Performance of TCP and UDP Protocols in Multi-Hop Multi-Rate Wireless Networks

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Abstract— **An interesting feature of IEEE 802.11 Wireless LAN cards is that they support multiple transmission modes. For example, the 802.11b cards support four transmission modes of 1, 2, 5.5 and 11 Mbps, whereas, the 802.11a cards support eight transmission modes, upto a maximum of 54 Mbps. In this paper, we study layer four protocols over multi-rate multi-hop wireless networks and attempt to answer the question whether higher bandwidth links necessarily outperform lower bandwidth links in these networks. We examine this question by taking into account the transport layer protocols such as the TCP and UDP. While network capacity is a topic of active interest in the research community, a comparative study of the ad hoc network throughput at different link bandwidths has not been made. We then propose a bandwidth based ad hoc routing protocol and look at how to integrate QoS with routing.**

I. INTRODUCTION

IEEE 802.11 [1] has emerged as the most widely used Wireless LAN standard in commercial environments. IEEE 802.11b and IEEE 802.11a cards are typically designed to support multiple data rates. Whereas IEEE 802.11b is a Wireless LAN (WLAN) standard for high-speed transmission in the 2.4 GHz band, IEEE 802.11a WLAN is a standard for high-speed transmission in the 5 GHz band. IEEE 802.11b supports four transmission modes, 1, 2, 5.5 and 11 Mbps ([14]) and 802.11a supports eight transmision modes and provides data rates up to 54 Mbps. Each mode uses different coding rate and modulation level. Generally, the higher the bit rate, the more vulnerable to channel errors and hence higher transmission power should be used to maintain the SNIR to an acceptable level [14], [13].

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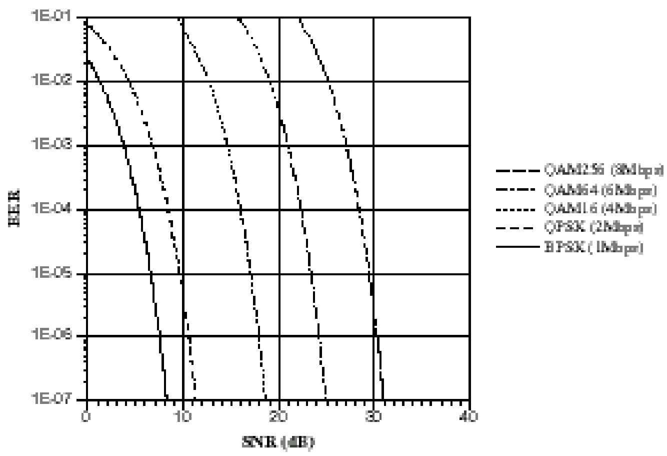

Fig. 1. SNR vs BER curves for different data rates

Transmitting at higher rate, where possible, typically results in a higher single-hop throughput. However, in networks where nodes forward each other's packets (e.g., ad hoc wireless networks), the advantage of high bandwidth links is not so apparent, particularly from the point of view of TCP and UDP protocols. Higher rate transmissions suffer from higher bit-error rates, hence reducing the effective reception radius. A typical bit-error rate (BER) vs signal-to-noise (SNR) ratio curve [2] for different data rates is shown in Figure I. A higher data rate corresponds to a smaller area of successful reception for the same signal power at the transmitter. Hence a connection such as TCP or UDP will require to traverse more number of hops to cover the same distance at higher data rates.

In this paper, we study the performance of TCP and UDP protocols over multi-hop multi-rate wireless networks. In multi-rate ad hoc networks, the rate at each hop may be different. We study the impact of multiple-rates on the throughput of UDP and the goodput of TCP traffic. We propose an ad hoc routing protocol based on bandwidth or transmission rates. Our study is based on simulation results and analysis from first principles.

In an earlier paper [6], we present a general methodology for modeling TCP over IEEE 802.11b networks. We compute the long term average throughput achieved by a single TCP session over a linear chain of nodes. Even though the paper [6] has many assumptions in order to make the analysis tractable, we believe that the results in the paper are useful towards understanding the performance of TCP over ad hoc wireless networks with IEEE 802.11 MAC.

In [4], the authors examine the problems with IEEE 802.11 MAC protocol in multi-hop networks. They present two problems existing in IEEE 802.11 based multi-hop wireless ad hoc networks. These are the TCP instability problem and the unfairness problem. In [5], the authors study the interactions of the IEEE 802.11 MAC and ad hoc forwarding and the effect on capacity for several simple configurations and traffic patterns. The paper examines the capacity of wireless ad hoc networks via simulations and analysis from first principles.

