Analyzing the Effect of Routing Protocols on Media Access Control Protocols in Radio Networks

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Abstract

We study the effect of routing protocols on the performance of media access control (MAC) protocols in wireless radio networks. Three well known MAC protocols: 802.11, CSMA, and MACA are considered. Similarly three recently proposed routing protocols: AODV, DSR and LAR scheme 1 are considered. The experimental analysis was carried out using GloMoSim : a tool for simulating wireless networks. The main focus of our experiments was to study how the routing protocols affect the performance of the MAC protocols when the underlying network and traffic parameters are varied. The performance of the protocols was measured w.r.t. five important parameters: (i) number of received packets, (ii) average latency of each packet, (iii) throughput (iv) long term fairness and (v) number of control packets at the MAC layer level. Our results show that combinations of routing and MAC protocols yield varying performance under varying network topology and traffic situations. The result has an important implication; no combination of routing protocol and MAC protocol is the best over all situations. Also, the 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. A novel aspect of our work is the use of statistical technique, *ANOVA (Analysis of Variance)* to characterize the effect of routing protocols on MAC protocols. This technique is of independent interest and can be utilized in several other simulation and empirical studies.

1 Introduction and Motivation

Design of protocols for wireless mobile networks have been gaining momentum in the recent years. Researchers direct their effort towards design of protocols at various levels of the protocols stack. These include MAC layer protocols, routing protocols and transportation layer protocols; nowadays these are considered as independent sets of protocols that interact with each other. This effort is very challenging, especially, in case of ad-hoc wireless networks which do not rely on any fixed infrastructure in the form of base stations. The pioneering work in this field has been done by DARPA which sponsored **PRNET** (Packet Radio Network) [JT87], and **SURAN** (Survivable Adaptive Networks) [SW] projects. 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].

The goal of this paper is to undertake a systematic experimental study to analyze the performance of MAC/routing protocol combination for wireless ad-hoc networks. In particular, we are interested in determining if the performance of a particular MAC protocol is affected by the specific routing protocols used and vice-versa.

See Section 2 for additional details.

MAC Protocols. Three well known MAC protocols are considered: CSMA, MACA and 802.11 DCF. The choice of these protocols is based upon the earlier work in [BD+94, WS+97, RLP00]. The carrier sense multiple access (CSMA) first senses the channel for any ongoing transmissions. If the channel is empty the transceiver begins transmission; else it backs off a random amount of time and tries again. The main drawback of this protocol is it inability to cope with the classical hidden terminal problem. Many protocols have been proposed to avoid the hidden terminal problem. 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. On the other hand the protocol does not explicitly heck to see if the channel is empty before initiating the RTS/CTS handshake. Thus CSMA and MACA represent interesting cases wherein one can see the relative merits of collision avoidance mechanisms: carrier sensing versus RTS/CTS. MACAW builds on this idea but also recognizes the importance of congestion, and exchange of knowledge about congestion level among entities participating in communication. An advanced backoff mechanism is used 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 the source. 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. Detailed description of these protocols and the issues surrounding them are omitted due to lack of space and can be found in [BD+94, 802.11].

Routing Protocols. We briefly review the routing protocols used in our simulations: DSR, AODV, and LAR scheme 1 [JM96, PR99, KV98]. Again the choice of these protocols is based upon the earlier work in [DP+, BM+98, JL+00] on experimentally analyzing some of these protocols. To our knowledge the performance of LAR scheme 1 has not been extensively investigated. All of these protocols are on-demand (reactive) routing protocols – i.e. routes are found on a need to know basis. The Dynamic Source Routing Protocols (DSR) was introduced by [JM96]. A node in the network maintains routing information on nodes that are known to it. When the source node needs routing information, and this information is not in its node cache or the information has expired, the node initiates a *route discovery*. The node sends out a route request packet (RREQ) that contains the address of the source and destination node, and a unique identification number. Each intermediate node checks whether it contains route information on the destination node. If not, it appends its address to the route request packet, and resends the packet to its neighbors. Addresses of intermediate nodes are used to ensure that a given node forwards the route request packet only once. The route reply (RREP) is either produced by an intermediate node, or the destination node. In the former case, the route information of the intermediate node is used, and is appended to the reversed sequence of addresses from intermediate nodes; in the latter case the route reply is formed completely by the destination node by reversing the sequence of addresses from intermediate nodes. *Route maintenance* is performed by the protocol if there is a fatal problem, e.g., a route was disconnected by a node failure. In this case the protocol generates a *Route Error* (RERR) packet. Nodes that receive this packet adjust their node caches by removing the route information on routes beyond the failed node. DSR also uses acknowledgment packet to verify correct operation of its discovered routes.

The Ad-hoc On-demand Distance Vector Routing (AODV) [PR99] is an extension of the Destination-Sequenced Distance Vector Routing (DSDV) [PB94] in the direction of reactive behavior. DSDV is based on the classical Bellman-Ford routing algorithm. In DSDV each node maintains a table that lists all available destinations. It also routes to them the number of hops (or any other metric) necessary to reach such a destination along with next hop information, and a sequence number to distinguish between old and new routes. Each node periodically transmits the routing table to its neighbors which incorporate that information into their own routing table. This exchange can be also triggered by significant changes in the network. The routing table updates are sent either as incremental or full. Each node assigns a unique sequence number to the routing updates. The sequence number is used to keep track of new and old routes in node cache. AODV tries to minimize the number of routing table updates by spawning this mechanism on need-to-know basis. When a source node needs to find a route to a destination it broadcasts a route request packet. This packet is forwarded over the network and forwarding nodes store the node address from which the route request came for the first time in their routing tables. This information is later reversed and used by the route request packet to find the route to the source. The route request packets use sequence numbers to ensure loop-free routes. When the route request packet encounters an intermediate node with information on the route to the destination, or the destination node itself, it follows the route that was used to reach this node and on the way updates routing tables of intermediate nodes with the routing information to the destination. This mechanism is also spawn by link failure, or other fatal problems.

