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Title:

EFFECT OF MOBILITY ON PERFORMANCE OF WIRELESS AD-HOC NETWORK PROTOCOLS

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Effect of Mobility on Performance of Wireless Ad-hoc Network Protocols

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Abstract

We empirically study the effect of mobility on the performance of protocols designed for wireless ad-hoc networks. An important objective is to study the interaction of the Routing and MAC layer protocols under different mobility parameters. We use three basic mobility models: grid mobility model, random waypoint model, and exponential correlated random model. The performance of protocols was measured in terms of (i) latency, (ii) throughput, (iii) number of packets received, (iv) long term fairness and (v) number of control packets at the MAC layer level. Three different commonly studied routing protocols were used: AODV, DSR and LAR1. Similarly three well known MAC protocols were used: MACA, 802.11 and CSMA. The main conclusion of our study include the following:

1. The performance of the network varies widely with varying mobility models, packet injection rates and speeds; and can be in fact characterized as fair to poor depending on the specific situation. Nevertheless, in general, it appears that the combination of AODV and 802.11 is far better than other combination of routing and MAC protocols.
2. MAC layer protocols *interact* with routing layer protocols. This concept which is formalized using statistics implies that in general it is not meaningful to speak about a MAC or a routing protocol in isolation. Such an interaction leads to trade-offs between the amount of control packets generated by each layer. More interestingly, the results raise the possibility of improving the performance of a particular MAC layer protocol by using a cleverly designed routing protocol or vice-versa.
3. Routing protocols with distributed knowledge about routes are more suitable for networks with mobility. This is seen by comparing the performance of AODV with DSR or LAR scheme 1. In DSR and LAR scheme 1, information about a computed path is being stored in the route query control packet.
4. MAC layer protocols have varying performance with varying mobility models. It is not only speed that influences the performance but also node degree and connectivity of the dynamic network that affects the protocol performance.

The main implication of our work is that performance analysis of protocols at a given level in the protocol stack need to be studied not locally in isolation but as a part of the complete protocol stack. The results suggest that in order to improve the performance of a communication network, it will be important to study *the entire protocol stack* as *a single algorithmic construct*; optimizing individual layers in the 7 layer OSI stack will not yield performance improvements beyond a point.

A methodological contribution of this paper is the use of statistical methods such as *design of experiments and analysis of variance methods* to characterize the interaction between the protocols, mobility patterns and speed. This allows us to make much more informed conclusions about the performance of the protocols than would have been possible by merely running these experiments and observing the data. These ideas are of independent interest and are applicable in other contexts wherein one experimentally analyzes algorithms.

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1 Introduction

Design of Mobile ad-hoc networks is currently an extremely active area of research. Mobile ad-hoc networks lack a fixed infrastructure in the form of wireline, or base stations to support the communication. Interest in ad-hoc networks for mobile communications has also resulted in a special interest group for Mobile, Ad-hoc Networking within the Internet Engineering Task Force (IETF) [MC].

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 [Sa95, RS96, Ra96, Pa97a, Ba98].) As ad-hoc networks lack fixed infrastructure in the form of base stations, fulfilling the above stated functional requirements becomes all the more difficult.

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

The role of routing protocols for mobile/ad-hoc networks is to find the shortest path from the source to the sink of a data transmission. The quality of these protocols is measured by the number of hops that data packets need to reach its destination. Routing protocols fall in one of the two categories: *proactive*, or *reactive*. Reactive routing protocols are also referred to as *on-demand*. Proactive protocols attempt to maintain routes to all destinations at all times, regardless of whether they are needed. Into the second category belong routing protocols which try to establish a route to the recipient when it is needed – on-demand. Example of such a protocol is DSR [JM96] where information about possible routes is done by flooding the network with routing packets. Methods based on *distance vectors* have been proposed – DSDV [PB94], AODV [PR99]. DSDV is derived from the classical distributed Bellman-Ford algorithm. 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].

In this paper, we consider three well known routing protocols: (i) Dynamic Source Routing Protocols

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

Many mobility models for ad-hoc networks simulations have been proposed. These include the *random waypoint* model [JM96], *random mobility model* [ZD97], and *exponential correlated random model (ECRM)* [RS98]. The first two specify movement for individual nodes, whereas the ECR model is a group mobility model. It specifies movement of a group of nodes in a correlated way. This model provides a more realistic model for node movement. A more sophisticated model is the *Reference Point Group Mobility (RPGM)* model [HG+99]. Other models are discussed in [BCSW98], [DCY00], [Ha97], [LH99].

2 Our Contributions

The goal of the present work is to empirically and statistically quantify the effects of mobility on the performance of multihop ad-hoc networks. 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 very different. The grid mobility model has a very strict movement pattern and this results in a steady node degree and connectivity property of the network over time. On the other hand, the random waypoint mobility model has a mobility pattern that is hard to predict, and thus results in frequent changes in network invariants such as degree and connectivity. The ECR mobility model falls somewhere in between and includes features from both the previous models. In this model the network remains stable within a given group but changes if nodes from different groups are intermixed.

Apart from mobility patterns, we study the effect of speeds and injection rates of packets on the system performance. Thus our input variables are (i) three routing protocols: DSR, AODV and LAR Scheme 1, (ii) three MAC protocols: CSMA, MACA and 802.11, (iii) three mobility models, (iv) three injection rates, (v) four speeds.

Our evaluation criteria consists of following basic metrics: (i) *Latency:* Average end to end delay for each packet as measured in seconds, (ii) Total number of packets received, (iii) *Throughput:* The total number of unique data packets received in bits/second, (iv) Long term fairness of the protocols, i.e. the proportional allocation of resources given to each active connection and (v) *Control Overhead:* The number of control packets used by MAC and routing layers.

The total number of scenarios we thus need to consider is 324. We ran each experiment 10 times to reduce the variance. This resulted in 3240 runs. We have done a *factorial experimental design* and measured the response for each of the 5 response variables (output metrics). We also depicted our results as plots. Some of the plots are shown in the Appendix. Given the scope of data it is not possible to show all of the experimental data in detail here but is available from the authors upon request.

A methodological contribution of this paper is the use of statistical methods such as design of experiments and analysis of variance methods to characterize the interaction between the protocols, mobility patterns and speed. This allows us to make much more informed conclusions about the performance of the protocols than would have been possible by merely running these experiments and observing the data. These ideas are of independent interest and are applicable in other contexts wherein one experimentally analyzes algorithms. To our knowledge such methods have not been used in performance modeling of protocols in communication networks.

Scenario specific results: We first summarize results specific to each of the scenarios. The results for the first two scenarios is discussed in further in the subsequent sections. The discussion of results for the remaining scenarios is omitted due to lack of space.

