A Comparative Experimental Study of Media Access Protocols for Wireless Radio Networks

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***Abstract*— We conduct a comparative experimental analysis of three well known media access protocols: 802.11, CSMA, and MACA for wireless radio networks. Only static ad-hoc networks are considered. The experimental analysis was carried out using GloMoSim : a tool for simulating wireless networks. The main focus of experiments was to study how (i) the size of the network, (ii) number of open connections, (iii) the spatial location of individual connections, (iv) speed with which individual nodes move and (v) protocols higher up in the protocol stack (e.g. routing layer) affect the performance of the media access sublayer protocols. The performance of the protocols was measured w.r.t. four important parameters: (i) number of received packets, (ii) average latency of each packet, (iii) long term fairness and (iv) throughput. The following general qualitative conclusions were obtained; some of the conclusions reinforce the earlier claims by other researchers.**

1) **Typically, all protocols degrade significantly at higher packet injection rate. Moreover, the degradation often happens rather sharply.**
2) **In general while the performance of 802.11 was better than CSMA at lower injection rates, the performance of 802.11 is worse than that of CSMA at higher injection rate, on the other hand, CSMA assigns inequitable amount of resources; in this regard 802.11 performs quite well.**
3) **MACA typically was dominated either by CSMA or by 802.11 w.r.t. any of the performance measures.**
4) **Protocols in the higher level of the protocol stack affect the MAC layer performance.**

The main general implications of our work is that No single protocol dominated the other protocols across various measures of efficiency. In other words the performance of protocols depends on all of the parameters mentioned above.

***Index Terms*—MAC Layer Protocol, 802.11, MACA, CSMA.**

I. Introduction and motivation

Design of MAC layer protocols for wireless mobile networks has become an important area of research in recent years (See [7], [10] and the references therein). An extreme form of wireless mobile networks are the ad-hoc networks – networks that do not rely on any fixed infrastructure, e.g., base stations. The upsurge in a variety of mobile computing devices such as laptops, PDAs, and other portables has caused an unprecedented interest in this form of communication. Early progress on multihop radio networks was funded by DARPA. This includes the **PRNET** (Packet Radio Network) [9], and **SURAN** (Survivable Adaptive Networks) [31] 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) [18].

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Network protocols in general 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 [3], [12], [24], [25], [26], [30].) Since ad-hoc networks lack fixed infrastructure in the form of base stations, fulfilling the above stated functional requirements becomes all the more difficult. Many MAC layer protocols have been proposed and designed to meet one/many of these criteria; the research area continues to be very active.

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, recently, multiple channel extensions have been proposed [19]. Many protocols have been proposed to avoid the hidden terminal problems. Two notable examples are the MACA [10] and MACAW [7] 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 [22] was designed with a reservation system similar to MACA or MACAW in mind. 802.11 has also improved fairness characteristics, however, in [16] authors point out deficiencies in the fairness of this protocol, as well.

Because of the limited bandwidth of wireless channels message complexity of both MAC layer and network layer (routing) protocols needs to be kept low. Informally speaking, we define the message complexity of a protocol as the ratio of the number of data packets successfully transmitted to the total number of packets actually sent (including control packets, duplicates etc.). Latency is defined to be the average time it takes for a packet to reach its destination. Note that as defined, the definition does not distinguish between the type of packets received. Thus it is conceivable that a connection might be deemed to have good latency but might not deliver too many new packets. Thus a good protocol should have the following characteristics: (i) high throughput as measured by the total number of good packets received in a unit time and (ii) fairness. Intuitively speaking, high throughput implies low message complexity and low latency.

The interplay between message complexity and latency with dynamically changing network connectivity, and traffic load is the main focus of the study described in this document. Additionally, we study the effect of (i) spatial locations of sources and sinks, (ii) injection intervals of packets, and (iii) type of network on quality of service. We chose the following MAC layer protocols to test: 802.11, CSMA, and MACA. All simulations were done in GloMoSim, a tool specialized in wireless networks simulation.