MAC protocols have been proposed where transmitters select data rates dynamically subject to the channel condition ([11]). Such an adaptive MAC protocol results in a network with links of different bandwidths. In [15], the authors present how the throughput in an ad hoc network is affected by using variable data rate. The paper concludes that it is of great importance to take data rate into consideration when routing and have traffic adaptivity to be able to make use of variable data rate in an ad hoc network. The results in the paper assume a TDMA ad hoc network.

We have implemented the support for variable rates in the *ns* simulator [8], [9]. We consider receiver sensitivity thresholds obtained from typical wireless card implementations [14], [7], [13]. For a transmission power of 108 mW, the corresponding reception ranges for the different data rates is tabulated in Table I. Note that in wireless networks, there are two thresholds defined: the carrier-sense threshold and the receive threshold. The carrier-sense threshold is typically much smaller than the receive-threshold. Thus the range of carrier-sense (or interference) is typically much more (for example, twice) that of the receive threshold [12].

The paper is organized as follows. In Section II, we study a multi-rate multi-hop network. More specifically, we study the TCP goodput and UDP throughput in a chain of nodes where the nodes are based upon the IEEE 802.11 protocol. We then study the UDP throughput versus the data rate of source node. Subsequently, we examine how the TCP goodput varies as a function of the channel bandwidth and node mobility. In Section III, we study TCP over a heterogeneous chain of nodes where links have different bandwidths. In Section IV, we discuss a new ad hoc routing protocol that is based on link bandwidths. Finally, in Section V, we conclude the paper.

CS Range	1 Mbps	2 Mbps	5.5 Mbps	11 Mbps
978 m	550 m	437 m	292 m	232 m

TABLE I
CHANNEL BANDWIDTH VERSUS THE DISTANCE BETWEEN TWO NODES IN A CHAIN TOPOLOGY

II. A MULTI-RATE MULTI-HOP NETWORK

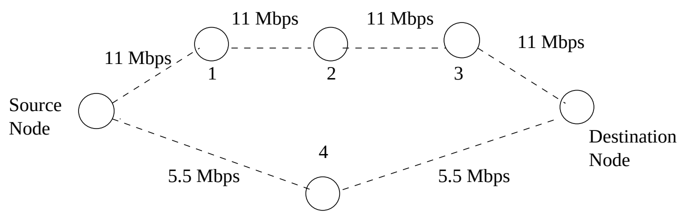

Fig. 2. Figure showing two paths from Source to Destination: a four hop path with 11 Mbps links and a two hop path with 5.5 Mbps links.

Figure 2 shows an ad hoc network with two paths from a source S to a destination D. The first path is a four hop path from S to D where the link on each hop has a bandwidth of 11 Mbps. The second path is a two hop path from S to D where the link on each hop as a bandwidth of 5.5 Mbps. Thus an interesting question arises: which is a better path for TCP traffic - a four hop path with 11 Mbps bandwidth links or a two hop path with 5.5 Mbps bandwidth links? Note that the answer to this question is not straightforward. Even though a four hop path has a greater end-to-end packet error probability compared to a two hop path, the link data rate in the four hop path (shown in Figure 2) is twice the link data rate in the two hop path. Therefore any performance degradation of transport layer protocols due to an increase in the number of hops seems to be counteracted by a higher link bandwidth. Hence a need arises to perform simulations and analysis to understand such networks better.

In an ad hoc network with nodes based upon the IEEE 802.11b or IEEE 802.11a MAC, heterogeneous paths with different rates arise and it is not clear how TCP or UDP perform over wireless paths where links have different rates. It is with this in mind we study the TCP goodput and the UDP throughput versus hop count of path for different rates in the IEEE 802.11 network. The results in this paper are restricted to IEEE 802.11b. Note, however, that the extension to IEEE 802.11a protocol is straight-forward with the only difference that there are more data rates in IEEE 802.11a. In IEEE 802.11a, Table I will need to be revised appropriately.