Scenario 1: Grid mobility model. Performance of CSMA and MACA was poor. 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 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, but the protocol performed substantially better than CSMA and MACA at low speed of nodes. 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).

Scenario 2: Random waypoint model. This experiment illustrated the difference 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 quite high. As a result the performance parameters exhibit the worst behavior in this scenario. CSMA and MACA performed poorly. Performance of 802.11 depended on the routing protocol used, and performed best with AODV.

Scenario 3: Exponential correlated random model. ECRM represents a model with a very good uniform distribution of nodes. Moreover, the nodal degree and connectivity characteristics of nodes within a group stays 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.

Scenario 4: Channel bandwidth and quality of service for mobile networks. In this experiment we used the random waypoint model, but we increased the channel bandwidth to 5 Mb/s. The performance of 802.11 has increased proportionally, and the deterioration was now only visible at the high injection rate. There was no increase of performance for CSMA or MACA. The conclusion that we can draw is that increase of the channel bandwidth cannot be a cure on high interaction between MAC and routing layer protocols as well as collision based performance degradation of MAC protocols. More bandwidth increases performance only proportionally, whereas interaction of MAC and routing layer protocols decreases the performance at much higher rate.

Scenario 5: Scaling with the number of nodes. We used the random waypoint model, but the number of nodes was increased from 49 to 100. The channel bandwidth was 5 Mb/s. There was a slight increase in latency, the increase was proportional to the additional number of hops needed as there were twice as many nodes. The number of control packets at MAC layer level increased proportionally to the extra number of hops needed. This behavior is mainly due to the higher channel bandwidth which was able to accommodate the data and control packets.

Broad Conclusions and Implications

1. The performance of the network varies widely with varying mobility models, packet injection rates and speeds; and can be in fact characterized as fair to poor depending on the specific situation. Nevertheless, in general, it appears that the combination of AODV and 802.11 is far better than other combination of routing and MAC protocols.

2. MAC layer protocols *interact* routing layer protocols. This concept which is formalized using statistics implies that in general it is not meaningful to speak about a MAC or a routing protocol in isolation.

Such an interaction leads to trade-offs between the amount of control packets generated by each layer. More interestingly, the results raise the possibility of improving the performance of a particular MAC layer protocol by using a cleverly designed routing protocol or vice-versa.

3. Routing protocols with distributed knowledge about routes are more suitable for networks with mobility. This is seen by comparing the performance of AODV with DSR or LAR scheme 1. In DSR and LAR scheme 1, information about a computed path is being stored in the route query control packet.
4. MAC layer protocols have varying performance with varying mobility models. It is not only speed that influences the performance but also node degree and connectivity of the dynamic network that affects the protocol performance.

The main implication of our work is that performance analysis of protocols at a given level in the protocol stack need to be studied not locally in isolation but as a part of the complete protocol stack. The results suggest that in order to improve the performance of a communication network, it will be important to study *the entire protocol stack* as *a single algorithmic construct*; optimizing individual layers in the 7 layer OSI stack will not yield performance improvements beyond a point.

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).

3 Experimental Setup

We first describe the details of the parameters used.

3.1 Measures of Performance

The independent (input) variables are the scenario, connection, protocol triple and the injection interval for packets. The following three pieces of information (also called the dependent variable) were collected: (i) Average end to end delay for each packet as measured in seconds, (ii) Total number of packets received, (iii) Throughput in bits/second, (iv) Adjusted number of control packets at MAC layer level per 1,000 data packets[3] , (v) Total number of control packets at routing layer level.

3.1.1 Measuring average Fairness, Latency and Throughput

Apart from latency and packets received that are plotted for each connection (recall for most part we deal with two connections), we also report the average behavior of the protocols. We briefly describe the method we use to calculate this. Average throughput and average latency is simply the average over 20 runs of each protocol over the two connections (10 for each connection). For fairness, let $r = p_1/p_2$ denote the ratio of packets received for a given run of the protocol for the two connections. Then $|r-1|$ denotes the deviation of the protocol from perfectly equitable allocation.[4] Average fairness is $\sum_{i=1}^{i=10} r_i$, where r_i is the above stated

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

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

1. **Network Topology:** We describe the experiment specific topologies in respective sections.
2. **Number of connections:** We use two connections.
3. **Routing protocols** : AODV, DSR, LAR scheme 1.
4. Movement of nodes at 10 m/s, 20 m/s, 30 m/s, 40 m/s.
5. The initial packet size was 256 bytes, the initial number of packets was 2,000, and the initial injection interval was 0.05 second. Each time the injection interval was reduced by a factor of 2, we also reduced the packet size by a factor of 2 but increased the number of packets by a factor of 2. For example, if the injection interval was halved to 0.025 seconds then the new packet size was 128 bytes and the new number of packets was 4,000. This allowed us to keep the injection at input nodes constant in terms of bits per second.
6. The bandwidth for each channel was set to 1Mbit. Other radio propagation model details are as follows: (i) Propagation path-loss model: two ray (ii) Channel bandwidth: 1 Mb (iii) Channel frequency: 2.4 GHz (iv) Topography: Line-of-sight (v) Radio type: Accnoise (vi) Network protocol: IP (vii) Connection type: TCP
7. **Simulator used:** GlomoSim.
8. The transmission range of transceiver was 250 meters.
9. The simulation time was 100 seconds.
10. Hardware used in all cases was a Linux PC with 512MB of RAM memory, and Pentium III 500MHz microprocessor.

Figure 1: parameters used in the Experiments.

ratio for the ith run of the protocol.

4 Statistical Analysis: Characterizing Interaction

We set up an experiment which evaluates 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).

1. **Routing protocols (denoted R):** AODV, DSR, LAR1
2. **Speed of Nodes (denoted S):** 10m/s, 20m/s and 40m/s.[5]
3. **MAC protocols (denoted M):** 802.11, CSMA and MACA
4. **Injection rates (denoted I):** low (0.05 second), medium (0.025 second) and high (0.0125 second).

An important research question we study is whether these four factors interact with each other in a significant way. 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. In our analysis, we analyze, if the above 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. We first summarize our general implications in Figure 2.

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

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. **ECRM Mobility Model**
    - (a) **Latency:** Significant 3 way interaction – Routing protocols, Transceiver (node) speeds and the MAC protocols interact significantly.
    - (b) **Number of packets received:** All 2-way interactions *except* Routing protocol/Injection rate and Routing Protocol/Transceiver Speed are significant.
    - (c) **Fairness:** Only Routing protocols and MAC protocols interact. All other interactions are completely insignificant.
3. **Random-way 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 to be significant.
    - (c) **Fairness:** The only 2-way interactions that are significant are MAC protocol/Injection rate and Routing protocol/MAC protocols.

