memory at nodes and bigger size of route request/reply packets as they encapsulate the complete route. TORA [PC97] 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].

Recently, many researchers advocated use of the Global Positioning System (GPS) in efficient routing. Based on GPS coordinates in LAR scheme 1 and scheme 2 [KV98] 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) [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.[6]

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 protocols, routing protocols, nodes' speed and injection rates in mobile ad-hoc networks. Our work is motivated by the earlier work by Balakrishnan et al. [Ba98, KKB00], Ephremides [Ep02], Gerla et al. [GK+00] who studied the interaction between transport layer and the MAC layer and the recent results by Royer et al. [DP+, DPR, RLP00] that note the interplay between Routing and MAC protocols. In [DPR], 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.

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[6] The following terms are used interchangeably in this document: IEEE 802.11 DCF and 802.11, LAR Scheme 1 and LAR1, ECRM and ECR Model.

Apart from mobility patterns, we study the effect of MAC protocols, routing protocols, nodes' speed and injection rates of packets on the system performance. More details on the input variables are listed in Figure 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) Long term fairness[7] of the protocols, i.e. the proportional allocation of resources given to each active connection. Each of the input parameters and the performance measures considered here have been used in one of the earlier experimental studies [DP+, BM+98, KV98, RLP00, RS98]. We briefly comment on the parameters chosen in [DP+, RLP00] 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 zero 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 [DP+], 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 experiments: 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 [RLP00, DPR, DP+, BM+98].

Given the large number of variables involved i.e. MAC protocol, routing protocol, 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.*[8] 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 [Ba98, KKB00, GK+00, RLP00, DP+, DPR]. In [KKB00],

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

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

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 [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][9] 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.

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 [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.

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[9] 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 speeds, Injection rates and the MAC protocols interact significantly.
    - (c) **Fairness:** 2 kinds of 2-way interactions – Routing/MAC protocols and MAC protocols/Injection rates are significant.
2. **ECR Mobility Model**
    - (a) **Latency:** Significant 3 way interaction – Routing protocols, Transceiver speeds and the MAC protocols interact significantly.
    - (b) **Number of packets received:** All 2-way interactions *except* Routing protocols/Injection rates and Routing protocols/Transceiver speeds 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 rates, Routing protocols/Transceiver speeds and Routing/MAC protocols.
    - (b) **Number of packets received: All** 2-way interactions are significant except the interaction between Routing protocols and Transceiver speeds.
    - (c) **Fairness:** The only 2-way interactions that are significant are MAC protocols/Injection rates and Routing/MAC protocols.

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

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 [DP+, 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/reply 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.[10]

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

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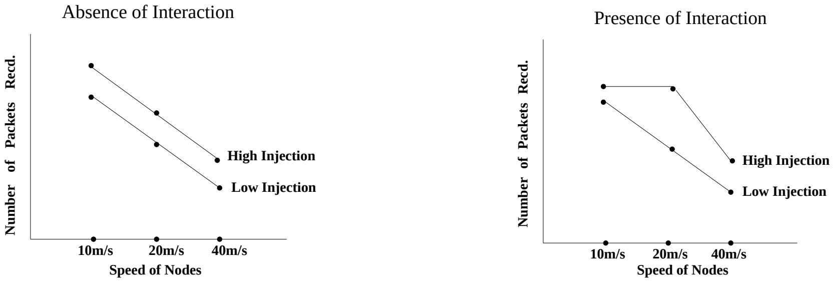
[10] There is no real data plotted for Figure 2. It is shown just for illustrative purpose.



(a) (b)

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

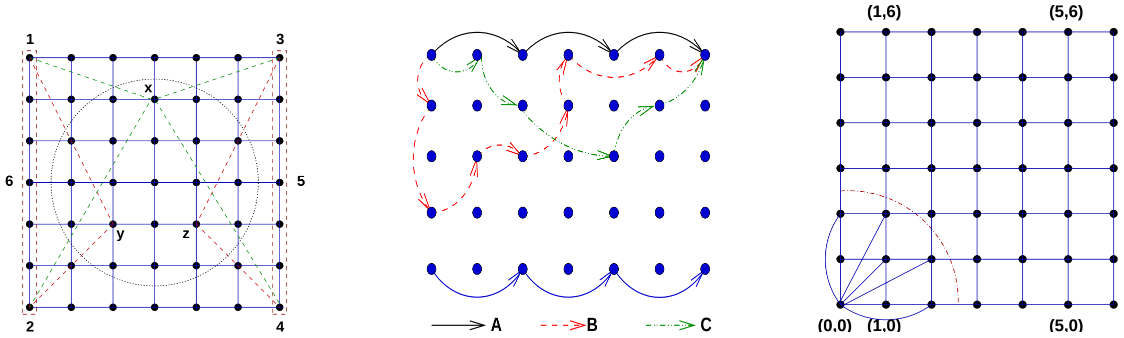
Table 1: This table shows the mean value of the response variable for high-low injection rates and different speed of the nodes. The interaction is found to be significant in case of response variable **number of packets received** but insignificant in case of **latency**.