Location-Aided Routing (LAR) [KV98] comes in two flavors: Scheme 1 and Scheme 2. We briefly describe Scheme 1. In this protocol, complexity of routing is reduced by using the physical location information, i.e., by limiting the search to a smaller zone. The *expected zone* is produced from the information about the physical whereabouts of the destination node. Scheme 1 produces the smallest rectangle that contains the source node and the expected zone. This rectangle is called the *request zone*. When a source nodes sends out a route request this request includes coordinates of the request zone. Intermediate nodes are allowed to forward the route request only to nodes within the request zone. This request zone is not modified by forwarding nodes. Forwarding mechanism for LAR is similar to DSR.

Each routing protocol and similarly each MAC protocol has its relative merits and shortcomings. Due to lack of space we refer the reader to [DP+, JL+00, RLP00, BD+94, TCG01] for a relative comparison.

2 Summary of Results and Implications

2.1 Overall Goal

We empirically characterize the effect of the interaction between the routing layer and the MAC layer in wireless radio networks. We only consider static networks in this paper. A follow on paper considers the effect of mobility. The work is motivated by research of (i) [Ba98, BS+97] that studies the interaction between TCP and the lower levels of the OSI stack (ii) [WS+97, NK+99, BD+94] that experimentally analyzes MAC layer protocols and (iii) recent results by Royer et.al. [DPR00, DP+, RLP00] that note the interplay between Routing and MAC protocols. In [DPR00], the authors conclude by saying – *"This observation also emphasizes the critical need for studying interactions between protocol layers when designing wireless network protocols"*. In [RLP00], authors conclude that the MAC protocol selection is a key component in determining the performance of a routing protocol and hence must be considered by any comparative study of routing protocols.

In order to analyze the issue of *interaction* rigorously, we resort to the popular statistical technique called ANOVA (the Analysis of Variance). ANOVA is commonly used by statisticians to study the sources of variation, importance and interactions among variables.[1] However, to the best of our knowledge, a detailed study aimed towards understanding the effect of interaction between MAC and routing protocols, using formal statistical tools, has not been undertaken prior to this work. Such methods provide simple yet formal and quantifiable ways to characterize interaction. We believe that these ideas are of independent interest and are likely to be useful in other similar settings.

Apart from routing and MAC protocols, we study the effect of injection rate and network topology on the performance variables. Thus our input variables are:

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

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

3. **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.

4. **Network topologies:** medium connectivity grid (Figure 5(a)(A)), high connectivity grid (Figure 5(a)(B)) and 6x6-3x3-6x6 corridor grid (Figure 5(b)). The choice of the networks is based upon earlier work in [BD+94, WS+97]

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, queuing and backoffs, (ii) Total number of packets received (and in some cases packet delivery fraction) (iii) *Throughput:* The total number of unique data packets received in bits/second, (iv) Long term fairness of the protocols, i.e. the proportional allocation of resources given to each active connection and (v) *Control Overhead:* The number of control packets used by MAC layer. Each of the input parameters and the performance measures considered here have been used by earlier experimental studies such as [DPR00, DP+, BM+98, KV98, RLP00, RS96].

The general results of this paper can be summarized as follows.

1. The performance of MAC layer protocols is affected by the routes chosen by the routing layer. Not surprisingly, when two routes share many common nodes, their performance tends to be worse than in scenarios when the routes do not share many common nodes. More interestingly, MAC layer performance deteriorates even when routes do not intersect but come close enough. As a result, the task of

[1] 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.

adaptive routing protocols that attempt to modify the routes after sensing the load on individual links (i.e. they are adaptive) becomes complicated.

2. The worst performer among the three protocols is MACA. This is somewhat surprising although similar results have also been reported by [RLP00]. MACA builds on CSMA/CA and thus one would expect somewhat better performance. But it appears that the RTS/CTS overhead offsets the gains made in successful transmission. At lower injection rates, 802.11 was the best of the three while at higher injection rates CSMA performs better as long as the interaction among active connections was low. The drop in performance for 802.11 was much more drastic at higher injection rates. This drop is largely due to the increase in RTS/CTS/ACK control packets. Again, routing protocols play a significant role in determining the loads and injection rates at a node.

3. The performance of protocols varies significantly from one run to another with regards to the resources assigned to connections. CSMA (and also other protocols to some extent) tends to inequitably assign resources to the two connections. One of the reasons for this behavior is interaction of the MAC layer protocol with the routing protocol with subsequent impact onto the long term fairness.

The main conclusion of our work is that *no single MAC protocol or MAC/Routing protocol combination dominated the other protocols across various measures of efficiency.* This motivates the design of a new class of parameterized protocols that adapt to changes in the network connectivity and loads. We refer to these class of protocols as *parameterized adaptive efficient protocols* (PARADYCE) and as a first step suggest key design requirements for such a class of protocols. These include: ability of the MAC protocols to dynamically change the usage of control packets with change in contention. we will discuss this issue further in the concluding section.