Figure 2: Brief Summary of Statistical Results.

Due to lack of space, we describe the details only for the *grid mobility model.*

This experiment generates 81 distinct scenarios by using different combinations of MAC, router, injection rate and the speed. Our performance matrix consists of three measures i.e. latency, number of packets received and the fairness.

Approach: We first construct a matrix of 4 dummy variables. For each factor we create a dummy variable. This variable takes a value 1, 2 and 3 depending upon which level of the factor is switched on during the calculation of the performance measure. For example, the dummy variable for MAC protocol, would take 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 calculate interactions between the factors, we use a statistical technique known as *analysis of variance* (ANOVA). 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 y_{ijklm} is the measurement of the performance variable (e.g. latency) for the ith router, jth speed, kth MAC and lth injection rate. m is the number of replicates which is 20 in our experiment. 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. The two way interaction terms are $(\alpha\beta)_{ij}$, which captures the interaction present between the routing protocols and the speed of the nodes; $(\alpha\gamma)_{ik}$, which measures the interaction present between the routing and the MAC protocols; $(\alpha\delta)_{il}$, which measures the interaction between the routing protocol and the injection rates. Similarly, $(\beta\gamma)_{jk}$, measures the interaction between the nodes' speed and the MAC protocol. $(\beta\delta)_{jl}$, the interaction between the nodes' speed and injection rates; $(\gamma\delta)_{kl}$, the interaction between the MAC protocols and the injection rates. The three way interaction terms are $(\alpha\beta\gamma)_{ijk}$ which captures the interaction present between the router, nodes' speed and MAC protocols; $(\alpha\beta\delta)_{ijl}$, the interaction present between the router, nodes' speed and injection rates; $(\alpha\gamma\delta)_{ikl}$, the interaction present between the router, MAC and injection rates; $(\beta\gamma\delta)_{jkl}$, the interaction present between the nodes' speed, MAC and injection rates. Finally the four way interaction is measured by $(\alpha\beta\gamma\delta)_{ijkl}$ which includes all the four factors. ε_{ijklm} is the random error.

We utilize 81 blocks of information, where a block is a combination of a MAC, router, nodes' speed and injection rate. For each block we generate 20 replicates/samples for the analysis. For example, CSMA, AODV, 10m/s and low injection rate would form one block. Given that we have four factors, each with three levels, we can create $3X3X3X3 = 81$ blocks (each block is a combination of values for each of the four variables).

Performance measure: Latency. To test four way interaction between the MAC, router, nodes' speed and injection rates and their effect on the latency, we perform the four factor ANOVA using the above mathematical model. Here y_{ijklm} represents latency as the performance measure. Note that for each combination of i, j, k, l we have 20 independent replicates.

The results of this test are shown in Table 1. In the following discussion, we explain the meaning of each column. DF refers to the degrees of freedom, SS refers to the residual sum of squares. 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.

We start with an initial model which is the largest possible model containing all the main effects, all the two factor effects, all the three factor effects and the four factor effect. We compare it with the next largest model and try to find the smallest model that fits the data. In our case, we first compare model 14 with model 13. The F-test shows that the model 13 fits the data as well as model 14 so the four way interaction is not significant. Similarly, we try to find which 3-way interactions are significant and try to find the most important combination by dropping each 3-way term one at a time. Then we compare each of the models with a dropped off 3-way term with the *All 3-way model* (e.g. comparing model number 12 and 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. Looking at the F-test results of model numbers 9 to 12,[6] we find model 12 to be the most significant. From that we conclude that the router, nodes' speed and the MAC protocol interact most significantly. Note that this was the combination that were dropped off from

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[6] Models 9 to 12 are being compared with model number 13.

Model	Interaction	Source	SS	DF	F**-test**
1	main effect	$[R][S][M][I]$	87879	1611	7.01*
2	2-way	$[RS][RM][RI][SM][SI]$	80071	1591	2.9
3	2-way	$[RS][RM][RI][SM][MI]$	79705	1591	1.07
4	2-way	$[RS][RM][RI][SI][MI]$	82480	1591	14.98*
5	2-way	$[RS][RM][SM][SI][MI]$	79541	1591	0.24
6	2-way	$[RS][RI][SM][SI][MI]$	83689	1591	21.05*
7	2-way	$[RM][RI][SM][SI][MI]$	79857	1591	1.83
8	All 2-way	$[RS][RM][RI][SM][SI][MI]$	79492	1587	1.41
9	3-way	$[RSM][RSI][RMI]$	77310	1563	0.17
10	3-way	$[RSM][RSI][SMI]$	77512	1563	0.68
11	3-way	$[RSM][RMI][SMI]$	77377	1563	0.34
12	3-way	$[RSI][RMI][SMI]$	79012	1563	4.44*
13	All 3-way	$[RSM][RSI][RMI][SMI]$	77240	1555	0.65
14	All 4-way	$[RSMI]$	76718	1539	

Table 1: **Results of Four-Factor ANOVA:** 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 variable or the performance measure is the* latency. $*$ shows that the F-test is significant at 99% confidence level.

model 12.

To find out if there is a smaller model i.e. model with 2-way interactions that can fit the data as well as the 3-way interaction model, we further look at the 2-way interaction models. We start by looking at a complete 2-way interaction model, i.e. model number 8 and then drop off one term at a time and compare the sum of square residuals to find out which of the 2-way interactions are most significant. 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 and MAC; nodes' speed and MAC. There is no interaction between router and nodes' speed as far 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 is the smallest possible model.[7]

Performance measure: Number of packets received. The interpretation of the results in Table 2 are very similar to Table 1. The only difference here is that the performance measure or the response variable is now the number of packets received instead of 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. All smaller models with 3-way and 2-way interaction also turn out to be 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 interaction 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 also, the smallest model has only $[RSMI]$ 3-way interaction terms.

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[7] The reason for trying to find the smallest possible model is to be able 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 with the remaining factors.