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 protocol 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.



(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.

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.

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; in includes all possible delays due to route discovery, queuing or backoffs, (ii) Ratio of number of packets received to number of packets injected in percentage points, (iii) Long term fairness: Assignment of resources to connections.

We used two connections in our analysis. Also we consider a fixed simulation area. In Section 7, we discuss our results when these two parameters are varied. Average number of packets received and latency is simply measured as arithmetic mean over 10 or 30 independent simulation runs. The total number of samples per simulation run was proportional to the number of connections. We compute (long term) fairness ratio q for each simulation run as allocation between the connection with the highest number of packets received and the the sum of packets received for the remaining connections. More formally, let n denote the number

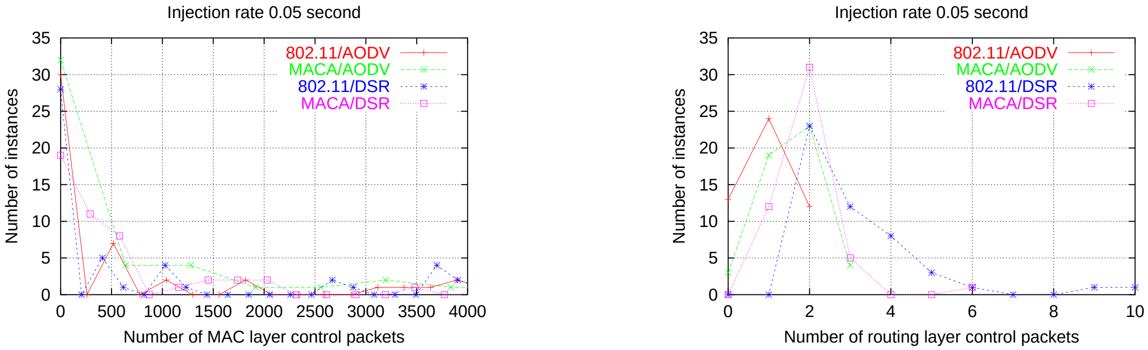


Figure 4: Figure showing the MAC and routing overhead packet distribution for Example 2. The overhead is plotted as number of nodes with a given number of routing or MAC layer packets. For example, the right hand figure shows that for the combination of 802.11 and AODV there were 31 nodes that produced 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.

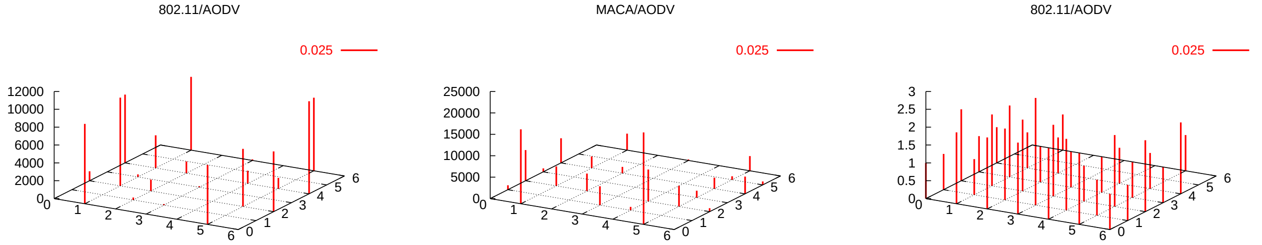


Figure 5: Figure showing the spatial distribution of the control overhead for Example 2. The network is as shown in Figure 3 (c). All the plots are for injection rate of 0.025 seconds. **Left**: Results for *MAC layer overhead* for (802.11,AODV). **Center**: Results for MAC layer overhead for (MACA,AODV) 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.

of connections, let p_i be the number of packets received by connection i, let $p_{max} = max\{p_1, \ldots, p_n\}$, and let k denote a connection such that $p_k = p_{max}$ then $q = \frac{p_{max} \times (n-1)}{\sum_{j \neq k} p_j}$. It follows that any deviation from $q = 1$ represents an inequitable allocation of resources. For $n = 2$ this ratio reduces to p_1/p_2 or $p_2/p1$. Note that for our simulations there has never been a case that $p_{max} = 0$ and q was set to 100.0 in the rare cases when the denominator equaled zero. Moreover, connections never shared sinks or sources, i.e., $\{source_1, \ldots, source_n\} \cap \{sink_1, \ldots, sink_n\} = \emptyset$. Fairness results in the form of graphs[11] were further adjusted. In case that $q > 6.0$ we set $q = 6.0$ to *emphasize smaller values* and subsequently this interval was normalized into $\langle 1, 2 \rangle$ interval. Finally, average fairness for u simulation runs is $\frac{1}{u}\sum_{i=1}^{u} q_i$ where q_i is the adjusted and normalized fairness for the ith simulation run. In a few cases for $n = 2$ we have plotted the average fairness so that the resources assigned to Connection 1 and Connection 2 could be uniquely identified. The result are graphs where q was normalized into $\langle 1, 2 \rangle$ interval if $p_1 \leq p_2$ and into $\langle 0, 1 \rangle$ interval otherwise where departure from $q = 1$ towards 2 or 0 means an inequitable assignment of resources with respect to Connection 1 or 2.