3 Experimental Setup

We now describe the details of the parameters used.

3.1 Measures of Performance: Average Fairness, Latency and Throughput

We briefly describe the method used to report the average behavior of the protocols. Average throughput and average latency is simply the average over 10 runs of each protocol over the two connections.[2] For average fairness let $q = (p_1/p_2) - 1$ if $p_2 \leq p_1$ and $q = (p_2/p_1) - 1$ if $p_1 < p_2$. The maximum allowed value for q is 5, i.e., if $q > 5$ we set q to 5 to emphasize smaller values. Average fairness is $\sum_{i=1}^{10} \hat{q}_i$, where $\hat{q}_i$ is q with maximum value 5 and normalized into $\langle 1, 2 \rangle$ interval for the ith run of the protocol.

3.2 Understanding the effects of Route Interaction

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 2(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 since y and z cannot simultaneously transmit under the radio propagation model.

Example 1: This example illustrates the effect of paths chosen by a routing protocol on the system performance. The underlying network is shown in Figure 2(b). We used 49 nodes to produce a grid of 7×7 nodes. The nodes in this experiment were positioned at a distance of 50 meters (i.e. grid unit = 50m) from each other gaining a physical size of the grid of 300×300 meters. Note that transmission radii from nodes in the very left column cannot directly communicate with nodes in the very right column, and vice-versa. In this particular example, we use CSMA as the underlying MAC layer protocol. We have two connections: one going from x to y and the other from z to w. The end points of the two connections were placed in such a way that if the routing protocol chooses the shortest path there would be no interference between the x-y connection and the z-w connection, see Figure 2. If the routing

[2] This gives a total of 20 runs, 10 from each connection.

1. **Network topologies:** medium connectivity grid (Figure 5(a)(A)), high connectivity grid (Figure 5(a)(B)) and 6x6-3x3-6x6 corridor grid (Figure 5(b)). The choice of the networks is based upon earlier work in [BD+94, WS+97]
2. **Number of connections:** Unless otherwise stated we use two connections.
3. **Routing protocol** : AODV, DSR, LAR scheme 1.
4. The initial packet size was 512 bytes, the number of packets was 1,000, and the injection interval was 0.1 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 0.05 seconds then the new packet size was 256 bytes and the new number of packets was 2,000. This allowed us to keep the injection at input nodes constant in terms of bits per second.
5. 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
6. **Simulator used:** GlomoSim.
7. The transmission range of transceiver was 250 meters.
8. The simulation time was 100 seconds.
9. Hardware used in all cases was a Linux PC with 512MB of RAM memory, and Pentium III 500MHz microprocessor.
10. The following information was collected to measure the performance: (i) Average end to end delay for each packet as measured in seconds (latency), (ii) Total number of packets received, (iii) Throughput in bits/second and (iv) Total number of control packets at the MAC layer level.

Figure 1: Parameters used in the Experiments.

protocol chooses a less than optimal routing, interference between connections will arise.

Several modes of operations were observed. One of them occurred when the routing protocol found the shortest path for the connections. In this case, the number of received packets at sink was 1,000, i.e., 100%. In the second case, the routing protocol did not find the shortest path for one of the connections. This caused interference between the two connections and resulted in delivering only one packet for the connection. The four basic modes of operation from 15 different runs are summarized here. Different modes were counted as follows:

1. We considered 1,000 received packets for connection 1, and 0 received packets for connection 2 the same as 0 for connection 1 and 1,000 for connection 2, i.e., in general, we regarded symmetric results to be the same for the two connections.
2. If the number of packets received for a connection was e.g. 995 we counted it as 1,000, i.e., in general, we discarded small fluctuations and regarded such results as identical.

Using the notation (α, β, γ) to denote that in γ runs of the experiment, the number of packets received by connections 1 and 2 were α and β respectively. The experiments showed the following four modes: $(1000, 0, 6)$, $(1000, 500, 5)$, $(500, 500, 3)$, $(1000, 1000, 1)$. Thus only in 1 case, both connections received equal number of packets. In contrast for 6 runs, one connection received all the packets while the other connection did not receive any packets. We see that the routing protocol (AODV) [3] managed to find the shortest path only in one case.

Example 2 As another example, we consider how the path lengths and the location of connections affect the MAC protocol performance. For this experiment we consider two different topologies. In the first case, we fix the grid (12 × 7 nodes, 1 grid unit = 100m). For each value of injection rate do the following: (i) First collect results

[3] We have run this experiment also with DSR. In that case the routing performance was worse then that of AODV.

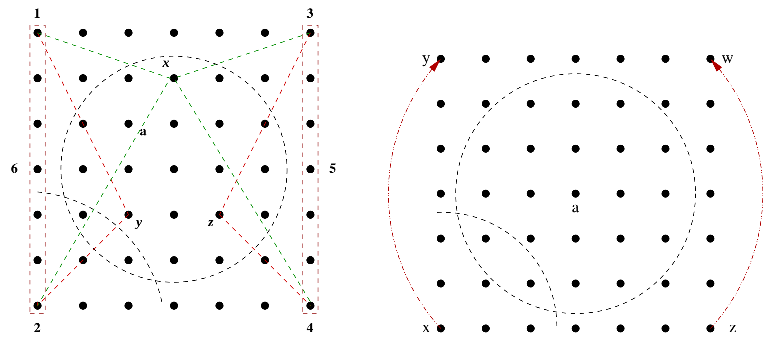

Figure 2: (a) Illustrating schematically the effect of routing paths on MAC layer protocols. The position of transceivers is shown as dots and for clarity the range of the center transceiver and the transceiver at the left bottom corner is shown. (b) Example 1: Effect of routing protocols. The topology induced is same as in Figure (a). The figure shows the possible paths used by the protocol. There are two parallel connections running along the boundary.