Model	Interaction	Source	SS	DF	F-test
1	main effect	$[R][S][M][I]$	354609	1611	92.28*
2	2-way	$[RS][RM][RI][SM][SI]$	283870	1591	347.24*
3	2-way	$[RS][RM][RI][SM][MI]$	166571	1591	4.87*
4	2-way	$[RS][RM][RI][SI][MI]$	189797	1591	72.66*
5	2-way	$[RS][RM][SM][SI][MI]$	172840	1591	23.16*
6	2-way	$[RS][RI][SM][SI][MI]$	199212	1591	100.14*
7	2-way	$[RM][RI][SM][SI][MI]$	166835	1591	5.64*
8	All 2-way	$[RS][RM][RI][SM][SI][MI]$	164903	1587	9.69*
9	3-way	$[RSM][RSI][RMI]$	156619	1563	26.67*
10	3-way	$[RSM][RSI][SMI]$	140957	1563	3.81*
11	3-way	$[RSM][RMI][SMI]$	141359	1563	4.40*
12	3-way	$[RSI][RMI][SMI]$	140992	1563	3.86*
13	All 3-way	$[RSM][RSI][RMI][SMI]$	138342	1555	4.76*
14	All 4-way	$[RSMI]$	131816	1539	

Table 2: **Results of Four-Factor ANOVA:** 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 variable or the performance measure is the* number of packets received. $*$ shows that the F-test is significant at 99% confidence level.

Performance measure: Fairness. Table 3 shows the ANOVA results for various models using 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 replicates instead of 20 for each of the 81 blocks mentioned above.[8] 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.

5 Experimental Results for Grid Mobility Model

The setup of this experiment is a grid network of 7×7 nodes. There are 49 nodes that are positioned on the grid. 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 (see Figure 3). The movement of the nodes is described quite simply. Let k range over the node IDs. Then 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. Thsi is esentially the reflecting boundary condition 9as opposed to periodic boundary conditions used in many other contexts). We run the simulation with four different node speeds: 10 m/s, 20 m/s, 30 m/s, 40 m/s.

The experimental results are depicted in Figures 4 through 12. The figures show results for 10 independent runs with various simulation seeds. First observe that both CSMA and MACA have very poor performance in this scenario. 802.11 performed significantly better; although its performance was heaveliy

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[8] This is due to the fact that fairness measure is calculated by taking a ratio of the throughput for the two connections.

Model	Interaction	Source	SS	DF	F-**test**
1	main effect	$[R][S][M][I]$	73372256	801	3.35*
2	2-way	$[RS][RM][RI][SM][SI]$	68058255	781	4.63*
3	2-way	$[RS][RM][RI][SM][MI]$	67318214	781	2.47
4	2-way	$[RS][RM][RI][SI][MI]$	67272725	781	2.34
5	2-way	$[RS][RM][SM][SI][MI]$	66676504	781	0.60
6	2-way	$[RS][RI][SM][SI][MI]$	69488169	781	8.80*
7	2-way	$[RM][RI][SM][SI][MI]$	66913918	781	1.29
8	All 2-way	$[RS][RM][RI][SM][SI][MI]$	66471106	777	1.06
9	3-way	$[RSM][RSI][RMI]$	63979087	753	0.62
10	3-way	$[RSM][RSI][SMI]$	63989025	753	0.64
11	3-way	$[RSM][RMI][SMI]$	64278351	753	1.06
12	3-way	$[RSI][RMI][SMI]$	64873740	753	1.93
13	All 3-way	$[RSM][RSI][RMI][SMI]$	63549699	745	0.80
14	All 4-way	$[RSMI]$	62451998	729	

Table 3: **Results of Four-Factor ANOVA:** 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 variable or the performance measure is the* fairness. $*$ shows that the F-test is significant at 99% confidence level.

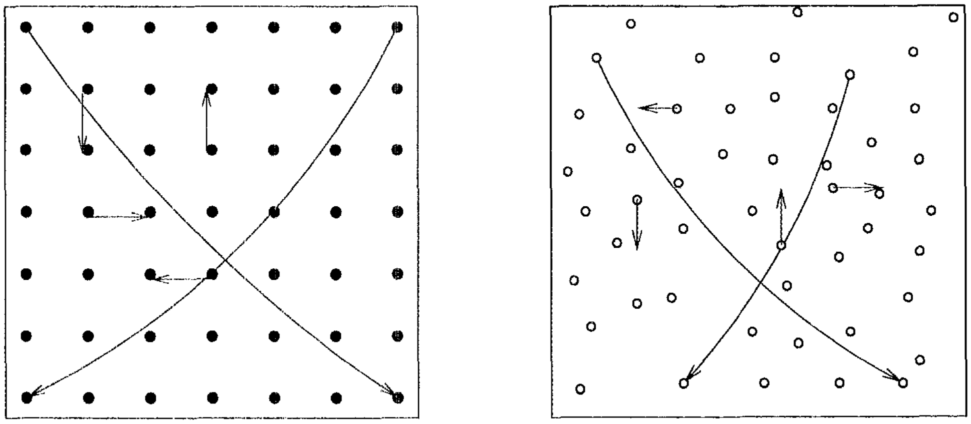

Figure 3: **Left:** Grid mobility. We position 49 nodes onto a 7×7 grid. The nodes are numbered from the top left corner in rowwise order. The movement starts as follows: 1st node - south, 2nd node - north, 3rd node east, 4th node - west, etc. In general, nodes belonging to the equivalence class $0 \equiv k \bmod 4$ 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. 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. **Right:** Exponential correlated random mobility model . We position 49 nodes uniformly onto a 300×300 meters area. The nodes are numbered in the order their random position is computed. The start movement depends on assignment to the four groups.

influenced by the particular routing protocol used (performs best with AODV). Moroever, at higher speeds, it starts exhibiting similar problems as the other protocols.

It is possible to qualitatively explain the results. First, the grid mobility network allows "capture effects" to influence the MAC layer protocols. Second, the carrier sensing and the RTS/CTS control format on its own is too weak in a highly mobile environment. Nodes at many moments during the simulation form highly dense clusters that give rise to hidden and exposed terminal phenomena. This fact alone is enough to negatively influence CSMA. In case of MACA we can see an enormous increase of the number of control packets. The increase in one case was a astounding 130 times the number of data packets. We note that this increase is at the low injection rate. At higher injection rate the number of data packets received is very low, and thus, the number of control packets goes down. This is partly because the total number of data packets delivered are substantially lower. The low number of data packets received stems partly from the internal mechanism of routing protocols. If a routing protocols does not find a route within a certain time, all data packets in node's buffer directed to the destination for which the routing protocol failed to find a route are deleted. This points out a strong interaction between the routing and MAC layer protocol – if the underlying MAC layer fails to deliver the control packets, then the routing protocol can be adversely affected.

We can also note the negative influence of routing protocols that keep the routing information in their route request packets, i.e., DSR and to an extent also LAR1. LAR scheme 1 is a basically a location aided protocol with route discovery similar to DSR. The performance of MAC layer protocols with AODV is better and this can be attributed to the distributed handling of the routing information; i.e. the information is stored at forwarding nodes rather than in the route request packet. This feature of routing protocols has lead for example to design of highly distributed routing protocols, e.g. TORA.