Additionally to the basic performance measures we have computed distributions of node degrees. This kind of distribution is important for understanding the variability in this measure. The resulting graphs show a dependence between a given node degree and its occurrence for r nodes in absolute terms. The distributions of MAC or routing layer control packets were computed as dependencies between a given number of control packets and the number of nodes using the given number of control packets for establishing access to the medium or engaging in route acquisition procedures. As before the y-axis shows the number of nodes in absolute terms. On the contrary to the various distributions described just above we have computed the spatial distributions of MAC or routing layer control packets as an average over u simulation runs. Spatial distributions uniquely tie a given average number of control packets used to the geographical position of a node. Obviously, spatial distributions could only be computed for static networks. The total of MAC layer control packets for a node was computed as a sum of control packets sent out, i.e. for 802.11 a sum of RTS, CTS and ACK packets, and for MACA a sum of RTS and CTS packets. The total of routing layer control packets was computed as a sum of RREQ and RREP for AODV, and RREQ, RREP and RERR for DSR and LAR scheme 1. The average number of control packets for a node was computed as an arithmetic mean over u simulation runs.

4.2 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 4 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 $0 \equiv k (\mathrm{mod}\ 4)$ start moving to the South, nodes belonging to the class $1 \equiv k (\mathrm{mod}\ 4)$ start moving to the North, nodes belonging to the class $2 \equiv k (\mathrm{mod}\ 4)$ start moving to the East and nodes belonging to the class $3 \equiv k (\mathrm{mod}\ 4)$ 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:

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[11] For statistical analysis the ratio has not been further adjusted or modified.

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 [DP+, JL+00] 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 [RLP00, WS+97].
5. The size of physical area simulated was 600×600 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. **Simulation runs:** 10 runs for any combination of input parameters.[b]
9. 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: UDP (viii) In-band data and control, i.e., a single channel for both data and control packets.
10. **Simulator used:** GloMoSim [BT+99].
11. The transmission range of transceiver was 250 meters.
12. The simulation time was 100 seconds.
13. Hardware used in all cases was a Linux PC with 512MB of RAM memory, and a 500, 850, or 1000 MHz microprocessor.

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

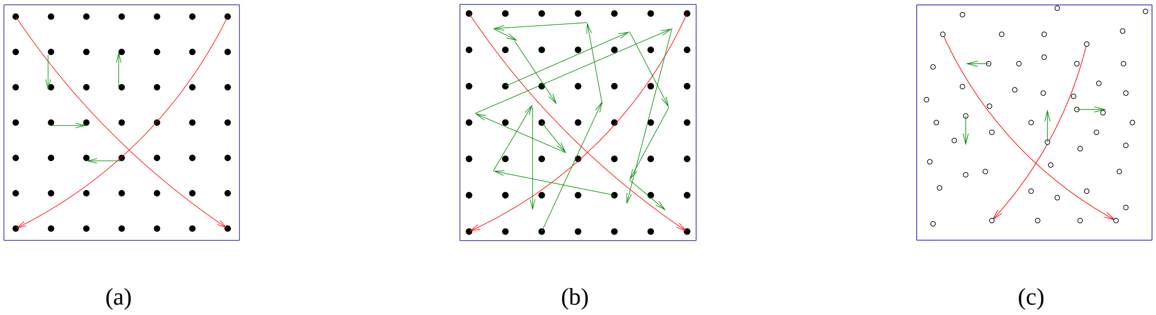
[b] Each simulation run with an independent simulation seed.

Figure 6: Parameters used in the Experiments.

10 m/s, 20 m/s, 40 m/s.

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 (pauses), 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 600×600 meters onto which we uniformly randomly position 49 nodes. Let the nodes be numbered from 0 to 48 in the order they are positioned in the area. 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.


(a)

(b)

(c)

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 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 600×600 meters area. The nodes are numbered in the order their random position is computed. The start movement depends on assignment of the four groups.

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.

5.1 Experimental Setup for the Statistical Analysis

Each set of experiment utilizes three different combinations of MAC protocol, routing protocol, 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 routing protocol 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).[12] 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 which is 10 in our experiment.

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[12] 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 non-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.

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

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.

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 MAC protocol, routing protocol, nodes' speed and injection rate 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[13] and refer it by $SS(14)$, which stands for residual sum of squares for model number 14. The degrees of freedom[14] is referred by $DF(14)$. Now

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[13] 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 [GH96] for more details. We use statistical package Splus to perform this analysis.