for a single connection. This is shown by the thick line between x and y in Figure 3(a). (ii) Run the experiment for 2 connections that are very far away. This is shown as connections $t - u$ and $r - s$ in Figure 3(a). Cases (i) and (ii) provide us with the base cases. The first tells us the basic variation introduced due to the simulator while the second case yields a base case in terms of how much effect a routing protocol has with no interaction between connections. (iii) Run the experiment when the two connections are very close as shown by $x - y$ and $w - z$. (iv) Finally, run it for connections that are slightly further off. This is also shown in Figure 3(a). For each value of injection rate, we measured latency, the number of packets received and the throughput of each of the three MAC protocols.

In the second sub-experiment we used three line graphs of varying length to reason about the influence of the length of route used in transportation of packets from source to destination. The length of line graphs were 7, 15, and 30 nodes. The rational was to show that length of route has an effect on latency of packets and also to quantify this latency. The minimum connectivity for start and end nodes was two and maximum connectivity was six. The setup is depicted in Figure 3(b).

Figure 4 shows the average fairness, latency and throughput for *Non-interfering* and *Very-Close* connections connections for the three MAC protocols. L and H extensions refer to low and high injection rates respectively. In case of non-interfering connections, all MAC protocols behave equally well in terms of average fairness,[4] latency and throughput except for MACA at high injection rate. MACA-H appears more unfair, have higher latency and lower throughput. However, when the connections are very close and interfering, 802.11 and MACA at high injection rate, are more unfair, have higher latency and lower throughput compared to CSMA. Although, 802.11 at low injection rate, is the most fair with least latency and best throughput among all the MAC protocols. The graphs for *partially-interfering* connections and *single* connection are omitted here to avoid repetition. However, the following conclusions summarize the results for the entire experiment.

1. 802.11 and CSMA show almost identical behavior when we compare the single connection and two connections that are far apart. In case of MACA there was a difference between the two cases which may have been caused by the interaction between MACA and the routing protocol, AODV. Suboptimal routing increased interaction between the two connections and the lack of carrier sensing in MACA became a factor.

2. Allocation of resources in the case of the two connections that are slightly apart is characterized by worst performance of CSMA at all injection rates, and 802.11 at high injection rate. In case of CSMA this is caused by the simplicity of the protocol, and in case of 802.11 this is caused by interference of control packets at high injection rate.

3. Even from this simple setting we can see that no MAC layer protocol dominates.

In the second set of experiments we show relation between the length of route and basic performance parameters such as latency and packets received. The setup is shown Fig-

[4] Here fairness is measured by the deviation from being perfectly fair. So higher the fairness measure or deviation, more unfair a protocol is.

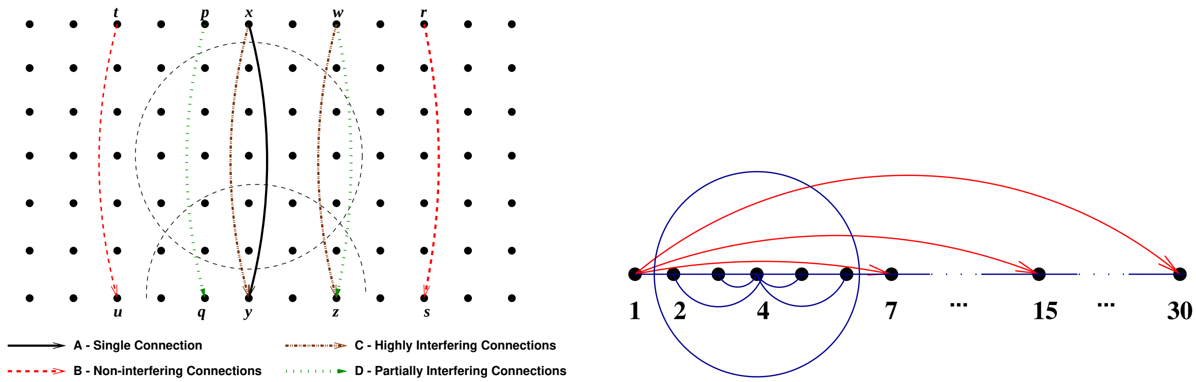

Figure 3: Set up for second experiment. (a) This experiment started with base cases consisting of connections that were far away and then progressively got them closer. Corridor grid. Two 6×6 grid connected with a 3×3 grid. (b) Effect of Path lengths. The figure shows three different line-squared graphs with length of 7, 15, and 30 nodes. The source and destinations for each of the three cases are shown by the arrows.