A. TCP/UDP Throughput

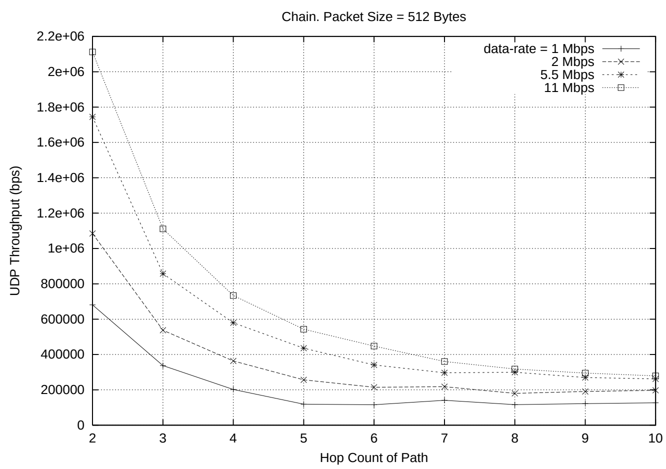

Fig. 3. UDP Throughput for a Chain Running One End-to-End Connection

In Figure 3, we plot the hop count of path versus the UDP throughput (in bits per second) for a linear chain of nodes. There are four plots, each corresponding to a different date rate. For each data rate, we observe that the throughput of UDP traffic decreases with an increase in the hop count of path (i.e., the number of hops from source to destination). This trend is well known: the packet error probability increases with an increase in the number of hops causing the UDP throughput to decrease. We also observe from the plot that for a fixed hop count of path, the UDP throughput for a higher data-rate is higher than that for lower data-rate. However, the difference between the UDP throughput decreases with an increase in the hop count of path. Note that some interesting inferences can be drawn from the plot. If we keep the UDP throughput fixed, the plot shows the *(hop count, data-rate)* pairs that yields similar throughput. Thus, for example, we see that a chain with four hops and 2 Mbps bandwidth links has almost the same throughput as a chain with six hops and 5.5 Mbps bandwidth links. Both these scenarios yield a throughput of approximately 350 Kbps. Such inference for both UDP and TCP traffic may not be possible without a detailed simulation of the multi-rate multi-hop network.

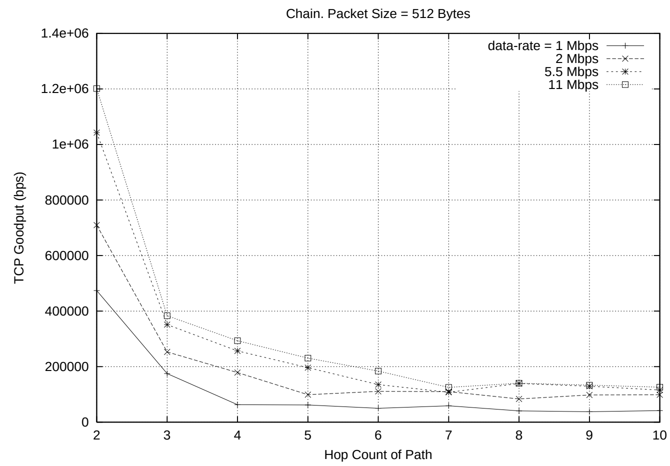

Fig. 4. FTP Goodput for a Chain Running One End-to-End Connection

In Figure 4, we plot the hop count of path versus the TCP goodput (in bps) for a linear chain of nodes. The two plots in Figure 3 and Figure 4 are essentially similar. Note, however, that for a fixed hop count of path and a fixed bandwidth, the TCP goodput is lower than the UDP throughput. This is as expected and is due to the reliable nature of the TCP protocol where every packet transmitted from the source is acknowledged by the destination node.

From Figure 3 and Figure 4, we see that the gain in throughput of UDP and TCP is not in proportion to the increase in the link rate; this is because the actual packet transmission time has a fixed part which does not depend on the link speed significantly. Thus increasing the link speed only reduces the transmission of the packet but not the (almost) fixed MAC overhead. On the other hand increasing link speed causes more errors and, in addition, reduces the span of the network.

B. UDP Throughput versus the Source Transmission Rate

In Figure 5, we plot the UDP throughput versus transmission rate at the source for a chain of nodes. The distance between the end points of the chain is fixed and is equal to 7000 meters. The packet size is equal to 1024 Bytes. There are four plots with channel rates of 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps. For each channel rate, we see that as the transmission rate at the source increases, the UDP throughput increases till a point, after which the throughput drops to a value and then saturates, any