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

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 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. 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 routing protocol, 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 routing and MAC protocol. The other most significant 2-way interaction is between nodes' speed and MAC protocol. The rest are all insignificant. This shows that the 3-way interaction between the routing protocol, nodes' speed and the MAC protocol are due to the 2-way interaction between routing/MAC protocol and

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 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.

speed/MAC protocol. There is no interaction between routing protocol 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 routing protocol, nodes' speed, MAC protocol 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 protocol and injection rate interact most significantly. The routing and the MAC protocol also interact very significantly. In 3-way interaction, it is the routing protocol, MAC protocol 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 routing protocol, 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.[15] 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 routing and MAC protocol interact in the most significant way in affecting the fairness. The interaction between the MAC protocol and injection rate is also significant but not to the extent of routing and MAC protocol interaction. In this case, the smallest model has only $[RM][MI]$ 2-way interaction terms.

5.3 ECR Mobility Model Results (Experiment 2)

Performance measure: Latency. Table 3 shows the ANOVA results for the ECR mobility model. Again, columns 4-6 show the interaction results when latency is used as the response variable. The analysis done here is similar to the grid mobility model case. The results show that there is significant 3 way interaction between routing protocol, transceiver (node) speed and the MAC protocol. Models 6 and 7 reconfirm that interaction. Model 6 shows that routing and MAC protocol interact significantly and model 7 shows that routing protocol and speed interaction is important.

Performance measure: Number of packets received. Columns 7, 8 and 9 of Table 3 show results for the number of packets as the performance measure. Unlike in the grid mobility model, here we do not find any significant 4-way or even a 3-way interaction between the variables. All 2-way interactions *except* routing protocol/injection rate and routing protocol/transceiver speed are significant.

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[15] 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.

Response Variable			Latency			Num. of Packets Recd.			Fairness		
No.	Interaction	Source	SS	DF	F-**test**	SS	DF	F-**test**	SS	DF	F-**test**
1	main effect	$[R][S][M][I]$	59078	1611	3.54*	971992	1611	8.51*	91650121	801	1.96
2	2-way	$[RS][RM][RI][SM][SI]$	56565	1591	3.05	875080	1591	6.39*	87802691	781	3.17
3	2-way	$[RS][RM][RI][SM][MI]$	56295	1591	1.08	869226	1591	3.69*	86833820	781	0.99
4	2-way	$[RS][RM][RI][SI][MI]$	56314	1591	1.22	882616	1591	9.86*	86900548	781	1.14
5	2-way	$[RS][RM][SM][SI][MI]$	56377	1591	1.68	866640	1591	2.49	86471784	781	0.18
6	2-way	$[RS][RI][SM][SI][MI]$	57568	1591	10.32*	919267	1591	26.77*	88986111	781	5.82*
7	2-way	$[RM][RI][SM][SI][MI]$	56686	1591	3.92*	865304	1591	1.88	86595981	781	0.46
8	All 2-way	$[RS][RM][RI][SM][SI][MI]$	56145	1587	1.85	861228	1587	1.08	86388163	777	0.94
9	3-way	$[RSM][RSI][RMI]$	54520	1563	1.51	846792	1563	1.01	84725467	753	1.89
10	3-way	$[RSM][RSI][SMI]$	54490	1563	1.40	846206	1563	0.88	83596135	753	0.62
11	3-way	$[RSM][RMI][SMI]$	54365	1563	0.95	850800	1563	1.94	83440690	753	0.45
12	3-way	$[RSI][RMI][SMI]$	55082	1563	3.55*	844576	1563	0.50	83739425	753	0.78
13	All 3-way	$[RSM][RSI][RMI][SMI]$	54103	1555	1.98	842382	1555	0.92	83037851	745	0.99
14	All 4-way	$[RSMI]$	53012	1539		834026	1539		81273633	729	

Table 3: ***(Experiment 2), ECR 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.

Performance measure: Fairness. Since the interpretation of all the performance measures are the same as explained before, we just highlight the main results for each of them. Columns 10, 11 and 12 of Table 3 show that only MAC and routing protocol interact in affecting the fairness. All other 2-way, 3-way and 4-way interactions are insignificant for this measure. Note that so far all selected models have had MAC and routing protocol interacting significantly. This was true for grid mobility models also.

5.4 Random Waypoint Mobility Model Results (Experiment 3)

Performance measure: Latency. Table 4 shows ANOVA results for random waypoint mobility model. 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 significant ones are MAC protocol/injection rate, routing protocol/transceiver speed and routing/MAC protocol.

Performance measure: Number of packets received. Columns 7, 8 and 9 of Table 4 show that **All** 2-way interactions are significant except for routing protocol and nodes' speed.

Performance measure: Fairness. The last three columns of Table 4 show that there is no 3-way or 4-way interactions present in affecting the fairness. The only 2-way interactions that are significant are MAC protocol/injection rate and routing/MAC protocol. Again, note that MAC/routing protocol interactions are the most robust of all.

6 Additional Observations and Explanation

In this section we briefly explain specific results for the three mobility models. For clarity of exposition, we only present results when the speed is 20 m/s and injection rate (interval) is 0.025 second. Latency and percentage of packets received are presented for various injection rates. The results are depicted in Figures 8 to 13. Figures for the complete set of experimental parameters outlined in Figure 6 can be obtained from the authors.