Due to lack of space we refer the reader to [1], [7], [26] for more details on the three protocols considered in this paper.

II. Summary of Results and Implications

Building on the earlier work of [7], [17], [33], we experimentally evaluate the performance of three well known MAC protocols in wireless radio networks. The goal is to see how (i) the network topology, (ii) the traffic injection interval, (iii) the spatial location of the source destination pairs, all affect the performance of the protocols. Moreover, we want to do this in settings where the results are *interpretable*; hence to the extent possible, we have chosen very simple instances to effectively argue about an issue.

A. Scenario Specific Results

For now, view a scenario as a combination of the injection rate, spatial connection locations and network topology. We have considered three basic scenarios – each scenario consists of a number of sub-scenarios. Alternatively, each scenario can be viewed as an experimental design set up to verify/test a certain hypothesis. The experimental designs are discussed in detail in Section III. We first discuss these results.

1) The **first scenario** was created to verify performance of MAC layer protocols under hidden terminal situations. For this we designed the basic hidden terminal sub-scenario as well as extensions of this idea to the case of multi-hop networks. Results show that CSMA inequitably assigned resources to the two connections over individual runs. On the other hand CSMA performed quite well in terms of latency and in fact had the lowest latency among all the three protocols for this case. MACA had a very high latency as well as inequitable resource assignment. 802.11 had worse latency than CSMA but was better than MACA. On the other hand, it allowed the most equitable access to the media and had the best throughput. See Section IV-A for more details.
2) The **second scenario** was to test behavior under low and high connectivity. We can see that the protocols fail to perform in extreme situations. Here we have a case where communication depends on a few isolated nodes that convey packets between clusters of nodes. CSMA dominates in this scenario. 802.11 failed in both the latency and packets received. MACA's performance is quite poor under high injection rate. It shows up that exchange of RTS/CTS pair is not very efficient in negotiating data packets transfer.
3) The **third scenario** was to convey results on the effect of grid width and sparsity. CSMA shows domination in terms of latency. MACA shows low latency but only for low injection rates. The reason is the overhead caused by exchange of RTS/CTS pairs. 802.11 performs well in terms of packets received but at extremely high injection rates the protocol performance plummets. CSMA on the other hand shows improved performance with increased injection rate.
4) All the protocols do an inequitable assignment of channel resources for low injection interval. We have deliberately refrained from calling this unfair: what does it mean to be fair is not obvious and has been subject of a extensive research in the past in Economics and Social Science.
5) For high injection interval 802.11 assigned resources equitably. On the other hand CSMA and MACA had a wide variation.
6) At least two notions of equitable resource allocations can be formulated: one in which we see how the protocol does in a particular run and one in which measure the relative resources assigned to each connections over a given set of runs. Using the other measure CSMA and MACA appear to have a more equitable resource assignment.
7) Many researchers have in the past designed specific algorithms and argued (heuristically or formally) about the fairness of protocols. We believe that the topic deserves more attention. For instance in [32] the authors propose distributed fair scheduling algorithm. The essential idea is to assign resources to each flow in proportion to the amount that is backlogged for that particular flow. In [17], the authors have discussed per-node versus per-flow fairness. We point out that each such proposed mechanism can have subtle side effects; the goal is merely point out undertaking a more in-depth study[1].

B. Explanation and conclusions

A qualitative explanation of many of the results can be given. For instance, CSMA has low overhead since it does not have the RTS/CTS control mechanism; this makes collisions more likely but on the other hand allows for lower latency (at least for the connections that are given access) and adequate throughput for the connections that are scheduled. 802.11 has RTS/CTS mechanism; the overhead that such a control mechanism causes for small packets is evident from the degradation of 802.11 for small packet sizes. MACA appears to be probably the worst overall: it has high latency and inequitable resource allocation. The main conclusions of our study include the following:

[1] A very simple example will make the point. Consider for instance an adversary, who wishes to slow down a network without any goal of transmitting useful information. Furthermore, imagine the adversary to have control over the protocol stack. The adversary can easily compromise the network's good throughput by not implementing a voluntary back off scheme and thus flooding the intermediate nodes. If per flow fairness is implemented this will end up giving unusually high resources to this connections making the other connections have low throughput.