The figures show the number of routing protocols are adjusted to 1,000 nodes injected at sources. At the highest injection rate we inject 8,000 packets. If we adjust the number of the control packets proportionally to the number of data packets received we see that the number of control packets could go up as much as 1,000–3,000 times to the number of data packets.

We note that a grid mobility model yields stable average temporal node degree and connectivity values. This allows routing and MAC protocols to perform much better than when the transceivers move using the random waypoint model.

6 Experimental Results for ECRM Model

The setup of this experiment is an area of 300 × 300 meters onto which we uniformly randomly position 49 nodes. Let the nodes to 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 $0 \equiv k \mod 4$ form the first group, nodes belonging to the class $1 \equiv k \mod 4$ form the second group, nodes belonging to the class $2 \equiv k \mod 4$ form the third group, and nodes belonging to the class $3 \equiv k \mod 4$ form the fourth group. The setup is shown in Figure 3. The four groups follow the exponential correlated random model described by an equation of the form

$$x(t+1) = x(t)e^{(-1/\tau)} + s \cdot \sigma \cdot r \cdot \sqrt{1 - e^{(-2/\tau)}}$$

where: (i) $x(t)$ 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 his orientation is reversed, i.e., after the orientation of all nodes is reversed, the group starts moving to the opposite direction.

ECRM represents a mobility model that keeps the relative distances of nodes within a group roughly constant. The correlated movement of nodes creates for each node within a group a set of neighbors that stays intact. This facilitates routing and there are lower requirements on the MAC layer protocols. There are changes as the four groups interact, however.

The results are depicted in Figures 13 to 21. The performance of 802.11 has improved significantly. The performance of MACA is better than for other mobility models; CSMA performs poorly.

We can see a quite good performance of 802.11, especially in connection with AODV. This is partly due to the mobility model's lower requirements on negotiation of transfer of data packets. For example, at the injection rate of 0.025 second we see that there are about 14,000 control packets used by the MAC layer protocol. This constitutes a requirement of 5kb/s (plus 100kb/s for data packets). This is well below the channel capacity of 1Mb/s; the overall performance is very good and gives space for control packets of the routing layer. The figures show a very stable performance of MACA with any of the three routing protocols. That means that channel capacity and the number of control packets at the routing layer level was not a bottleneck.

CSMA seems to be unsuitable for any reasonable mobility model, and would perform well only in the case of completely disjoint groups (in our setup) with communication only within these groups with a very low number of connections.

LAR scheme 1 again dominates DSR. Location aided algorithms in general look to perform better than algorithms without this capability. We can compare performance of 802.11 with DSR and 802.11 with LAR scheme 1. The latter algorithms lowers the number of required control packets at routing layer level and facilitates use of the available channel capacity.

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Appendix: Figures

Grid mobility

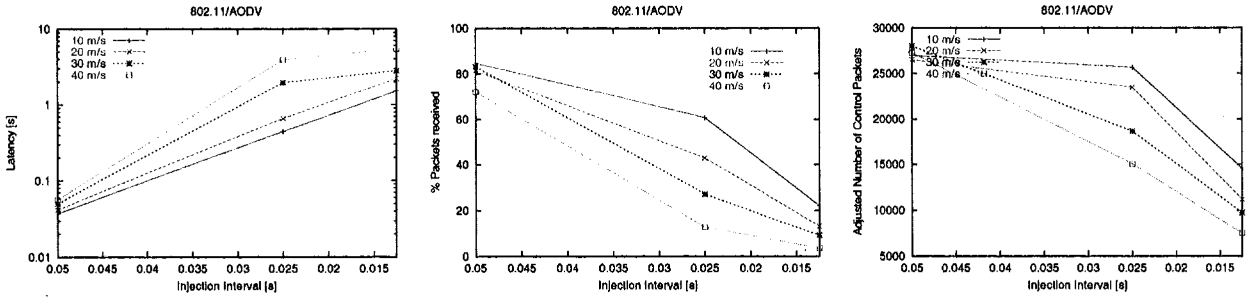

Figure 4: Grid mobility, 802.11 with AODV. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets at the MAC layer level. The figure shows an average over 10 independent simulation runs with different seeds. The figure shows that performance of 802.11 decreases with the speed and injection rate. The reasons are the increased total number of control packets at MAC layer, and interaction with the routing layer. The routing protocol with increased speed and injection rate fails to deliver a route to the destination and this causes the data packets at node's buffer to be removed.

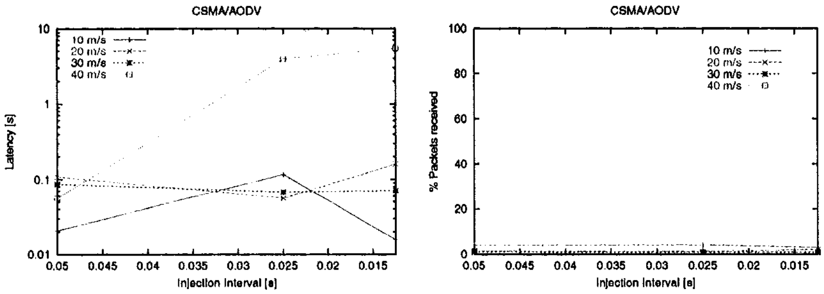

Figure 5: Grid mobility, CSMA with AODV. From left: (a) Latency, (b) Packets received. The figure shows an average over 10 independent simulation runs with different seeds. The performance of CSMA is very poor. The deficiencies of this MAC layer protocol and speed causes that routing control packets get lost, and a route to the destination is never delivered.

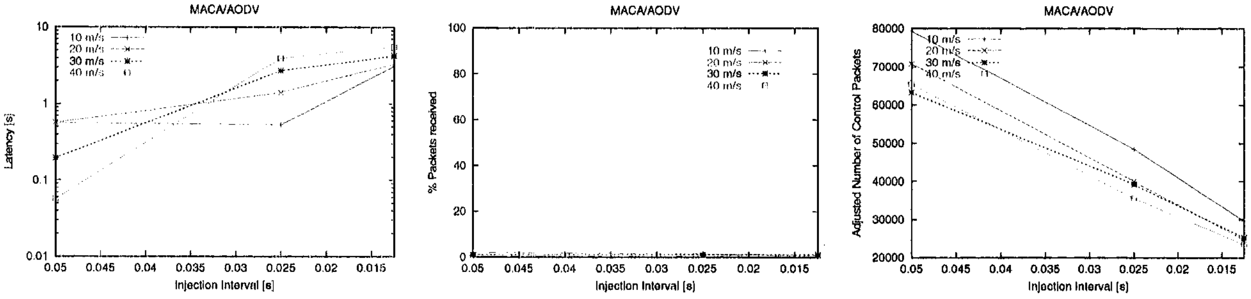

Figure 6: Grid mobility, MACA with AODV. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets at the MAC layer level. The figure shows an average over 10 independent simulation runs with different seeds. MACA completely fails in this case. The reasons are similar to the reasons given for CSMA.