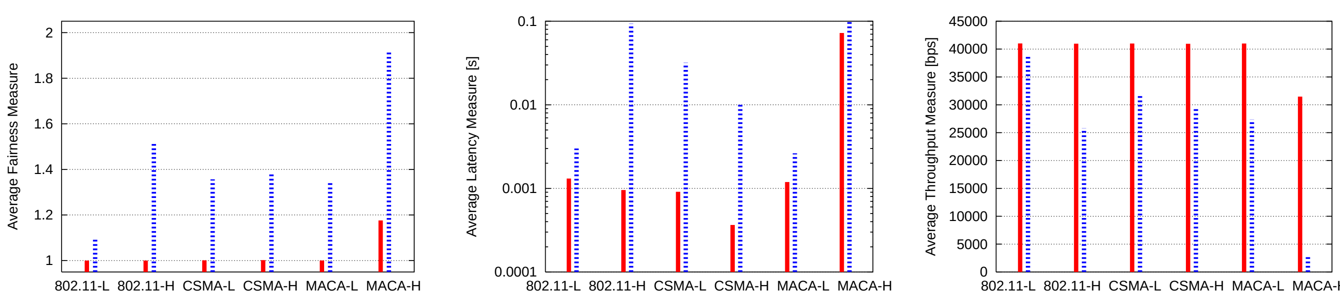

Figure 4: Average (Un)Fairness, Latency and Throughput of the three MAC protocols under low and high injection rates when we have for (a) Non-interfering connections (full line), and (b) Very close connections (dashed line).

ure 3(b). The basic conclusions from this set of experiment are:

1. Latency and number of control packets increase with the length of the line graph, and the number of packets received decreases with the length of the line graph.

2. In simple settings with low interaction, CSMA performs much better than the more advanced 802.11 or MACA. For MAC layer protocols with advanced RTS/CTS control packet mechanisms, deterioration comes at lower injection rate due to increased interaction between data and control packets.

We briefly discuss the specific parameter values chosen in this paper. The values have been chosen by taking into account the following guidelines: (a) the size of networks and the number of connections were chosen keeping in mind the computational limitations of the current simulator and the number of runs we wished to perform, (b) the type of networks chosen was motivated by the earlier studies in [DPR00, DP+, WS+97, NK+99, BD+94] and the specific goal of showing interaction betwen the MAC and routing layer, (c) The injection rate chosen is on the higher side when compared to other studies but still very realistic. Moreover, this is done in settings where the results are interpretable; to the extent possible, simple instances are chosen to effectively argue about an issue.

4 Characterizing Interaction Using Statistical Methods

We set up an experiment which evaluates the performance of the following four factors; the MAC protocol, routing protocol, network topology and the injection rate. Each of these four factors (variables) have three levels (values the variables take) as described in Section 2. This experiment generates $3^4 = 81$ distinct scenarios by using different combinations of MAC, router, network and injection rate. For each scenario, we generate 20 replicates/samples for the analysis. Our performance matrix for this experiment consists of three measures i.e. latency, number of packets received and the fairness.

Using statistical methods we study whether these four factors interact with each other in a significant way. In the presence of interaction, the mean differences between the levels of one factor are not constant across levels of the other factor. A general way to express all interactions is to say that the effect of one factor can be modified by another factor in a significant way. 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.

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. Similarly, 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. To calculate interactions between the factors, we use a statistical technique known as *analysis of variance* (ANOVA). 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 y_{ijklm} is the measurement of the performance variable (e.g. latency) for the ith network, jth router, kth MAC and lth injection rate. m is the number of replicates which is 20 in our experiment. α_i is the effect of network topology, β_j is the effect of the routing protocol, γ_k is the effect of the MAC protocol and δ_l is the effect of the injection rate on the performance measure. The two way interaction terms are; $(\alpha\beta)_{ij}$, which captures the interaction present between the network topology and the routing protocols; $(\alpha\gamma)_{ik}$, which measures the interaction present between the network topology and the MAC protocols; $(\alpha\delta)_{il}$, measures the interaction between the network topology and the injection rates. Similarly, $(\beta\gamma)_{jk}$, measures the interaction between the router

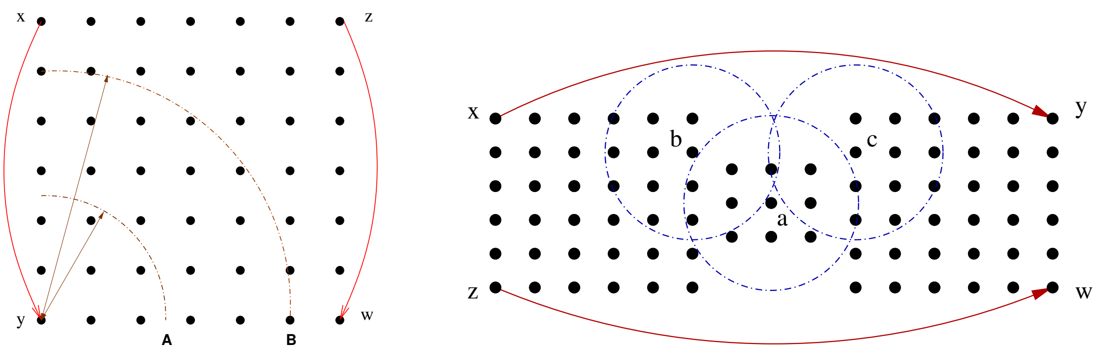

Figure 5: (a) Medium and high connectivity grid of 7 × 7 nodes. (A) medium connectivity, and (B) high connectivity. (b) Corridor grid. Two 6 × 6 grid connected with a 3 × 3 grid.

and the MAC protocol. $(\beta\delta)_{jl}$, the interaction between the router 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 network, router and MAC protocols; $(\alpha\beta\delta)_{ijl}$, the interaction present between the network, router and injection rates; $(\alpha\gamma\delta)_{ikl}$, the interaction present between the network, MAC and injection rates; $(\beta\gamma\delta)_{jkl}$, the interaction present between the router, 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.