1) The network connectivity, spatial location of connections, injection rate and packet size all play a crucial role in determining the performance of a media access protocol. While, the effect of last two parameters has been studied earlier to some extent [7], [33], the effect of first two parameters has not been extensively studied to the best of our knowledge.
2) In general the following broad conclusions can be drawn: (i) higher injection rates, (ii) smaller packets and (iii) increased density of network affect the protocol performance adversely. Section II discusses this in more detail and provides qualitative reasons for this.
3) *No single protocol 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.

III. Experimental Setup

The experimental set up consists of a description of (i) the scenarios used, (ii) simulation setup, (iii) input and output variables.

A. The scenarios

We studied the performance of the three protocols under three different basic scenarios. Each scenario consisted of a number of sub-scenarios. Each scenario was designed to test a distinct hypothesis. Unlike most of the earlier studies, our scenarios were designed to understand the performance of the MAC protocols at the "network level" rather than at "link level", i.e. most of our scenarios consisted of source sink pairs that were at least 2 links apart. We briefly describe the scenarios below; additional details for each scenario are given in the section describing the results for that scenario.

1) **Scenario 1: Effect of General Hidden terminal.** This scenario is motivated by the well known hidden terminal problem. It has been well documented that hidden terminal configuration causes CSMA to assign inequitable resources to connections. 802.11 overcomes this problem using the RTS/CTS/ACK mechanism. We wanted to see if the random delays introduced by the network can mitigate the hidden terminal to some extent. We call this the *generalized hidden terminal scenario*. Section IV-A describes the scenario setup in more detail.
2) **Scenario 2: Effect of Network Connectivity.** In this scenario, our goal was to investigate the effect of network connectivity on MAC layer protocols. We consider successively denser network keeping the set of nodes constant. Another motivation for this scenario was to provide insights into optimal power settings for power aware MAC protocols. Intuitively, increasing the network density has two conflicting effects. On one hand, increasing the power range implies that paths between source destination pair tend to be shorter (the packets make faster progress towards their destination); this reduces the number of collisions that a packet might participate in. On the other hand, the network becomes dense (the node and edge connectivity); this implies that one is likely to encounter more spatial interference from adjacent radios. The second issue has been studied analytically by a number of authors for CSMA and ALOHA like protocols, most notable by Nelson, Kleinrock, Takagi and Tobagi [11], [13], [20], [21], [27]. But no such analytical results are known for 802.11; moreover, the analysis in [11], [13], [20], [21], [27] is done only on randomly distributed set of points.
3) **Scenario 3: Effect of Separator size and sparsity.** In the final scenario, we aim to understand the effect of network sparsity and separator size on the performance of MAC protocols. Intuitively, it is obvious, that smaller separator implies higher probability of collisions and thus reduced performance. Again, as mentioned earlier, our broad goal is to look for network level effects as opposed to link level effects. The importance of separators has been well established in the study of circuit switched networks.

B. Simulation Setup Characteristics

We now describe the details of the parameters used.