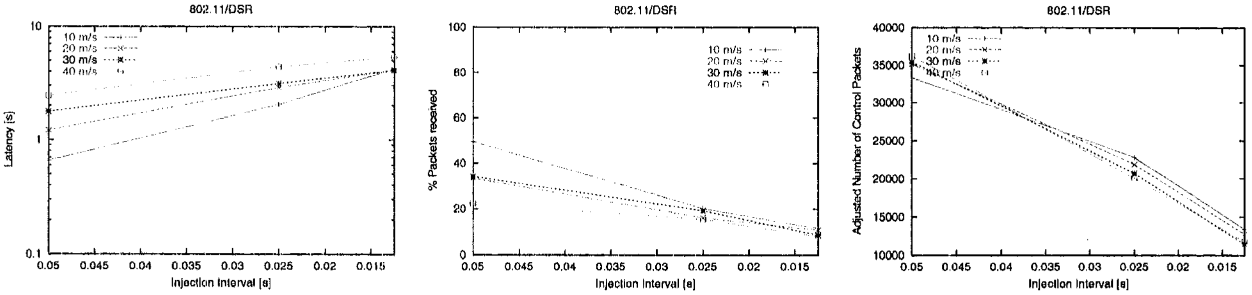

Figure 7: Grid mobility, 802.11 with DSR. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets at the MAC layer level. The figure shows an average over 10 independent simulation runs with different seeds. Worse performance of DSR in this case was the reason behind the worse overall performance as compared to 802.11 with AODV.

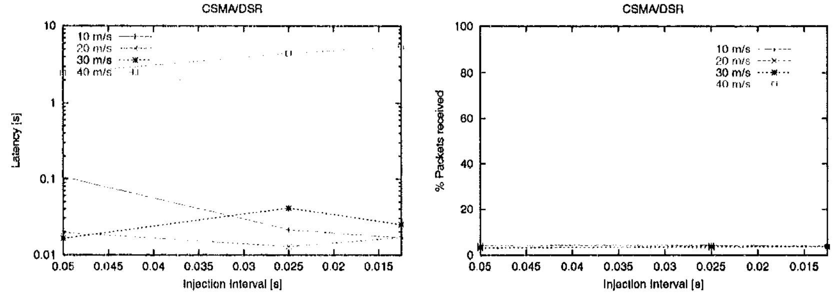

Figure 8: Grid mobility, CSMA with DSR. From left: (a) Latency, (b) Packets received. The figure shows an average over 10 independent simulation runs with different seeds.

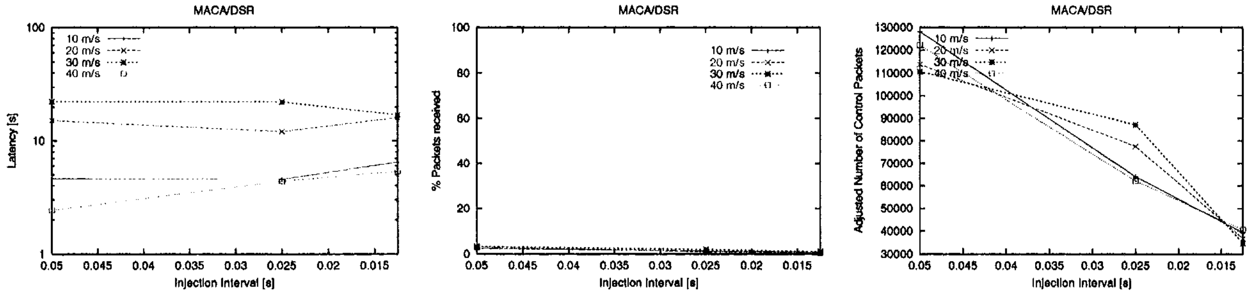

Figure 9: Grid mobility, MACA with DSR. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets at the MAC layer level. The figure shows an average over 10 independent simulation runs with different seeds.

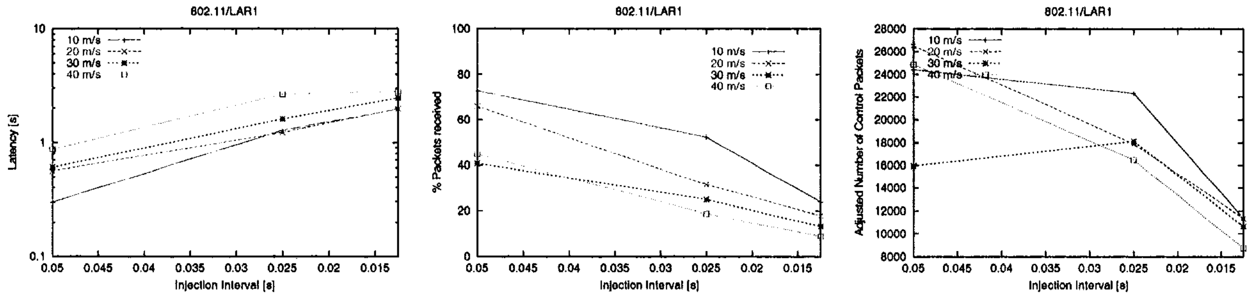

Figure 10: Grid mobility, 802.11 with LAR scheme 1. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets at the MAC layer level. The figure shows an average over 10 independent simulation runs with different seeds. The overall performance is in between the performance of 802.11 with AODV and DSR. We see better performance than with DSR and the reason is the location routing capability of LAR.

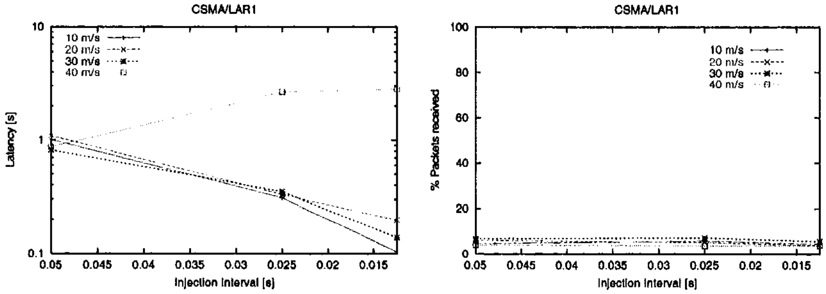

Figure 11: Grid mobility, CSMA with LAR scheme 1. From left: (a) Latency, (b) Packets received. The figure shows an average over 10 independent simulation runs with different seeds.

