An Experimental Scaling Law for Ad Hoc Networks[*,†]

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Abstract

We report on the results of an experimental study of scaling laws in ad hoc networks employing IEEE 802.11 technology. Our results show that the per node throughput declines like $\frac{c}{n^{1.68}}$ bits/sec, where n is the number of nodes in the network. These results are considerably worse than the scaling laws shown to be attainable in theory. The results point to the need for improvements to existing hardware and protocols if one is to entertain the possibility of building ad hoc networks with a large number of nodes.

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1 Introduction

Consider an ad hoc network with n nodes randomly located in a domain of area A square meters, as shown in Figure 1.

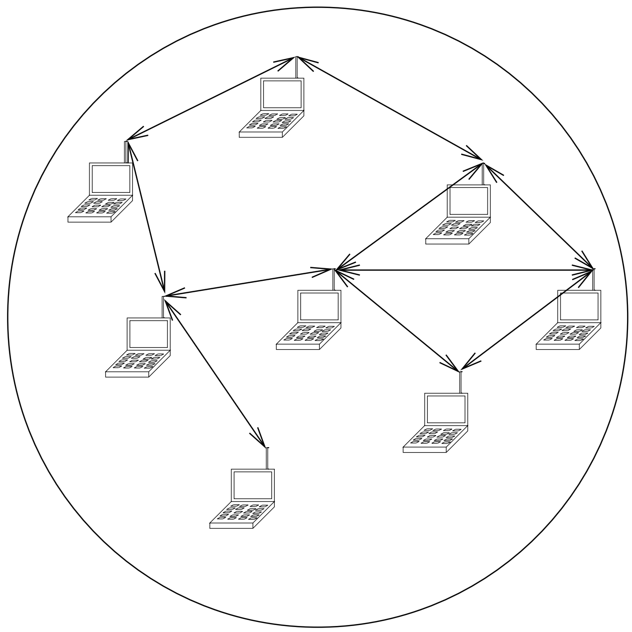


Figure 1: An ad hoc network with n nodes in an area of A sq. meters.

It was shown in [1] that under a Protocol Model of interference, such a network could provide a per node throughput of $\frac{c'}{\sqrt{n \log n}}$ bits/sec. It was also shown there that even under the best possible placement of nodes, such a network could not provide a per-node throughput of more than $\frac{c''}{\sqrt{n}}$ bits/sec.

The above are theoretically optimal results, and it is an important question how current technology fares in this regard. There have been proposals to create ad hoc networks with a very large number of nodes, and in order to evaluate such plans, experimental results are invaluable. This raises the question: What are the experimental scaling laws for ad hoc networks with today's technology and protocols? This paper investigates this issue.

2 The Main Result

We report on the experimental scaling law: The per node throughput decays like $\frac{c}{n^{1.68}}$ bits/sec.

Figure 2 provides a plot of the throughput per node as a function of the number of nodes.

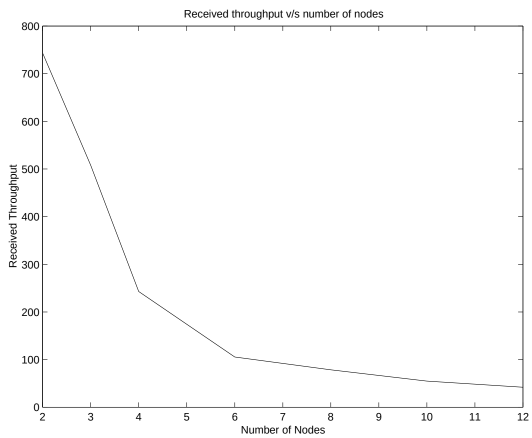


Figure 2: Received throughput (in kbits/s) v/s number of nodes in the network.

Figure 3 provides a plot of log (throughput per node) as a function of log (number of nodes). The plot is nearly linear. Its slope of 1.68 yields the power law noted above.