1) **Network Characteristics:** In each scenario we have kept the following parameter constant:
   - **Network Topology:** Although specific scenarios use specific network topologies, one particular topology is used frequently. We call it the *grid-squared* topology. It consists of 7×7 node grids with the radio radius of 2.5 grid units (1 grid unit = 100m). The name comes from the fact that it can be viewed as constructing $G^2(V_1, E_1)$, where $G(V, E)$ denotes the grid. In the graph G^2, there is an edge between u and v iff u and v were no more than a distance 2 apart. A vertical connection, i.e. source being $(x, 0)$ and destination $(x, 6)$ required at least three hops for a packet to reach its destination, whereas for a diagonal connection at least four hops were required. Finding out the number of hops required to reach a destination from a source is an easy task and is omitted. Most of our topologies are derived from this basic structure.
   - **Number of connections:** We used two connections, except for the experiment in which we studied influence of number of connection on quality of service (See [5] for more details on how the number of connections influences the performance.).
   - **Routing protocol** : AODV (See [23]).
2) **Mobility Parameters.** There was no movement of nodes.
3) **Traffic Characteristics.**
   - The initial packet size was 512 bytes, the initial number of packets was 1,000, and the initial injection interval was 0.1 second. We reduced the packet size by a factor of 2 and increased the number of pack-

ets by a factor of 2 every time the injection interval was reduced by a factor of 2. For example, if the injection interval was halved to 0.05 second 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.
- The bandwidth for each channel was set to 1Mbit. The propagation path-loss model was two-ray.
- 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.

4) **Simulation Characteristics.**
- To keep the simulation time 100 seconds, and the total size of packets in traffic constant, we halved the size of packets with each doubling of packet injection interval.
- Unless otherwise stated, we used two connections (source destination pairs) per run. For each protocol and each value of injection interval 30 independent runs using a new random seed were carried out for each sub-scenario. In a few cases the number of runs were reduced to 10; but in all such cases the basic trend is evident.
- Hardware used in all cases was a Linux PC with 512MB of RAM memory, and Pentium III 500MHz microprocessor.
- Simulation tool: GloMoSim v2.0.

C. Input Variables and Measured Quantities

The MAC layer protocols studied are 802.11, CSMA and MACA. The independent (input) variables for a given scenario were: the network topology and the injection interval for packets. The following three pieces of information were collected: (i) Latency: Average end to end delay for each packet as measured in seconds, (ii) Total number of packets received, (iii) Throughput: number of in bits/second received. Note that while calculating latency, we only consider packets that were successfully received.

Apart from latency and packets received that are plotted for each connection (recall for most part we deal with two connections), we also report the average behavior of the protocols. We briefly describe the method used to calculate these parameters. Average throughput and average latency is simply the average over 60 runs of each protocol over the two connections (30 for each connection). An example of a plot showing average fairness (discussed below), throughput and latency is seen in Figure 5.

Measuring and Plotting Fairness. Informally speaking, a fair assignment of resources means that all the agents participating in the game/process get equal access to the resources. This informal notion can be extended in several ways and indeed formalizing the concept is beyond the scope of this paper. Here as discussed earlier, we only consider long term fairness of protocols as opposed to short term fairness.

To measure long term 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 denotes the fairness index of the protocol. Note that in case of perfectly equitable allocation the fairness index is 1. Average fairness is $\frac{1}{30}\sum_{i=1}^{i=30}\max\{r_i, \frac{1}{r_i}\}$, where r_i is the above stated ratio for the i^{th} run of the protocol[2]. One way to see the behavior of a protocol w.r.t. its fairness characteristics is to plot the fairness index for each run. For example consider any one of the 6 plots in Figure 4. The X-axis has the run number and the Y-axis displays the fairness index of the protocol for each run. These points are connected by a straight line so that differences in the height of the points is better reflected. Additionally, in order to depict smaller changes, all ratios above 10 are scaled down to 10. Thus the maximum y-value is always 10; the maximum x-value is 30 denoting the number of independent runs. Note that the runs are just independent invocations of the simulator with exactly the same parameters but with a different random seed. The dotted line is a horizontal line with y-value equal to 1. This denotes the expected behavior of a perfect protocol that assigns equitable resources. Any deviation of the curve above or below this line implies that the protocol was not fair. Also note that a fairness index such as $.2$ is in essence the same as 5 – in both cases one connection got 5 times more resources than the other connection.