Recall that the ECR model represents a mobility model that keeps the relative (average) 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 $t + k$, $k = (0, ST\rangle$, ST is the simulation time. The random waypoint model represents a movement pattern that is hard to predict. Note that we do not insert any pauses into the model, i.e., pauses were 0 second. On the other hand, the grid mobility model has a very deterministic movement pattern that is easy to predict.

We make the following observations. Some of the observations were also made in [DPR, RLP00].

- CSMA and MACA do not perform well for any of the three mobility models. 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 a 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

Response Variable			Latency			Num. of Packets Recd.			Fairness		
No.	Interaction	Source	SS	DF	F-**test**	SS	DF	F-**test**	SS	DF	F-**test**
1	main effect	$[R][S][M][I]$	10607	1611	3.79*	464087	1611	26.84*	68018661	801	2.60
2	2-way	$[RS][RM][RI][SM][SI]$	10290	1591	10.34*	391646	1591	73.13*	65649520	781	8.40*
3	2-way	$[RS][RM][RI][SM][MI]$	10049	1591	0.90	335409	1591	4.85*	63071889	781	0.61
4	2-way	$[RS][RM][RI][SI][MI]$	10089	1591	2.46	358047	1591	32.34*	63210850	781	1.03
5	2-way	$[RS][RM][SM][SI][MI]$	10045	1591	0.74	334379	1591	3.60*	62892626	781	0.07
6	2-way	$[RS][RI][SM][SI][MI]$	10131	1591	4.11*	368572	1591	45.11*	64076723	781	3.65*
7	2-way	$[RM][RI][SM][SI][MI]$	10136	1591	4.31*	333074	1591	2.02	63453354	781	1.77
8	All 2-way	$[RS][RM][RI][SM][SI][MI]$	10026	1587	0.74	331408	1587	2.00	62867260	777	0.65
9	3-way	$[RSM][RSI][RMI]$	9893	1563	0.37	322958	1563	2.87	61319722	753	0.27
10	3-way	$[RSM][RSI][SMI]$	9901	1563	0.53	323667	1563	3.30*	61517964	753	0.57
11	3-way	$[RSM][RMI][SMI]$	9912	1563	0.74	319065	1563	0.51	61691607	753	0.83
12	3-way	$[RSI][RMI][SMI]$	9945	1563	1.39	320379	1563	1.31	61757483	753	0.93
13	All 3-way	$[RSM][RSI][RMI][SMI]$	9874	1555	0.45	318220	1555	0.39	61139838	745	0.59
14	All 4-way	$[RSMI]$	9828	1539		316922	1539		60357510	729	

Table 4: ***(Experiment 3), Random Waypoint 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.

speeds (40 m/s) and injection rates (0.0125s) in case of ECRM. One obvious reason for this observed behavior is that increased mobility causes frequent changes in routes resulting in frequent MAC overhead required for route discovery and update.

- Figure 8 depicts the distribution of node degrees at three distinct times in the simulation. Intuitively, such distributions and their temporal properties are a good measure of geographical reconfiguration change over time. Networks with higher mobility have different temporal properties than static or low mobility networks. Fluctuations in these distributions are directly co-related with the performance of routing and MAC protocols. The degree distributions show variation across the mobility models. The grid mobility model and the random waypoint model started from a grid topology. This created three major peaks in the distribution. However, such peaks quickly disappeared during the run of a simulation. Nodes for ECRM were initially positioned randomly. We can see that in case of the random waypoint model the maximum node degree continually increases. This observation is in accordance with the recent results reported in [Be01]. For the two other models the maximum node degree increases only very slowly.

- Figures 9 to 11 show the performance of protocols in terms of three response variables: Fairness, latency, and ratio of packets received, respectively. 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.

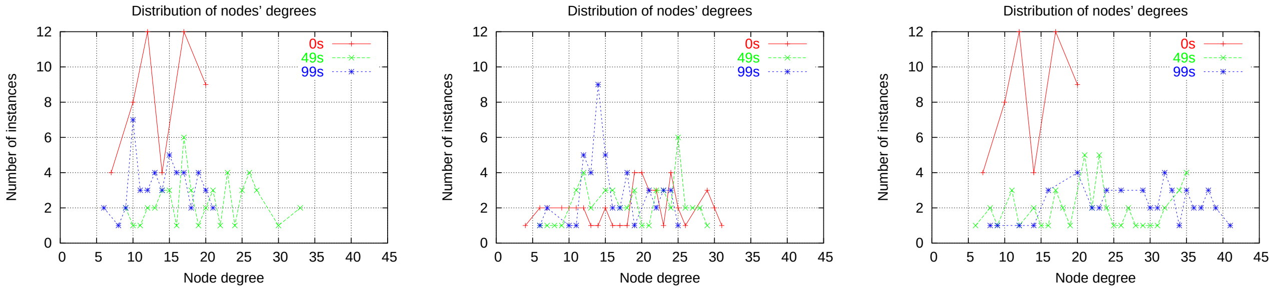
- Figures 12 and 13 show the distributions of MAC and routing layer control packets for three different combinations. Due to the discussion above, the MAC layer protocol considered is always 802.11. The routing layer protocols used are AODV, DSR and LAR1 respectively. We can see that the ECR model produced the least number of MAC layer control packets. This is consistent with our assertion that ECR model puts the least pressure on the protocols stack.