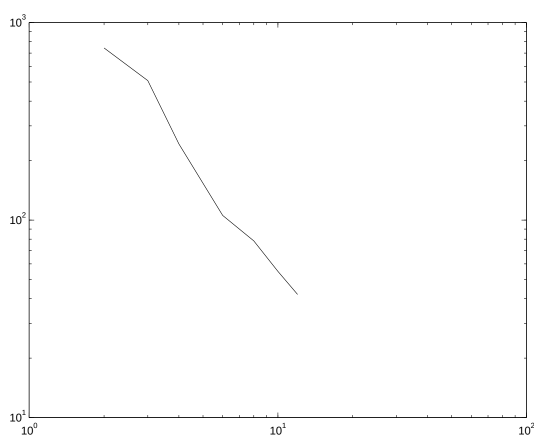


Figure 3: Received throughput (in kbits/s) v/s number of nodes in the networks: A log-log scale plot.

It may be noted that this is a very bad scaling. For example it is even much worse than a purely colocated case where one expects $\frac{c'''}{n}$ bits/sec from simple time division multiplexing, and of course it is much worse than the $\frac{c'}{\sqrt{n \log n}}$ or $\frac{c''}{\sqrt{n}}$ random case and best case results, respectively, shown to be achievable in theory. It is clearly imperative to improve the exponent in the scaling law if one wants to contemplate the possibility of large ad hoc networks.

The rest of this paper provides the details of the experimental setup.

3 Experimental Setup

The setup used to conduct the experiments consisted of Pentium laptops running Linux. Specifically, the setup had three Gateway Solo 2300 laptops and six Toshiba Terca 500CS laptops running Slackware Linux 4.0 and three IBM ThinkPad 755CD laptops running RedHat Linux 6.0 (laptops were used in that order to meet the experimental requirements). Laptops were networked using Lucent Technologies' IEEE 802.11 compliant WaveLan Turbo Bronze PCMCIA cards. IEEE 802.11 compliant cards were used as they are the most popular as well as the de facto standard wireless networking hardware. The specified data rates of the WaveLan Bronze cards are 2 Mbits/s in the standard mode and 6 Mbits/s in the Turbo mode. To ensure compatibility with older cards, all cards were configured to operate in the standard mode of 2 Mbits/s.

We next describe the traffic generation and measurement techniques employed in the experiments.

3.1 Traffic generation and measurement

Each node in the network generated packets at a periodic rate. The size of each packet was 1 kbyte. (It would be interesting to study the variation in the throughput capacity with the packet size). For each packet that a node generated, the node picked a random destination independently and uniformly from the list of reachable nodes in its routing table. The node then established an user datagram protocol (UDP) socket [2] for the chosen destination, and passed on the packet to its operating system kernel. The kernel in turn forwarded the packet to the next hop on the route to the chosen destination, as per its routing table. We used UDP sockets as TCP/IP is known to not perform well in the wireless environment. (It would be of interest to repeat the experiments with a more reliable transport mechanism – perhaps with one of the proposed modified versions of TCP/IP for wireless [3]-[7].)

We originally intended to employ a specific distributed routing algorithm to dynamically setup efficient routing tables at nodes in the network. However, the available implementation of the routing algorithm did not perform as expected, and we ended up manually hard coding the routes in each node's routing table. The results, of course, can only be worse if a routing algorithm is used, due to the overhead of the routing protocol.

In the above setting, we used the average number of correctly received packets per second as a measure of the received throughput at a node. The traffic sending rate was varied over a wide range to obtain the variation in the received throughput. The maximum value of the received throughput averaged over all nodes in the network was used as a measure of the throughput capacity of the network.

4 Experiments and Data Analysis

We conducted experiments on networks of different sizes, ranging from 2 to 12 nodes. The first two sets of experiments were done on networks consisting of 2 and 3 nodes (Figures 4 and 5, respectively). In these experiments the laptops were arranged on a table, and thus every node was within transmission range of every other node in the network., i.e., the nodes were colocated. In the subsequent sets of experiments with networks of larger size (Figures 6-10), the laptops were placed in the various rooms of an office building. This was done so that the network connectivity was neither too dense nor too sparse. The actual laptop placement and the corresponding network connectivity graphs are given in the above mentioned figures.

For each network, the rate at which each node in the network generated traffic was varied from 1 kbits/s to 1000 kbits/s. As expected, the average received throughput in each experiment increased with the traffic sending rate up to a certain point, beyond which it remained nearly constant. The saturation point of the average received throughput gave a measure of the throughput capacity of the network. Figure 2 summarizes the results by plotting the variation in the average received throughput with the number of nodes in the network; a log-log scale version of the same plot is given in Figure 3. From a least-squares fit to the latter, we obtain that the average received throughput decreases as $\frac{2.583}{n^{1.68}}$ Mbits/s with the number of nodes n in the network.