IV. Results and Analysis

We have summarized the results of the experiments in form of graphs. The graphs show the data as a function of varying injection interval. We draw dependence of latency and number of packets received to injection interval [3].

Because of lack of space we provide detailed analysis and results for one scenario only. A comprehensive analysis which includes all scenarios can be found in [5]. More analysis for adhoc networks and interaction between MAC layer and routing layer protocols can be found in [6].

A. Scenario 1: Generalized Hidden Terminal Effect

We now discuss the experimental setup for the first experiment: effect of the generalized hidden terminal. The experimental design consists of three sub-scenarios and is depicted in Figure 1(A–C). Figure 1(A) depicts the base case; the classical hidden terminal setting. We have two connections: one from A to B and the other from C to B. The setting is such that B can hear both A and C but A and C cannot hear each other. Figure 1(B) depicts the first form of generalized hidden terminal setting. We have a grid-squared network and two connections shown by arrows from source to the destination. The arrows represent the rough flight path of packets: the path is not deterministic in general. As in the hidden terminal scenario, the connections have the same destination but different sources. The rationale is the following: although the destinations are the same, the packets are likely to encounter random delays as they traverse the network and hence it is likely that

[2] This is done so that all the summed quantities are at least 1.
[3] Note that we have used logscale for y axis in all graphs.

the inequitable resource assignment problem for CSMA is mitigated to some degree. Figure 1(C) considers another variant. Here the destinations are not the same but very closely located spatially. Again, one would expect the inequitable resource assignment problem is mitigated to a degree.

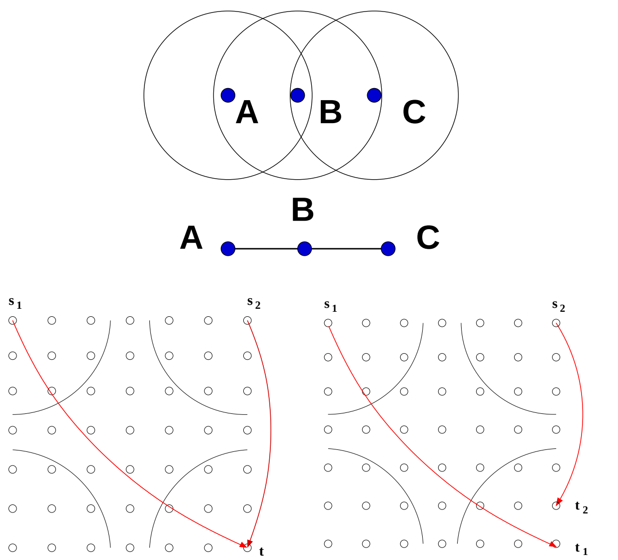

Fig. 1. Distinct sources. (A) Three-node hidden terminal, B can hear A and C, but A and C cannot hear each other; (B) Identical sinks; (C) Closely positioned sinks. Minimum connectivity for (B) and (C) is 8, and maximum connectivity is 21. The four quarter circles denote the radio range of the corner radios. Each radio has the same range. The basic connectivity is the same as in a grid-squared graph.

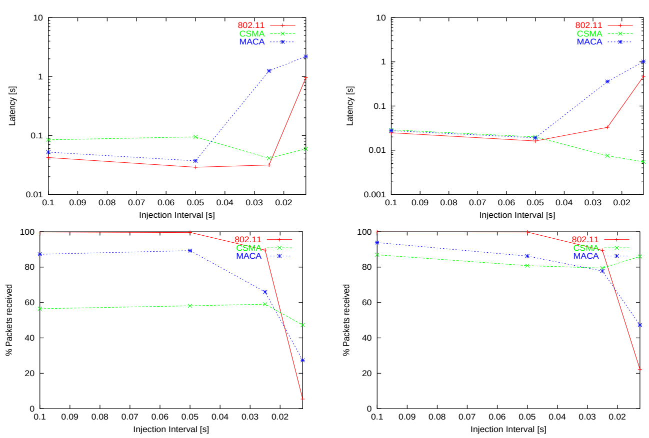

Fig. 2. Distinct sources, identical sinks. The two upper row figures represent data for latency (connection 1 and 2) and the two lower row show data for packets received (connection 1 and 2). The graphs shows dependency of these parameters on injection interval. These results correspond to scenario in Figure 1(B).