- Performance for other injection rates and speeds look similar to those shown. The difference in performance is proportional to increased or decreased injection rate, or speed.

- In highly mobile environments, the hidden and exposed terminal issues become more interesting. At high speeds new hidden terminals are simply created (or possibly destroyed) by movement of nodes during transmission of other nodes. Since these nodes were outside of the RTS-CTS or carrier sensing mechanism for a given data transmission, they are not aware of the radio environment around. After establishing themselves in an area they often move from that location almost immediately. This feature appears to be more prnounced in the random waypoint model than the grid mobility model. For ECRM nodes are always established within their respective groups. This suggests one measure of performance for mobile systems: the number of hidden terminals that are effectively present at each unit of time. Clearly, this depends on which nodes have packets that they wish to retransmit. This in turn depends on the routing protocol used.

- An important difference between AODV and DSR is the fact that DSR encodes complete routes into route request, route reply, and data packets. Any corruption of a route request/reply packet leads to a repeated route acquisition procedure. This also contributes to slightly higher consumption of bandwidth compared to AODV. The difference in performance between DSR and AODV is also due to differences in handling broken links. We note that the version of DSR implemented in GloMoSim uses salvaging. In DSR if there is a broken link the forwarding node tries to salvage packets waiting in send buffer by trying to search the Route Cache for an alternative route. If this procedure fails a route error is sent to the source and the source tries to resend the packet. In AODV local repair is possible as well. If a node detects link failure it sends a route request to the destination affected. The version of AODV in GloMoSim does not implement route error packets. However, an unsolicited route reply packet is sent upstream to notify all active sources.

- We note that speed of 40 m/s for both source and destination can easily mean that the destination is moving at 80 m/s relative to the source. Speed of 40 m/s (144 km/h) can represent a fast moving car on a speedway. Thus at latency for data packets exceeding 1 second the topology changes can be relatively big.
- Other researchers often alleviated the problem that occurs due to high mobility by inserting pauses in nodes' movement. These small pauses help nodes update their local states after they moved.[16] Our observations correspond roughly with conclusions made in [Ro01+] where authors show that node degrees as high as 15-20 are necessary for decent performance in a mobile setting. Our results extend their performance results for higher injection rates and speeds.
- It is likely that the ability of MAC/routing layer protocols to anticipate movement can improve the overall performance. Due to inherent randomness, such improvements are unlikely for the random waypoint model. However, the good performance for ECRM suggests that well established patterns for certain mobile nodes might be helpful. Intuitively, such nodes could act as pseudo-base-stations: once the routes are established between these nodes they might persist for fairly long periods. As a result routing protocols need to find appropriate routes only to the "nearest" pseudo-base-stations. The particular mechanisms used in LAR scheme 1 helped little in this respect as in our setting request zones in many cases coincided with the total area.



(a) (b) (c)

Figure 8: Distribution of node degrees at three different simulation times for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.

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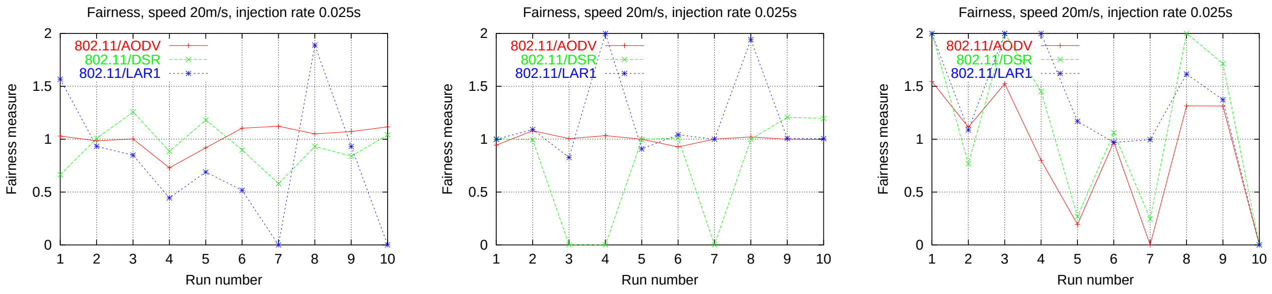
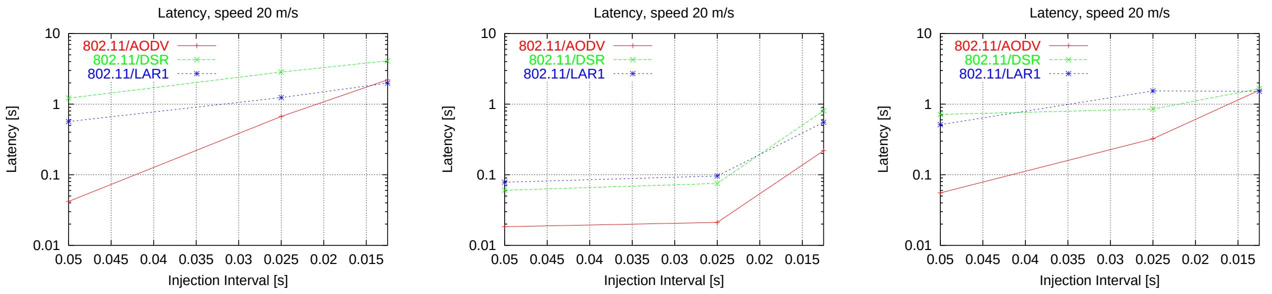
[16] For slower speeds the importance of pauses is lesser.