5 Concluding Remarks

The results provided here suggest that the current hardware and implemented protocols will need substantial improvement. In particular, a more efficient medium access protocol may be of interest.

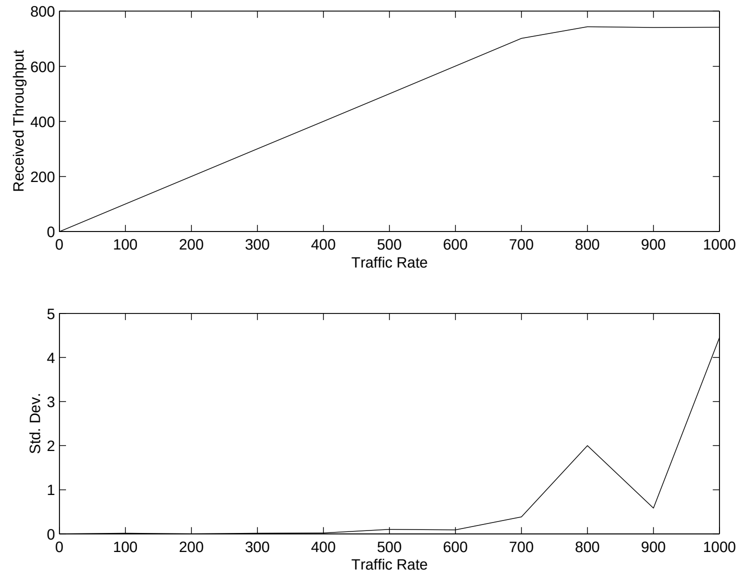


Figure 4: Average received throughput v/s traffic rate (in kbits/s) in a network of two nodes.

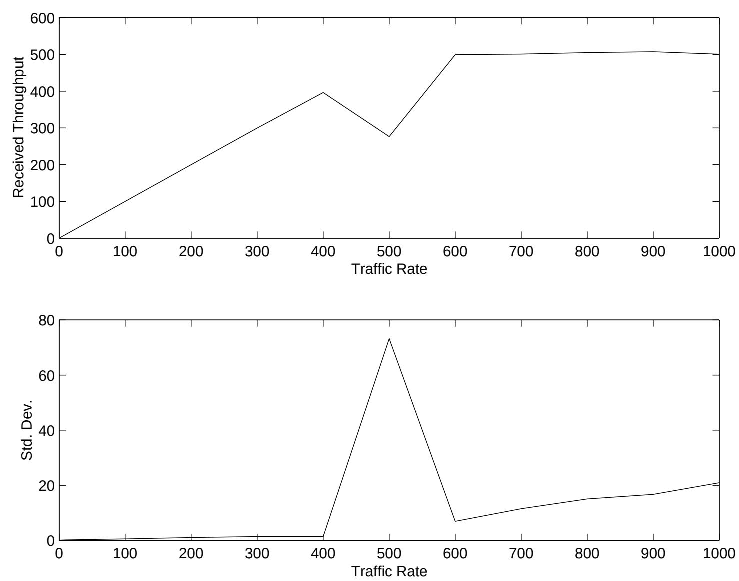
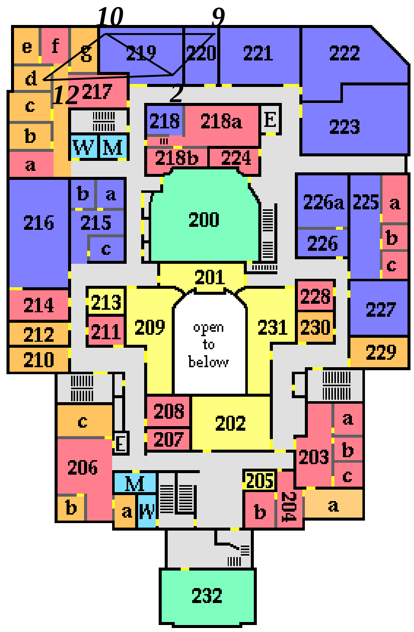
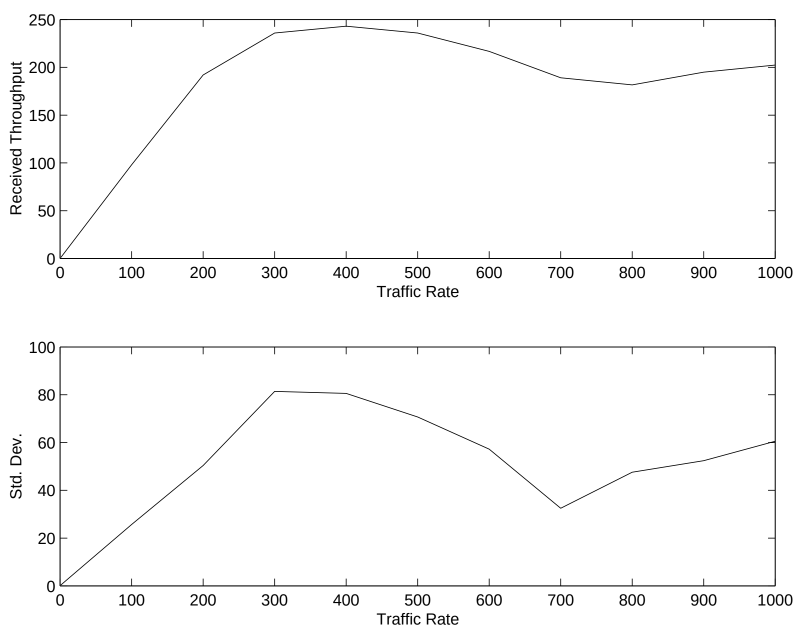