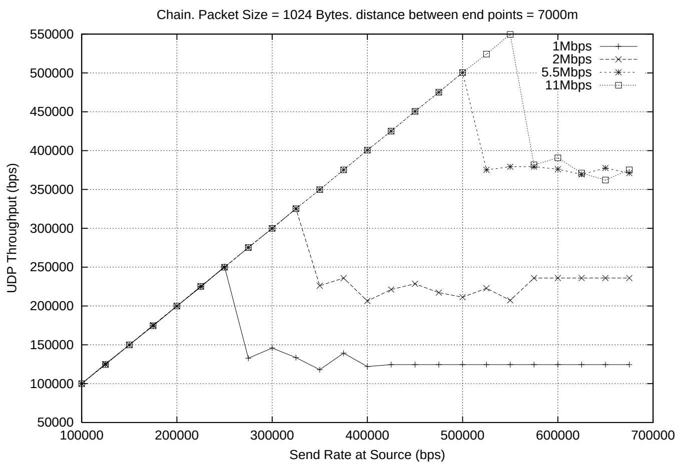

Fig. 5. UDP Throughput versus Transmission rate at Source for a Chain Running One End-to-End Connection.

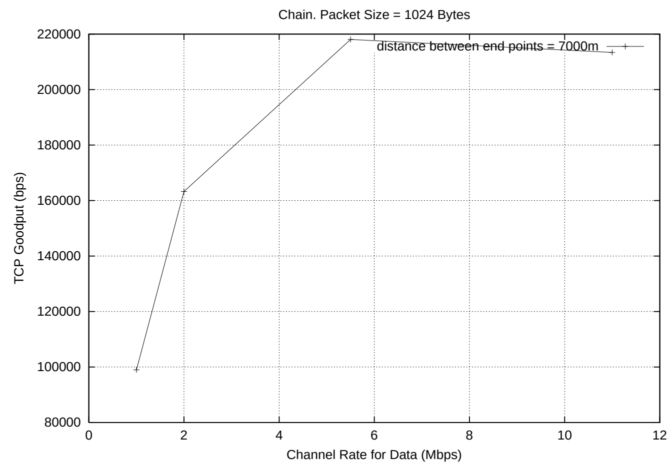

Fig. 6. TCP Goodput versus the Data Rate

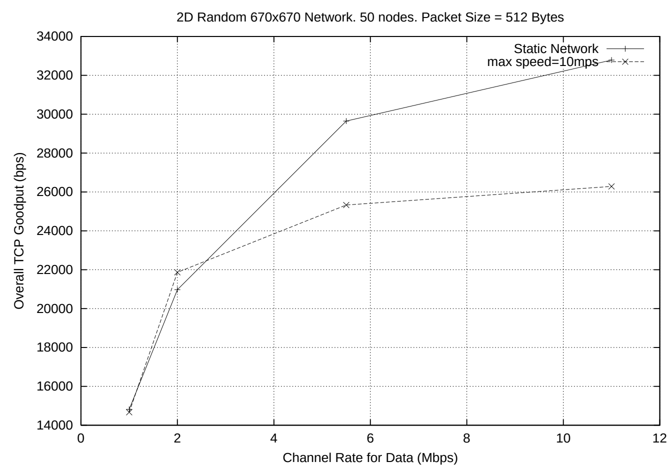

Fig. 7. The Effect of Mobility on TCP Goodput at Different Bandwidths

further increase in the sending rate does not affect the UDP throughput as it remains a constant. Note that as the channel rate increases from 1 Mbps to 11 Mbps, the UDP throughput increases and the saturation throughput is higher for higher channel rate. For example, in Figure 5, for a link with bandwidth 11 Mbps, the saturation throughput is approximately 375 Kbps when the UDP sending rate is greater than 550 Kbps; whereas, for a link with bandwidth of 2 Mbps, the saturation throughput lies between 200 Kbps and 250 Kbps when the UDP sending rate is greater than 350 Kbps.

Figure 5 is important since it helps us to select an appropriate transmission rate for a source with UDP traffic given the link bandwidth and the number of hops between the source and the destination.

C. *TCP Goodput versus Channel Data Rate*

We now study the sensitivity of TCP goodput to the channel bandwidth. In Figure 6, we plot the TCP goodput versus data rate in a linear topology of nodes. The distance between the source and the destination is kept fixed and is equal to 7000 meters. The TCP packet size is 1024 Bytes. We see that there is a large increase in the TCP goodput as we increase the data rate from 1 Mbps to 2 Mbps and from 2 Mbps to 5.5 Mbps. However, increasing the data rate beyond 5.5 Mbps does not show any increase in the goodput. In fact, the TCP goodput at 11 Mbps is almost the same as that in 5.5 Mbps. We have already seen this behaviour in Figure 4.