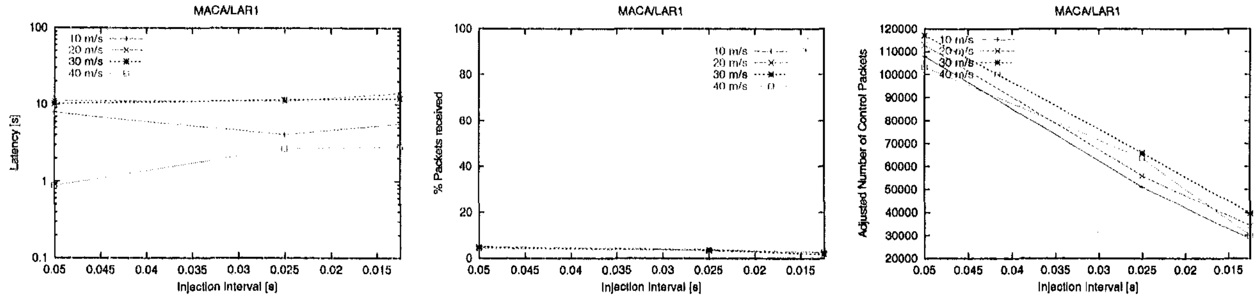

Figure 12: Grid mobility, MACA with LAR scheme 1. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets at the MAC layer level. The figure shows an average over 10 independent simulation runs with different seeds.

Exponential Correlated Random Model

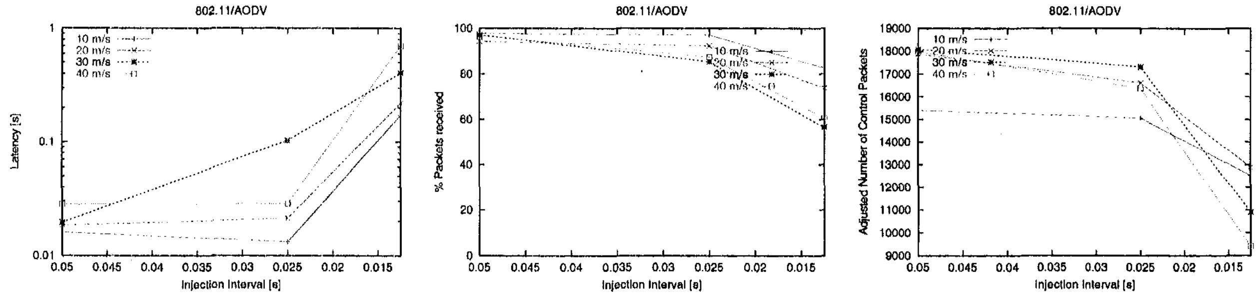

Figure 13: ECR mobility, 802.11 with AODV. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets. The figure shows an average over 10 independent simulation runs with different seeds. The performance is better than in the corresponding case with the grid mobility model.

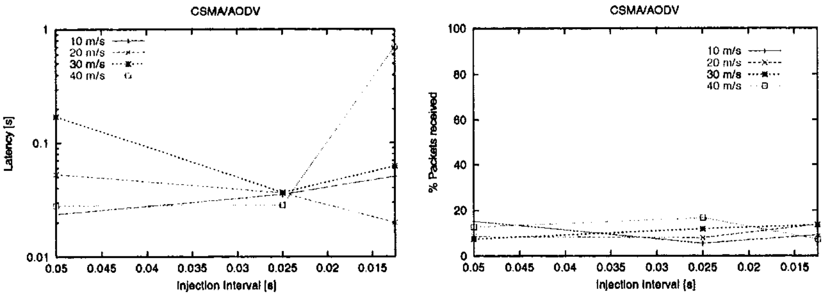

Figure 14: ECR mobility, CSMA with AODV. From left: (a) Latency, (b) Packets received. The figure shows an average over 10 independent simulation runs with different seeds. The performance of CSMA stays very poor even in the case of ECRM for all routing protocols.

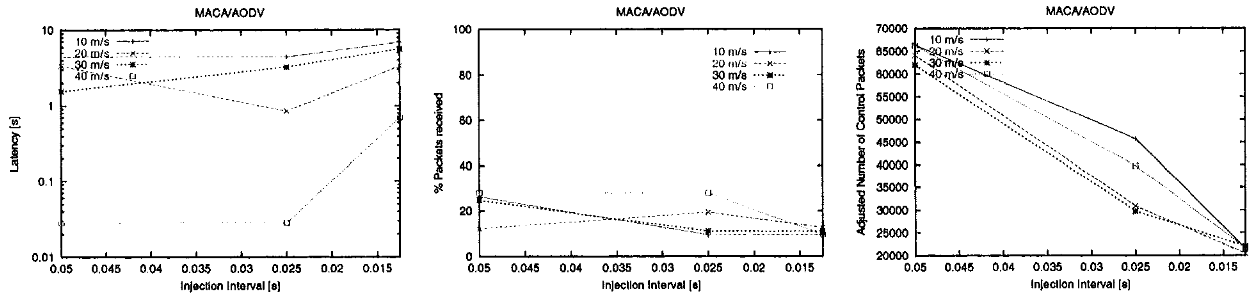

Figure 15: ECR mobility, MACA with AODV. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets. The figure shows an average over 10 independent simulation runs with different seeds. Performance is better than with the grid mobiloity model, but stays unacceptably low.

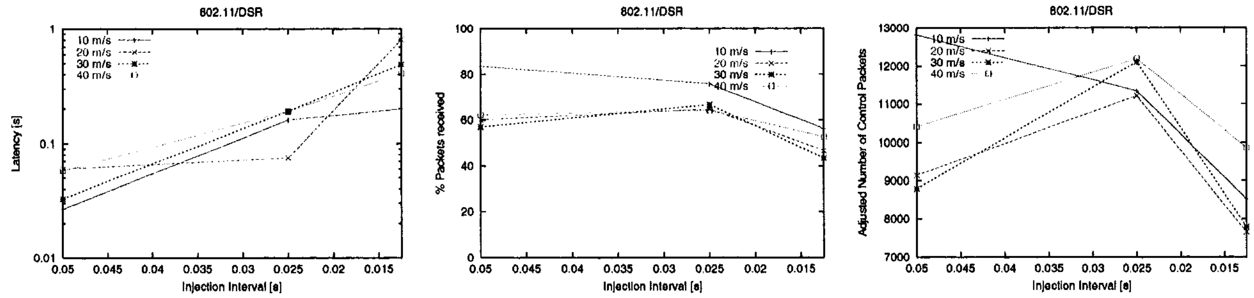

Figure 16: ECR mobility, 802.11 with DSR. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets. The figure shows an average over 10 independent simulation runs with different seeds. Performance of 802.11 with DSR is again lower that with AODV. The distributed handling of routing information of AODV seems to help in mobility scenarios.