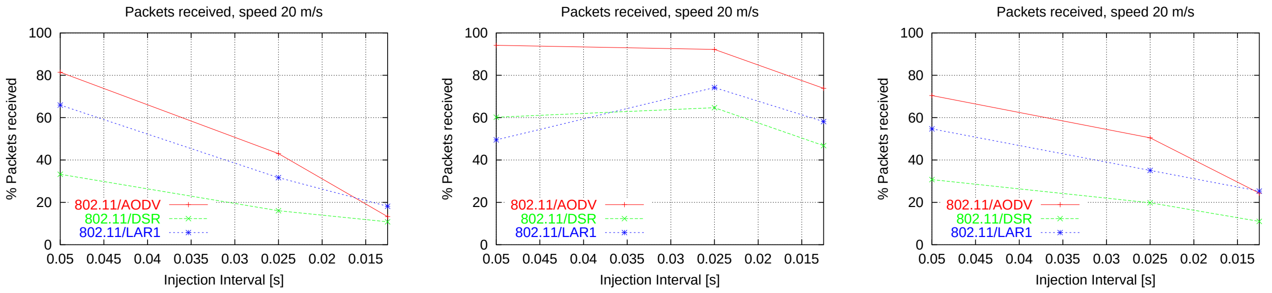
(a) (b) (c)

Figure 9: Long term fairness for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



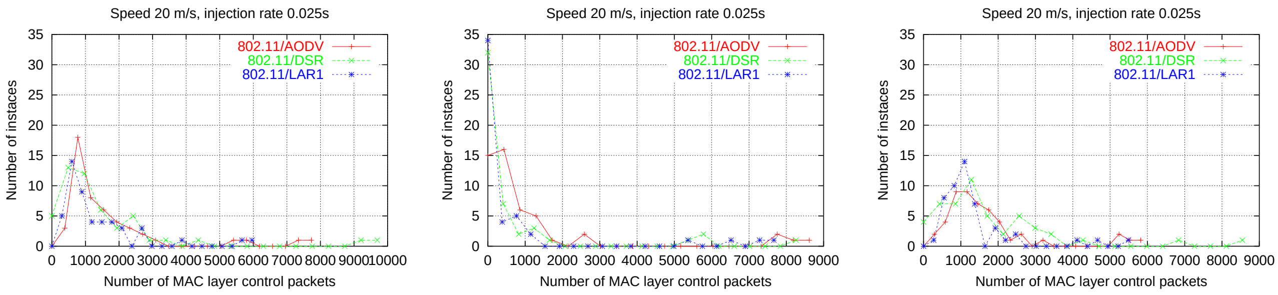
(a) (b) (c)

Figure 10: Latency for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



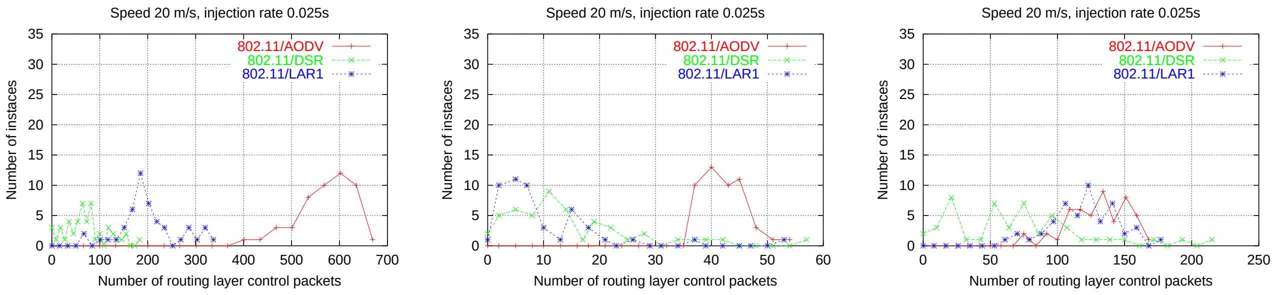
(a) (b) (c)

Figure 11: Packets received for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



(a) (b) (c)

Figure 12: MAC layer control packets distribution for the three mobility models. ¿From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



(a) (b) (c)

Figure 13: Routing layer control packets distribution for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.