In Figure 7, we plot the TCP goodput versus the channel bandwidth for a two dimensional ad hoc network both with and without mobility. We consider 50 nodes placed in a (670 m x 670 m) area and a packet size of 512 Bytes. We use the random waypoint model with a maximum node speed of 10 m/s. We see that with the addition of mobility, the TCP goodput reduces and the degradation in the TCP goodput is more pronounced at high bandwidth than at low bandwidth. This is to be expected since the higher the mobility, the higher the probability of a link break and this in turn implying high packet error probability for the TCP connections. Note, however, that as the bandwidth increases, the difference between the TCP goodput obtained from a static network and a network with mobility increases. This follows since at high data rates of 5.5 Mbps and 11 Mbps in an IEEE 802.11b network, the SNR is high and the link is extremely sensitive to mobility. The difference in TCP goodput between a static and a mobile ad hoc network is less pronounced at low data rates of 1 Mbps and 2 Mbps. The above observation points to the fact that *in an ad hoc network with high channel bandwidth, a high node mobility may not be desirable since it may result in poor TCP performance*.

III. TCP over a Heterogeneous Chain

Having studied the performance of TCP/UDP over a linear chain of nodes with 802.11 MAC and when all the links in the chain have the same bandwidth, we now focus on the following question: how do layer four protocols perform over a linear chain of nodes where links can have different bandwidth?

For simplicity, we begin with the setup where there are only two rates and where in an N node chain, only one link has a low bandwidth and the other (N-1) links are homogeneous with a higher bandwidth. We vary the position of the low bandwidth link in the chain and study the impact of this change on the the TCP protocol.

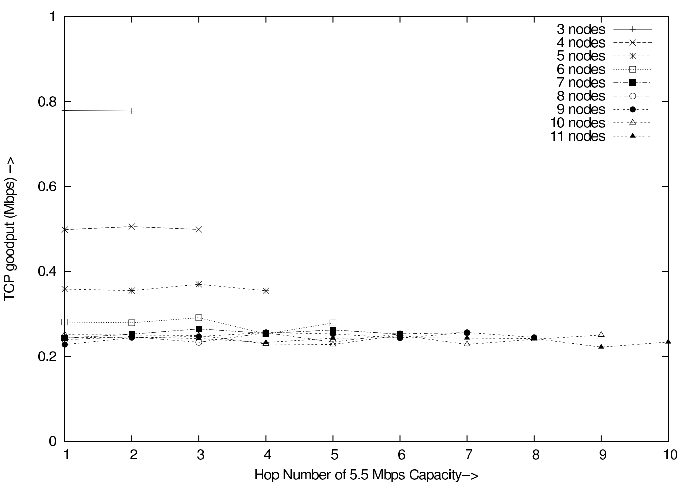

Fig. 8. TCP Goodput as a Function of the Hop Number of the 5.5 Mbps Link. All Other Links are 11 Mbps.

In Figure 8, we plot the TCP goodput versus the hop number of the 5.5 Mbps link. We study a chain of nodes, all based on the IEEE 802.11b protocol. All the links in the N hop chain have the same rate equal to 11 Mbps except one link which has a rate equal to 5.5 Mbps. The slow link is henceforth referred to as the *bottleneck link*. As we increase the number of nodes in the chain, the TCP goodput decreases and this is as expected. However, we observe that the TCP goodput is invariant to the position of the bottleneck link in a chain of nodes. For example, in an 11 node chain, when the bottleneck link (i.e., 5.5 Mbps link) is Link 1, the TCP goodput is almost the same as when the bottleneck link is Link 9.

Note that the result is somewhat counter-intuitive since one expects the TCP dynamics to be different depending upon whether the bottleneck link is close to the source, close to the destination or at the interior of a chain of nodes. Intuitively, TCP goodput is thought to be lower when the bottleneck link is at the interior nodes or near the destination node, but this is not what we observe. We are currently trying to understand this behaviour in more detail using analytic models [6].

IV. Link Bandwidth Based Ad Hoc Routing

The results in this paper are interesting and point to ad hoc routing protocol that is based upon the bandwidth of links. In this paper, we will use the term data rate and bandwidth interchangeably.