Broad Conclusions for Experiment 1: Results are shown in Figures 2, 3, 4, 5, and in Tables I, II. The plotted values are averaged over 30 runs with different random seed for each run of the simulator.

1) Looking at the numbers in Table II (results for Figure 1(A)), we see that CSMA essentially did not assign any resources when the connections started at the same time. In contrast, when the connections were started

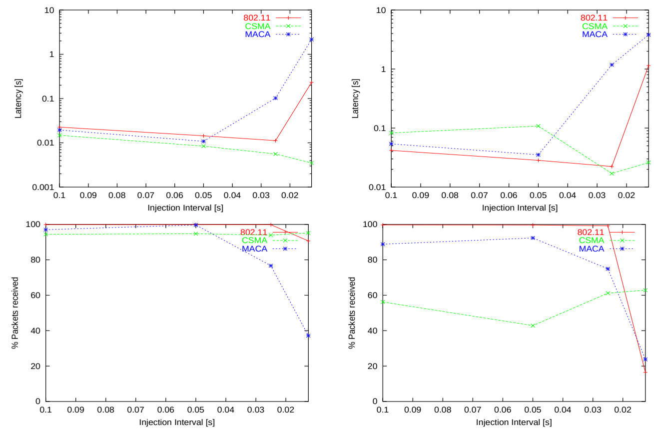

Fig. 3. Distinct sources, closely positioned sinks. The two upper row figures represent data for latency (connection 1 and 2) and the two lower row show data for packets received (connection 1 and 2). The graphs shows dependency of these parameters on injection interval. These results correspond to Figure 1(C).

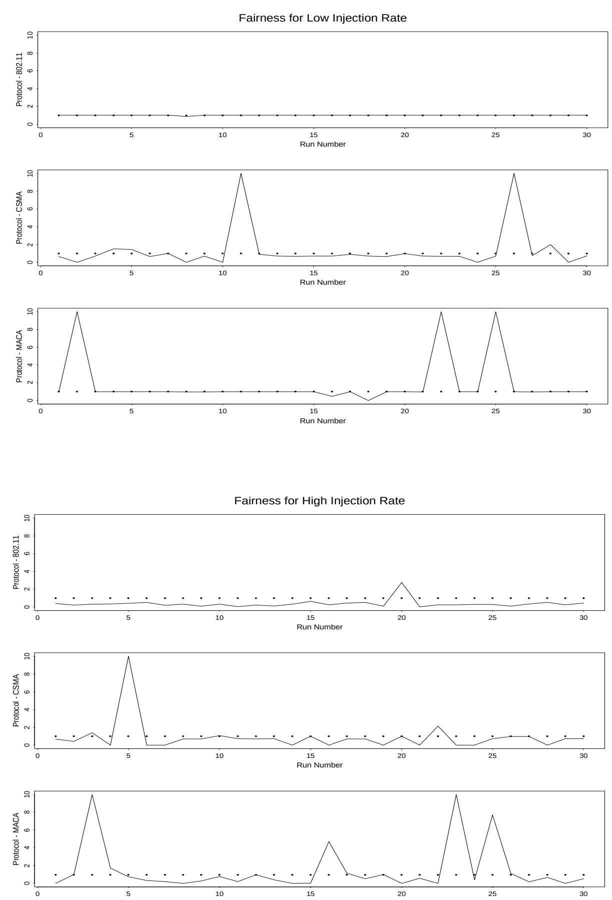

Fig. 4. Fairness over a set of 30 runs for the three protocols. The x-axis shows 30 runs with different simulation seeds. The y-axis shows the fairness as a ratio of packets received for connection 1 to packets received for connection 2. The dotted line shows a ratio of 1; for fair protocols plot should coincide with this line. Case (A) - low injection rate are shown in the left column, Case (B) - high injection rate are shown in the right column. See Section III-C for more detail on the fairness measure. These results correspond to Figure 1(B).