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 is based on the method of *backward elimination* where each term is checked for significance and eliminated if found to be insignificant. Our initial model is the largest possible model which contains all the four factor effects. We then eliminate terms from the initial model to eventually find the smallest model that fits the data. The reason for trying to find the smallest possible model is to eliminate factors and terms that are not important in explaining the response variable. After eliminating redundant factors, it becomes simpler to explain the response variable with the remaining factors. The smaller models can normally provide more powerful interpretations.

To test four way interaction between the MAC, routing protocol, network and injection rates in effecting the response variable, we perform the four factor ANOVA using the above mathematical model. This is also called the *full/saturated* model since it contains all 1-way, 2-way, 3-way and 4-way interactions. After running this model, we calculate the residual sum of squares [5] and refer it by $SS(14)$, which stands for residual sum of squares for model number 14. The degrees of freedom [6] is referred by $DF(14)$. Now we drop the 4-way interaction term i.e. $(\alpha\beta\gamma\delta)_{ijkl}$ and rerun the ANOVA model. The resultant model has now only have 1-way, 2-way and 3-way interaction terms. From this model, we can calculate the residual sum of squares for model 13, i.e. $SS(13)$ and degrees of freedom for model 13, $DF(13)$. We now compare model 14 with model 13 to find out if the 4-way interaction is significant. If the F-statistic turns out to be insignificant, we can say that 3-way interaction model i.e. model number 13 can explain the response variable as well as model 14. This implies that model 14 can be dropped off without loosing any information. Next we test for each term in model 13 and check which ones are significant. Any term that is not important in affecting the response variable can then be dropped off. This is achieved by dropping each 3-way term one at a time and then comparing the resulting model with model 13. In our tables, model 9 to 12 are being compared with model number 13. If the F-statistic is significant after dropping off the term, it implies that the term that was dropped off played a significant role and hence should not have been dropped. After checking 3-way interactions, we compare *all 2-way* interaction model (model 8) with *all 3-way* interaction model to see if there is a smaller model that can fit the data as well as the 3-way interaction model. Just like the 3-way model, we then

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

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

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 table, 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 1. 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.

Performance measure-Latency: Table 1 shows the ANOVA results. Columns 4-6 show the results for the response variable *latency*. We start with an initial model with all the 4-way interactions and compare it with all 3-way interactions model. Model 14 is being compared with model 13. The F-test, 0.67, 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. Looking at the F-test results of model numbers 9 to 12, we find model 9 to be the most significant and model 12 to be marginally significant. From that we conclude that the network, MAC and injection rates interact most significantly. Also, the network, router and the MAC interact significantly in 3-way interaction. Note that these were the combinations that were dropped off in models 9 and 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. The F-test values conclude that the most of the 2-way interactions are significant. The only exception is the interaction between router and injection rate. 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 that the smallest model that fits the data. If the F-test for these two models turns out to be significant, we conclude that the smallest model includes $[RMI][NRM]$, which means 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 $[RMI][NRM]$ is the smallest possible model.

Performance measure: Number of packets received Columns 7, 8 and 9 in Table 1 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 are also very similar to the latency results. Again we find that the four factor interaction is not significant. Among the 3-way interactions, F-test shows that the network, MAC and injection rates interact most significantly. The network, router and the MAC also interact significantly in 3-way interaction. Among the 2-way interaction terms, the router and injection rates are the only ones that show insignificant interaction, all other 2-way interactions turned out to be significant. As before, we find that the router and injection rate have very significant interaction in affecting the number of packets received. In this case also, the smallest model has only $[RMI][NRM]$ 3-way interaction terms.

Performance measure: Fairness The last three columns of Table 1 shows the ANOVA results for various models using long term fairness as the performance measure. The initial setup for a four way interaction effect of the factors on the fairness measure is done as explained before. The only exception is that now we have 10 runs instead of 20 for each of the 81 scenarios mentioned above.[7] 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 network and MAC is also significant but not to the extent of router and MAC interaction. In this case, the smallest model has only $[RM][NM]$ 2-way interaction terms.

5 Further Results and Qualitative Explanations

We try to quantify the statistical results presented in Section 4 by taking a closer look at performance variables latency, percentage of packets received and the number of

[7] 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	All 1-way	$[N][R][M][I]$	18733.78	1611	12.61*	1875199	1611	21.92*	3.86×10^9	801	5.48*
2	2-way	$[NR][NM][NI][RM][RI]$	16429.57	1591	15.22*	1535050	1591	31.77*	3.33×10^9	781	1.38
3	2-way	$[NR][NM][NI][RM][MI]$	15882.91	1591	0.88	1433837	1591	2.08	3.31×10^9	781	0.59
4	2-way	$[NR][NM][NI][RI][MI]$	16434.59	1591	15.35*	1454324	1591	8.09*	3.71×10^9	781	24.21*
5	2-way	$[NR][NM][RM][RI][MI]$	15998.74	1591	3.91*	1465026	1591	11.23*	3.32×10^9	781	0.81
6	2-way	$[NR][NI][RM][RI][MI]$	17168.48	1591	34.60*	1682018	1591	74.88*	3.36×10^9	781	3.6*
7	2-way	$[NM][NI][RM][RI][MI]$	16069.16	1591	5.77*	1438545	1591	3.46*	3.34×10^9	781	2.3
8	All 2-way	$[NR][NM][NI][RM][RI][MI]$	15849.33	1587	3.5*	1426720	1587	3.71*	3.30×10^9	777	0.77
9	3-way	$[NRM][NRI][NMI]$	15346.48	1563	7.5*	1393866	1563	10.05*	3.182×10^9	753	0.89
10	3-way	$[NRM][NRI][RMI]$	14908.73	1563	1.76	1331645	1563	0.93	3.188×10^9	753	1.07
11	3-way	$[NRM][NMI][RMI]$	14919.62	1563	1.91	1329497	1563	0.61	3.181×10^9	753	0.88
12	3-way	$[NRI][NMI][RMI]$	14999.95	1563	2.9*	1347649	1563	3.27*	3.21×10^9	753	1.75
13	All 3-way	$[NRM][NRI][NMI][RMI]$	14774	1555	0.67	1325312	1555	0.99	3.15×10^9	745	1.15
14	All 4-way	$[NRMI]$	14672.34	1539		1311724	1539		3.07×10^9	729	