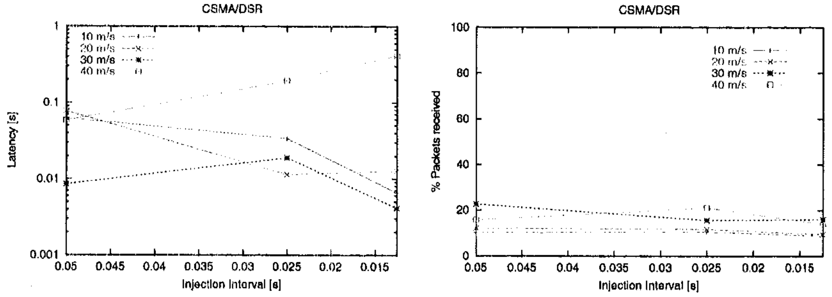

Figure 17: ECR mobility, CSMA with DSR. From left: (a) Latency, (b) Packets received. The figure shows an average over 10 independent simulation runs with different seeds.

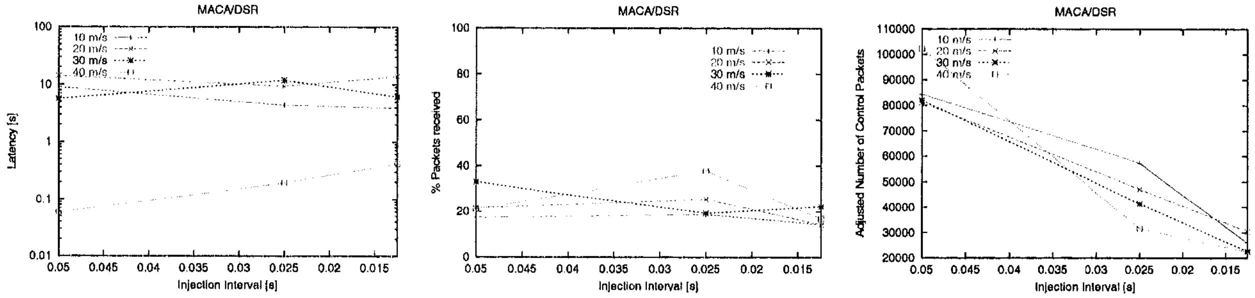

Figure 18: ECR mobility, MACA with DSR. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets. The figure shows an average over 10 independent simulation runs with different seeds.

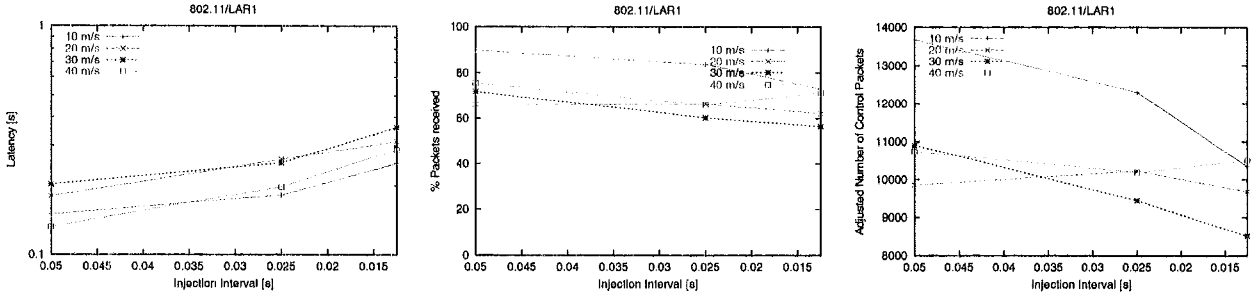

Figure 19: ECR mobility, 802.11 with LAR scheme 1. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets. The figure shows an average over 10 independent simulation runs with different seeds. The performace again in between the performance with AODV and LAR scheme 1.

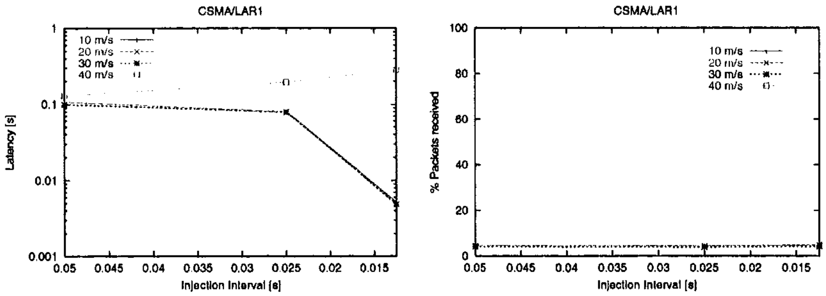

Figure 20: ECR mobility, CSMA with LAR scheme 1. From left: (a) Latency, (b) Packets received. The figure shows an average over 10 independent simulation runs with different seeds.

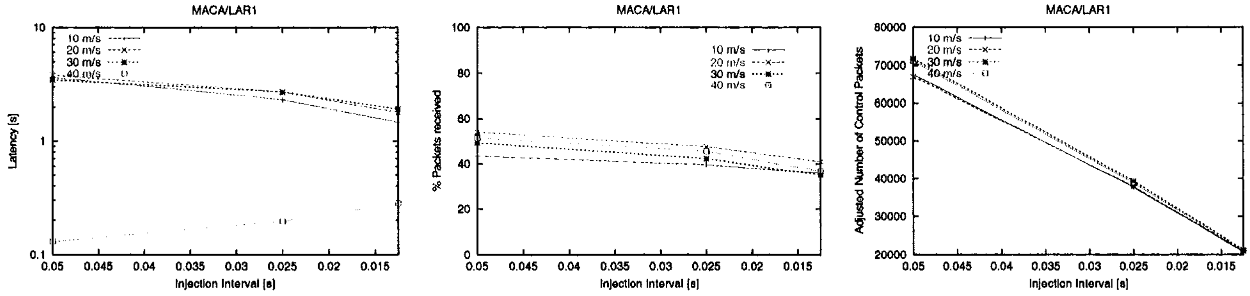

Figure 21: ECR mobility, MACA with LAR scheme 1. From left: (a) Latency, (b) Packets received, (c) Number of control packets per 1,000 data packets. The figure shows an average over 10 independent simulation runs with different seeds. We can see a relatively good performance of MACA with LAR scheme 1, however, the latency increased significantly.

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Title:

EFFECT OF MOBILITY ON PERFORMANCE OF WIRELESS AD-HOC NETWORK PROTOCOLS

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