Figure 5: Average received throughput v/s traffic rate (in kbits/s) in a network of three nodes placed on a table.

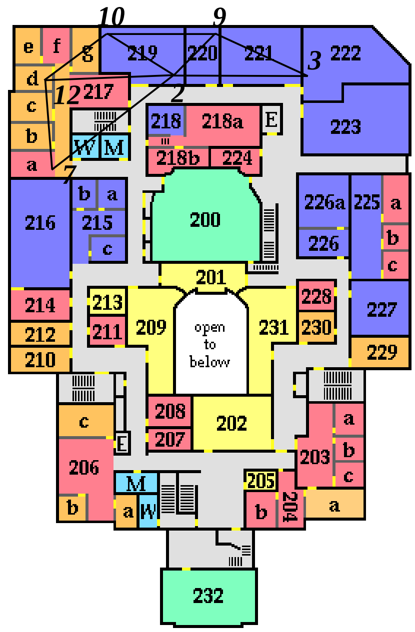


(a)



(b)

Figure 6: An 4-node network: (a) setup, and (b) average received throughput per node v/s traffic rate (in kbits/s).



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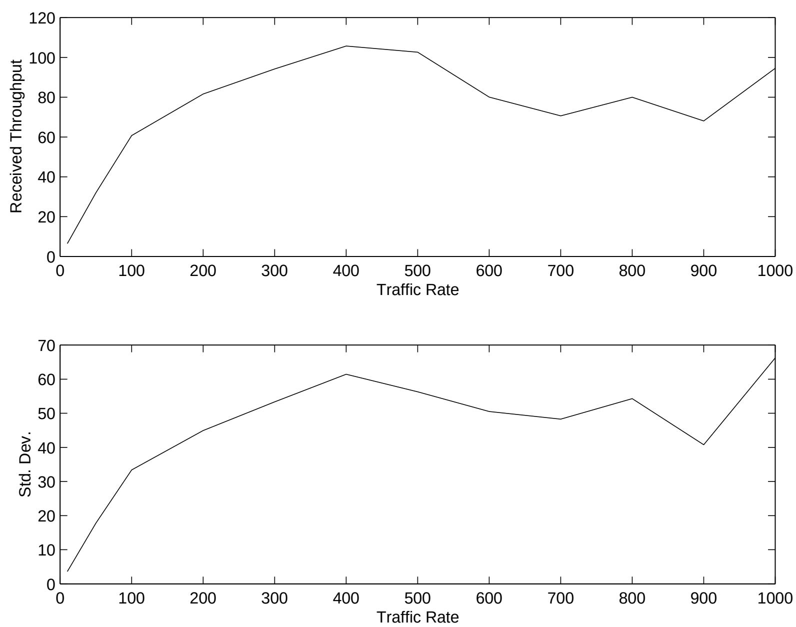
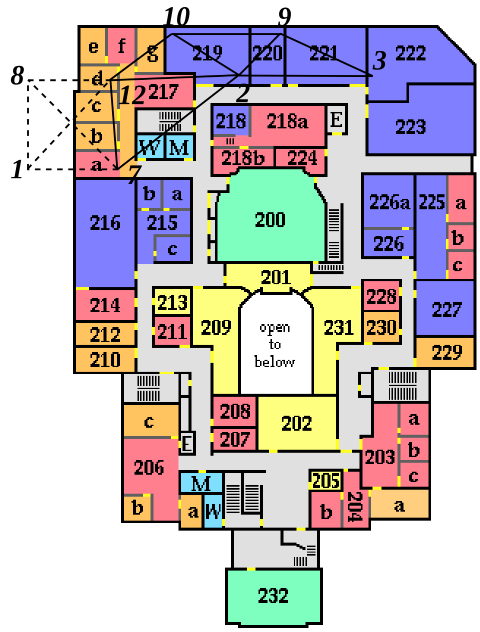
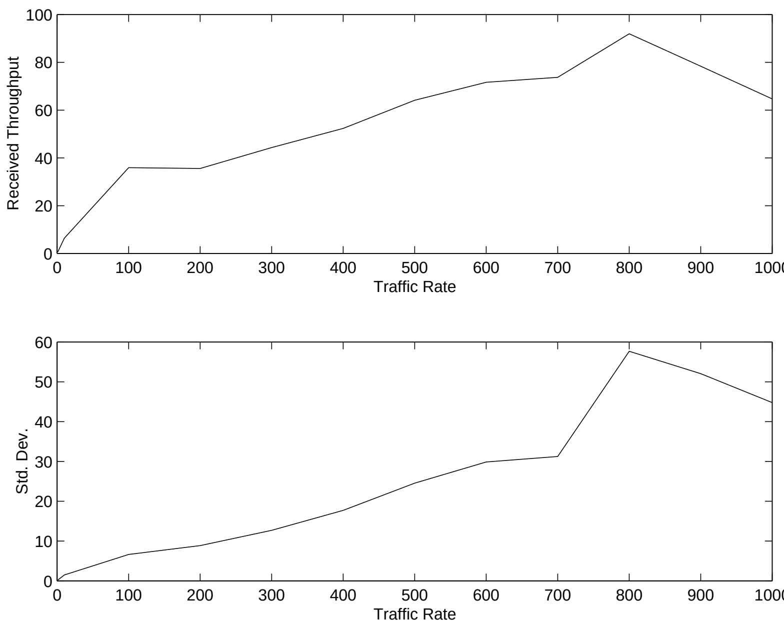


(b)

Figure 7: An 6-node network: (a) setup, and (b) average received throughput per node v/s traffic rate (in kbits/s).

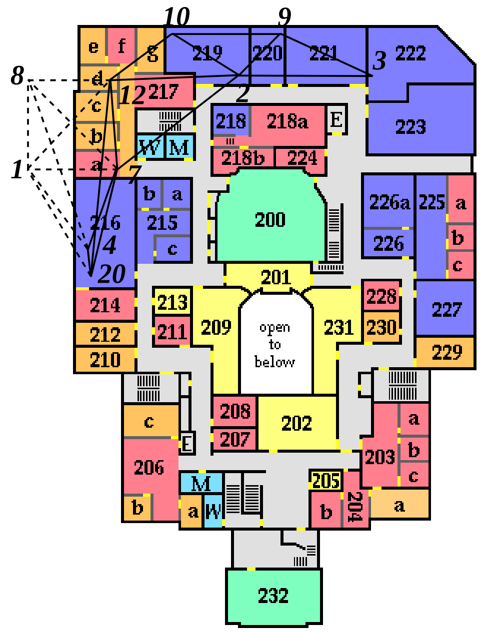


(a)