Protocol Case	802.11 A	802.11 B	CSMA A	CSMA B	MACA A	MACA B
Connection 1						
Injection interval [s]						
0.1	0.0097	0.0105	0.0037	0.0083	0.0258	0.0095
0.05	0.0067	0.0065	0.0028	0.0042	0.0218	0.0055
0.025	0.0051	0.0043	0.0024	0.0022	0.0200	0.0035
0.0125	0.0032	0.0032	0.0020	0.0011	0.0610	0.0610
Connection 2						
Injection interval [s]						
0.1	0.0097	0.0055	0.0019	0.0046	0.0262	0.0057
0.05	0.0067	0.0034	0.0016	0.0026	0.0217	0.0035
0.025	0.0051	0.0025	0.0015	0.0016	0.0200	0.0025
0.0125	0.0021	0.0021	0.0016	0.0010	0.0578	0.0578

TABLE I

THREE-NODE HIDDEN TERMINAL – LATENCY. CASE (A) THE CONNECTIONS STARTED AT THE SAME TIME. CASE (B) THE CONNECTIONS STARTED WITH A DIFFERENCE OF 1MS. RESULTS CORRESPOND TO FIGURE 1(A).

Protocol Case	802.11 A	802.11 B	CSMA A	CSMA B	MACA A	MACA B
Connection 1						
Injection interval [s]						
0.1	999	999	0	998	494	998
0.05	1998	1998	1	1998	998	1998
0.025	3997	3997	1	3997	1973	3996
0.0125	7995	7995	2	7995	7188	7188
Connection 2						
Injection interval [s]						
0.1	999	999	0	999	506	998
0.05	1998	1998	1	1998	1001	1997
0.025	3997	3997	1	3997	1969	3996
0.0125	7995	7995	2	7995	7184	7184

TABLE II

THREE-NODE HIDDEN TERMINAL – PACKETS RECEIVED. CASE (A) THE CONNECTIONS STARTED AT THE SAME TIME. CASE (B) THE CONNECTIONS STARTED WITH A DIFFERENCE OF 1MS. RESULTS CORRESPOND TO FIGURE 1(A).

1 millisecond apart, resources were assigned equitably. 802.11 did very well for both connections with and without any delays; in fact its performance was essentially indistinguishable. MACA's performance was somewhere in between the performance of CSMA and 802.11. The poor performance of CSMA is not obvious by looking at Figure 2 since the plots are obtained by averaging over 30 independent runs.

2) Results for the generalized hidden terminal scenario (Figure 2 and 3 for scenarios shown in Figures 1(B),(C)) show that latency is low for all protocols at low injection rates. However at high injection rates, both 802.11 and MACA exhibit much higher latency. The number of packets received falls steeply for 802.11 as one increases the injection rates. On the other hand CSMA shows a steady increase.
3) The results for the two variant hidden terminal scenarios (Figure 2 and 3 for scenarios shown in Figures 1(B),(C)) exhibit similar performance characteristics. In particular, as expected the random delays introduced by the network improved the fairness characteristics of CSMA considerably over its performance for scenario Figure 1(A).
4) Figure 4 shows the behavior of the three protocols w.r.t. fairness ratio discussed in the earlier Section. It shows that almost every run of the CSMA and MACA protocol produce inequitable assignment of resources to the two connections. CSMA assigns inequitable resources more frequently than MACA but MACA has much high levels of inequitable resource assignment when they are so assigned. 802.11 behaves quite well across low as well as high injection rates.
5) Figure 5 shows that no single protocol dominates the other protocols across the three different performance metrics (fairness, throughput and latency) and over range of injection rates. This is an important conclusion and will be reinforced as we alter the scenarios.