1. **Network topology:** The topology was given by 49 mobile nodes initially uniformly distributed over an area of 600 × 600 meters (1000 × 1000 meters) and the radio range of 250 meters. Later, the topology behaved accordingly to the Random waypoint model with pauses set to 0 seconds and the speed of nodes set to 15m/s.
2. **Number of connections:** We use 2, 4, or 8 connections. The sink and source connection pair was chosen randomly for each simulation run. Connections are denoted by $C_i,\ 1 \leq i \leq 3$.
3. **Routing protocols** : AODV, DSR.
4. **MAC protocols**: IEEE 802.11 DCF, CSMA.
5. **Speed of nodes**: A single speed: 15m/s.
6. **Injection rates:** We have kept the total number of packets injected during the 100-second simulation time constant at 8,000 packets. That determined the related injection rates and the numbers of packets injected in case of 2, 4, or 8 connections. For 2 connections we have injected 4,000 data packets per connection and the injection rate (interval) was 0.025 second; for 4 connections we have injected 2,000 data packets per connection and the injection rate was 0.05 second, and finally, for 8 connections we have injected 1,000 data packets per connection and the injection rate was 0.1 second.
7. **Simulation runs:** 30 simulation runs for each combination of input parameters.
8. Other parameters were identical to those in Figure 6.

Figure 14: Differences in parameters used in the experiment on the effect of increasing number of connections and other experiments from Section 4.2.

7 Number of Connections and Average Transceiver Density

So far we only considered the effect of two connections on the overall performance of ad-hoc networks. In this section we study the sensitivity of our results to increasing the number of connections and decreasing the area of simulation. This on an average increases the node density during the course of our simulations. Note that both these variables were kept fixed in our setup described in Section 4. The differences in the experimental setups with respect to experiments described in Section 4 are summarized in Figure 14.

In view of the results reported in the preceding section, we did a small focused experiment. Specifically, we used only 802.11 and CSMA as MAC layer protocols, and AODV and DSR as routing layer protocols. The injection rate was designed to keep the number of data packet injections constant at 8,000 packets over the simulation time. Some of the previously reported studies kept the per connection injection rate constant with the increasing number of connections. This approach does not allow one to distinguish the possible reasons behind the drop in performance. We have used a single node speed of 15m/s and a single mobility model which was the Random waypoint model.

Mixed Effects Model. One reason for not including number of connections in the earlier ANOVA based analysis was that the design space becomes very large, especially when one considers the levels that this variable can take in a full design. Indeed, in general, for an n node system, the total number of possible connections in a system can be $O(n^2)$ (assuming no more than one connection per node). To handle this situation, we use a mixed effect model. A combination of fixed and random effect model is called the mixed effects model. Mixed effects model consists of at least one random and one fixed effect factor. In our analysis we use MAC and routing protocols as fixed factors and number of connections as the random factor. In a fixed effect model, the levels of a factor considered are fixed (e.g. 802.11, CSMA as MAC protocols) and the inference is made only for the levels considered in the study. The inference derived for a fixed factor cannot be generalized to other levels of the factor which are excluded from the study. In contrast, in a random effect model, the levels of the factor are viewed as a random sample from an infinite population of normally distributed levels which can vary across different replications of the same experiment. One might perform the study using one set of levels but the inference can be generalized to other levels of that factor.

In order to address the issue of interaction between MAC and routing protocols when different number of connections are used, we consider the number of connections as a random factor. This allows us to use a few connections to perform the study and yet the conclusions would hold for the entire population of number of connections. We set up a three factor experiment to test whether MAC and routing protocols interact for different number of connections. MAC and routing protocols are assumed to be the fixed factors and the number of connections is the random factor. The two levels of the MAC protocol considered are 802.11 and CSMA; and the two levels of the routing protocol considered are AODV and DSR. The number of connections used are 2, 4 and 8. The response variables used to measure the performance of different factors are latency, the number of packets received and fairness. The experiments were carried out for two different areas as noted in Figure 14. The following conclusions were obtained, more details on the tests are omitted here but can be requested from the authors.

- The results show that for a 1000×1000 simulation area, all response variables i.e. latency, the number of packets received and fairness, there is significant interaction between MAC and routing protocols at 95% confidence level. Given that the number of connections is a random factor, we can conclude from the results that for any number of connections, MAC and routing protocols show significant level of interaction.
- Essentially identical results hold even when the simulation area was changed to 600×600.

Thus, we can conclude that the results in preceding sections are robust to changes in number of connections and node density.

8 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 [Ba98] 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 [BDM+] 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 on the performance and (ii) in a static network we can control the degree and connectivity parameters more effectively; our results show that these parameters play an important role in protocol performance.

We make an important observation: our statistical analysis was aimed at understanding the relative variation in the performance of the system with changes in the particular MAC/routing protocols used. As such the statistical results make a generic conclusion, namely, MAC and routing layers interact. They do not yield additional information about interactions between particular combinations (e.g. 802.11 and AODV). Section 6 deals with this aspect to some extent. A study to understand the cross layer interaction between specific combinations of MAC and routing protocols can easily be done using the methodology presented here and will be undertaken subsequently.

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.

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