Table 1: **Results of Four-Factor ANOVA:** This table shows results of four-factor ANOVA where the factors are network topology, routing protocol, MAC protocol and the injection rate. The *response variable or the performance measures are the* latency, number of packets received and fairness. $*$ shows that the F-test is significant at 99% confidence level.

control packets at the MAC layer level.

5.1 Interdependency of MAC, Routing Protocol and Network Topology

Table 2 shows the variation in performance range of *latency* and *packets received* as the injection rate changes from high to low. Following important observations can be made about the behavior and interaction of MAC, routing and the networks:

1. One typically gets higher latency when using DSR. This is true over all networks and MAC protocols. The working hypothesis is the following (i) the packet sizes are generally larger while using DSR since entire route information is embedded in a packet and (ii) the route discovery process is initiated every time a packet needs to be sent. Moreover, each RREQ received at the destination is reciprocated with a RREP packet.

2. In general latency increases substantially with increased injection rate. First note that latency is only measured for packets that are received successfully. Increased injection rate implies higher probability of collision and lower probability of finding free resource. This in turn implies higher latency.

3. In general, lower the injection rate, higher is the percentage of packets received. This is true since the probability of collision is smaller at lower injection rates.

4. For medium and high connectivity grid and for all injection rates, the system performs the best when using 802.11. This holds for all routing protocols. The results points out the utility of the CSMA/RTS/CTS/ACK mechanism.

5. The overall performance of the system is worst when using MACA as the MAC protocol. From these results it is fair to conclude that just the RTS/CTS mechanism in itself is not sufficient to improve throughput. But noting the performance of 802.11, one concludes that CSMA/RTS/CTS/ACK mechanism does yield good results

5.2 Spatial Distribution of Control Packets

We carried out further investigation on the spatial distribution of control packets generated in our simulations. To explain our results we focus on grid squared network with medium connectivity with two parallel connections and shown in Figure 6, 7, 8. To conserve space, we only show graphical results for the 802.11 protocol. However, results of both MACA and 802.11 are summarized below.[8]

1. The higher the injection rate, the higher is the number of control packets (normalized) generated. This is an expected result. At medium injection rate, 802.11/LAR1 generated more control packets as compared to 802.11/AODV and 802.11/DSR. At high injection rate, 802.11/AODV generated the

[8] CSMA is omitted since no control packets are generated under CSMA.

Medium Connectivity Grid: Performance range over varying injection rate									
	802.11			CSMA			MACA		
	AODV	DSR	LAR1	AODV	DSR	LAR1	AODV	DSR	LAR1
Latency %Pkts.	0.009-0.02 100-100	0.01-0.02 100-100	0.01-0.02 100-100	0.02-0.01 90-98	2-3 75-64	0.02-0.04 92-97	2-0.02 62-88	1-0.05 62-83	1-0.04 72-98
High Connectivity Grid: Performance range over injection rate									
	802.11			CSMA			MACA		
	AODV	DSR	LAR1	AODV	DSR	LAR1	AODV	DSR	LAR1
Latency %Pkts.	0.01-0.01 100-100	0.01-0.01 100-100	0.01-0.02 100-100	0.02-.05 53-58	1-4 36-25	0.01-1 38-23	10-0.01 8-80	4-0.06 10-75	9-1 23-72
Corridor Grid: Performance range over injection rate									
	802.11			CSMA			MACA		
	AODV	DSR	LAR1	AODV	DSR	LAR1	AODV	DSR	LAR1
Latency %Pkts.	2-0.02 10-88	6-0.06 18-85	3-2 20-62	0.01-0.03 48-50	3-3 38-40	0.01-0.06 58-56	2-0.02 20-76	3-0.09 18-52	2-0.04 18-68

Table 2: This table shows the latency and number of packets received (%) as function of injection rate for the three networks i.e. medium connectivity, high connectivity and corridor grid. The performance is shown as a range over decreasing injection rate. Note that the injection rates are inversely related to the injection interval. For each figure is annotated with the corresponding injection interval.

least number of control packets as compared to 802.11/LAR1 and 802.11/DSR.

2. MACA always generated substantially more control packets as compared to 802.11. The reason for this is simple: due to absence of carrier sensing mechanism, the number of collisions increases substantially causing in turn an increasing in the control packets.

3. Figure 6, 7, 8 clearly show the transceivers generating the MAC control packets are correlated with the paths chosen by the routing protocol. Figures 8 shows lesser number of control packets for high injection rate as compared to medium injection rate. This seeming anomaly is easily explained when one notices that the throughput at these rates is substantially smaller and hence the intermediate nodes do not have as much work to do.