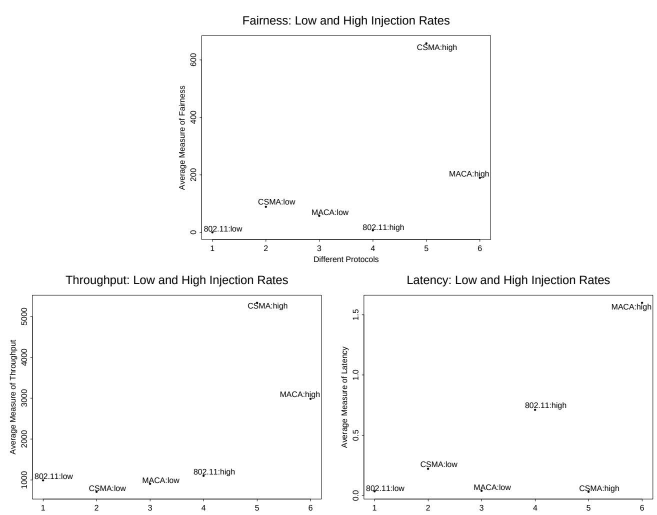

Fig. 5. Average (Un)Fairness, throughput and latency of the three MAC protocols under low and high injection rates. Note that at high injection rate we have correspondingly reduced the packet sizes. These results correspond to Figure 1(B).

Qualitative Explanations for Experiment 1: We provide plausible qualitative explanation for the above conclusions. First consider the relative behavior of 802.11 and CSMA. The RTS/CTS/ACK mechanism in conjunction with IFS (Interframe spaces) of 802.11 reduces the probability of collisions. On the other hand, it sometimes (unnecessarily) reserves media space thus disallowing other transmitters to use the space even if they could have probably used it without causing collisions. Additionally the control packets (RTS/CTS/ACK) imply additional overhead on the system which increases latency and decreases the good throughput (also known as goodput). These opposing aspects of the control packets used in 802.11 makes the analysis of 802.11 complicated. Nevertheless note the following: at high injection rates we use smaller packets and thus the relative overhead of the control packets in 802.11 exceeds the gain obtained by decreasing the number of collisions. Furthermore, the paths used by the two connections are by and large distinct (except near the destination). Thus the collisions we are avoiding are primarily those that occur between packets belonging to the same connection (collisions that occur while transmitting packets over three consecutive links of a routing path). At low injection rates, the number of control packets are significantly smaller and we have larger packet sizes: thus implying a higher bandwidth utilization. Moreover, although the collision probability is low, recovering from collisions at link level as done in 802.11 using the ACK part helps its overall performance. Thus 802.11 does quite well at low injection rates but deteriorates substantially at higher injection rates. It appears that the time for a packet to travel over one link together with the time it takes to move the packet from input buffer to the output buffer is less than the time it takes to generate the next packet at the source. Thus packets transmitted using CSMA do not typically experience collisions in this case. CSMA on the other hand does not assign equitable resources to the connections. This fact is clearer on inspecting Figure 4, rather than Figure 2 that reports the average over 30 runs. The reason for this is clear: once one connection gets access to the channel, it prevents the other connection from acquiring any resources. More surprisingly, MACA in spite of using RTS/CTS control packets, also exhibits inequitable resource assignment. Thus it appears that the random delays used in 802.11 play an important role in improving the fairness characteristics of 802.11. CSMA and MACA on the other hand rely on the transport layer to recover from collisions and thus pay a high price when collisions do occur. The qualitative difference between 802.11 and MACA at high injection rates is due to the ACK and IFS mechanism present in 802.11.

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