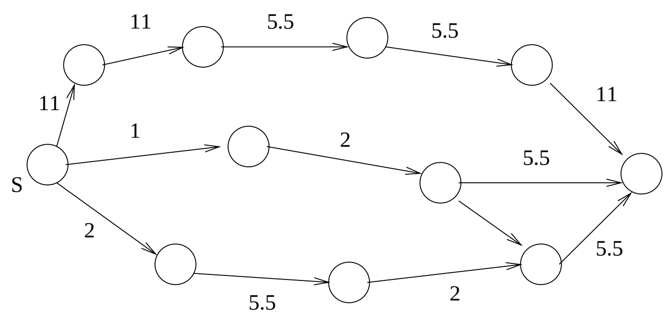

Fig. 9. Bandwidth Based Ad Hoc Routing. The Links Show Bandwidth in Mbps.

Consider again the IEEE 802.11 standard as an example. An 802.11b wireless LAN can support 11, 5.5, 2 and 1 Mbps, while an 802.11a wireless LAN can support upto 8 different rates. Depending on the channel conditions, especially their distance from each other, two wireless stations may choose different transmission rates in order to increase the probability of successful transmission. As shown in Figure 9, if the distance between two nodes is small, the link SNR is high and this results in high bandwidth links. On the other hand, if two nodes are far apart, the bandwidth of the link connecting them will be low. Thus the source node S has three paths to choose from: the 5 hop path (11, 11, 5.5, 5.5, 11), the 3 hop path (1, 2, 5.5) or the 4 hop path (2, 5.5, 2, 5.5). Note that all the rates are in Mbps. If we now establish a TCP (or a UDP) connection from S to D, it is not clear which would be the best path for a TCP/UDP connection. This is where Figure 3 and Figure 4 are of importance and come to our rescue.

In the bandwidth based ad hoc routing protocol, a node chooses its nearest neighbour based upon the link bandwidth. Assume that a node N_i has two neighbours N_a and N_b, the link from N_i to N_a has a transmission rate of 11 Mbps and the link from N_i to N_b has a transmission rate of 5.5 Mbps, then the ad hoc routing protocol will select node N_a as the neighbouring node since it corresponds to a higher bandwidth. Note that it is now highly likely that a route from a source to a destination is not the least hop count route as is generally the case in ad hoc routing; routes are now high bandwidth routes. High bandwidth routes may not necessarily be least hop count routes.

Note that at first thought, it may appear that bandwidth based routing is identical to either location based routing or SNR based routing, and both these metrics have been proposed earlier. However, bandwidth based routing utilizes the different rates that are characteristic of IEEE 802.11b and IEEE 802.11a based wireless nodes. From the point of view of TCP and UDP, it is easier to study and quantify their performance on links with different discrete bandwidths rather than the SNR values that change frequently with space and time.

The novelty of the proposed protocol is that we are exploiting the multi-rate features of IEEE 802.11b and 802.11a WLAN cards; in all the earlier works there was no multi-rate feature that was inherent in the ad hoc network. It is the flexibility of being able to change a rate at a node that gives novely to this work. Therefore, it is possible to decrease the bandwidth from 11 Mbps to 5.5 Mbps so that a node can cover larger distances and reach out to nodes that are beyond the nearest neighbour nodes.

We are currently working on the details of the bandwidth based ad hoc routing protocol. This protocol therefore arises naturally in ad hoc networks where nodes are based upon the IEEE 802.11b or IEEE 802.11a MAC.

V. Conclusion

In this paper, we have studied TCP and UDP traffic over a multi-hop multi-rate wireless ad hoc network where all the nodes are based upon the IEEE 802.11b protocol. The paper is a preliminary attempt to study layer four protocols over multi-rate ad hoc networks. The results in the paper are interesting and give an insight into several issues in these networks. There are several research directions that are not partially or fully addressed in this paper and remain as the major problems to dwell upon in the future works.

It will be interesting to extend the results in this paper to IEEE 802.11a standard. Note that IEEE 802.11a has larger rate set where the channel rates can take any value from amongst (6, 9, 12, 18, 24, 36, 48, 54) Mbps [13]. However, we do not expect the nature of the plots in this paper to change as we move from IEEE 802.11b to IEEE 802.11a standard.

It will be interesting to study the performance of TCP/UDP traffic over multi-hop ad hoc networks based on IEEE 802.11 standard where links have different rates. We are currently investigating the TCP goodput as a function of the TCP window size in an ad hoc network.

Bandwidth aware ad hoc routing promises to be an interesting area of future research. Note that applications demanding Quality of Service (QoS) in ad hoc networks may be greatly benefitted by bandwidth aware ad hoc routing. This paper is an attempt to integrate QoS with routing in a multi-rate multi-hop wireless networks. Several issues in bandwidth aware ad hoc routing remain open. We discuss the details of the proposed ad hoc routing protocol in a separate paper.

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