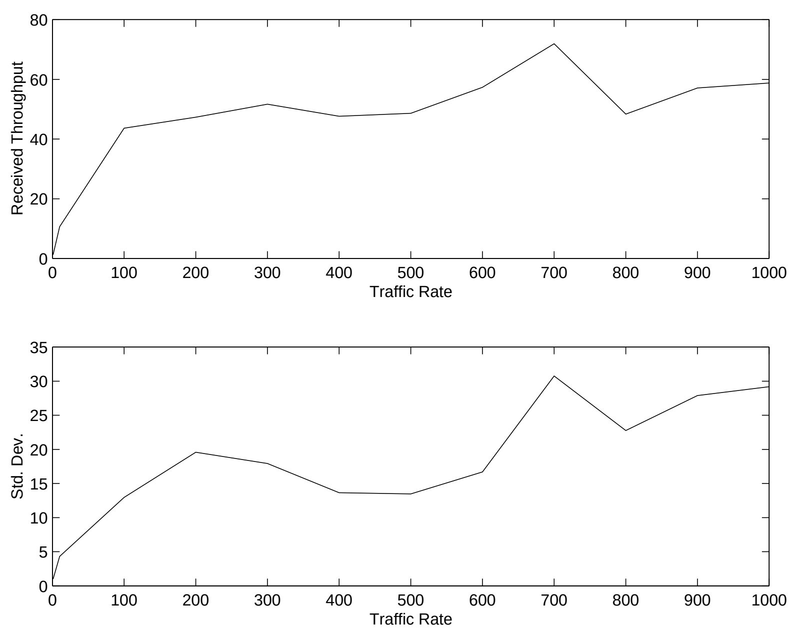


(b)

Figure 8: An 8-node network: (a) setup (nodes 1 and 8 were placed on the first floor, exactly below nodes 7 and 12, respectively), and (b) average received throughput per node v/s traffic rate (in kbits/s).

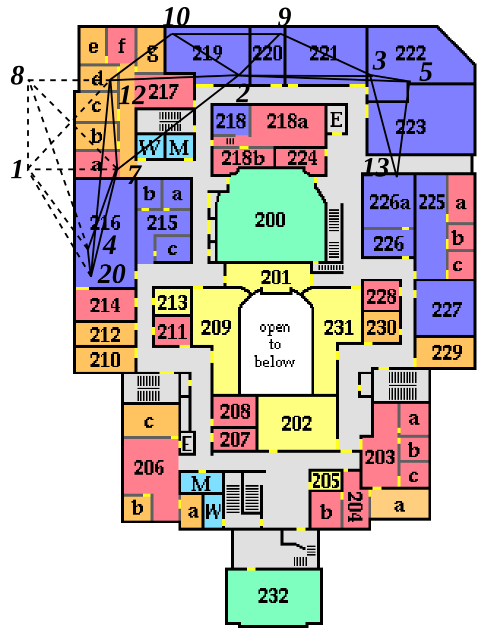


(a)

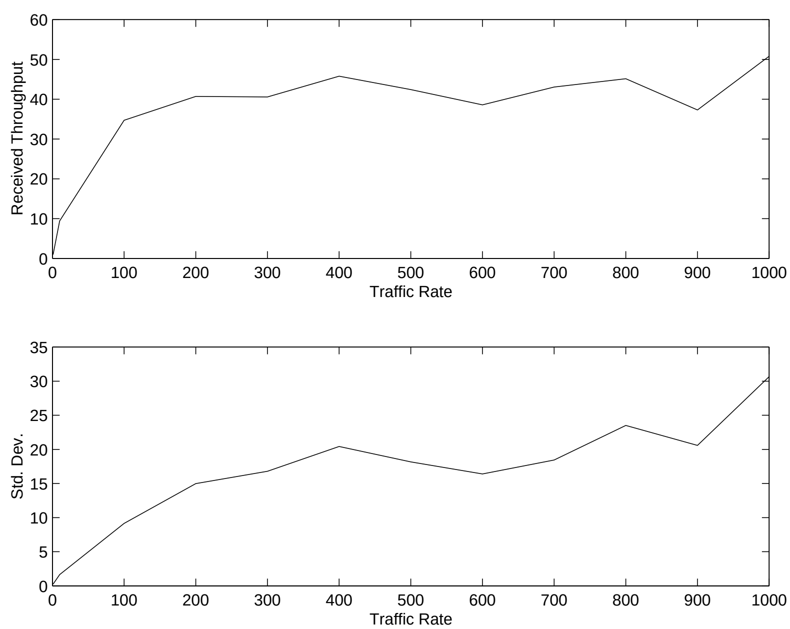


(b)

Figure 9: An 10-node network: (a) setup, and (b) average received throughput per node v/s traffic rate (in kbits/s).



(a)



(b)

Figure 10: An 12-node network: (a) setup, and (b) average received throughput per node v/s traffic rate (in kbits/s).

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