The observations made in this section clearly suggest that results and performance change significantly depending upon what combination of routing protocol, MAC protocol, network and injection rates are being used. The interactions among these variables affect each others performance in complicated ways.

6 Concluding Remarks

We undertook a detailed study to quantify the effects of ad-hoc routing protocols on MAC protocols. This study extends the earlier simulation based experimental work in [DPR00, DP+, BM+98, KV98, RLP00, RS96]. Intuitively it is clear that different levels in the protocol stack should affect each other in most cases but this issue is investigated more rigorously here; our results point out some of the subtleties involved.

An important implication of our results and those in [BS+97, RLP00] is 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. Specifically, optimizing a particular layer might improve the performance of that layer locally but might produce non-intuitive side effects that will degrade the overall system performance. The issue is likely to become more important in ad hoc networks where the topology is changing constantly and hence it is not even easy to discern what shortest paths mean.

The results also motivate the need for dynamic adaptive mega protocols that perform say the MAC/routing tasks simultaneously. For instance, it is plausible to extract good features of individual protocols to construct the mega protocols. Examples of this include: (i) Having RTS/CTS/ACK mechanism, but with the ability to shut it down in times of low traffic, (ii) routing protocols, that use location information as well as small amounts of information about intermediate nodes.

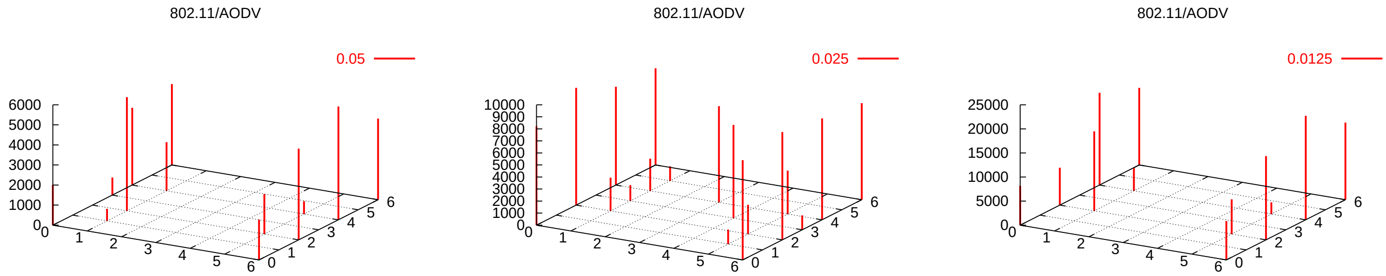

Figure 6: MAC control packets for (802.11,AODV) combination for three different injection intervals (.05, .025, .0125). **Note that smaller injection interval implies higher injection rate**.

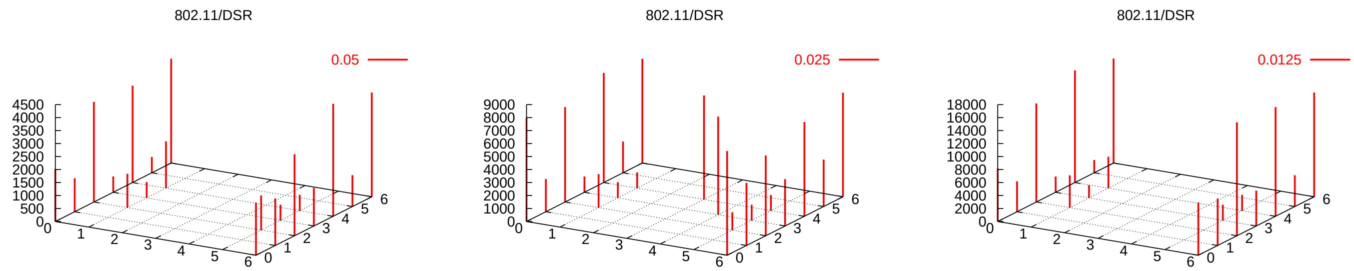

Figure 7: MAC control packets for (802.11,DSR) combination for three different injection intervals of .05, .025, .0125 seconds.

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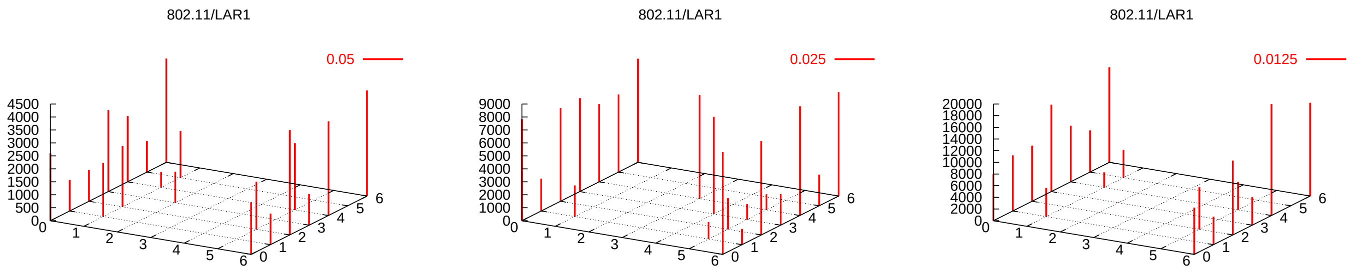

Figure 8: MAC control packets for (802.11,LAR1) combination for three different injection rates (.05, .025, .0125).

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