Available Bandwidth Estimation in IEEE 802.11-based Wireless Networks

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I. INTRODUCTION

Available bandwidth estimation is a vital component of admission control for quality-of-service (QoS) in both wireline as well as wireless networks. In wireless networks, the available bandwidth undergoes fast time-scale variations due to channel fading and error from physical obstacles. These effects are not present in wireline networks, and make estimation of available bandwidth in wireless networks a challenging task. Furthermore, the wireless channel is also a shared-access medium, and the available bandwidth also varies with the number of hosts contending for the channel.

Wireless last-hop networks employing the IEEE 802.11 protocol in Distributed Co-ordination Function (DCF) mode are becoming increasingly popular. In DCF mode, the 802.11 protocol [1] does not require any centralized entity to co-ordinate users' transmissions. The MAC layer uses a CSMA/CA algorithm for shared use of the medium. In this extended abstract, we present an available bandwidth estimation scheme for IEEE 802.11-based wireless networks. Our scheme does not modify the CSMA/CA MAC protocol in any manner, but gauges the effect of phenomena such as medium contention, channel fading and interference, which influence the available bandwidth, on it. Based on the effect of the phenomena on the working of the medium-access scheme, we estimate the available bandwidth of a wireless host to each of its neighbors [1].

II. AVAILABLE BANDWIDTH ESTIMATION

Figure 1 shows the stages in the transmission of a single packet using the IEEE 802.11 DCF MAC protocol. Details of the individual messages and gaps can be found in [1]. We measure the throughput of transmitting a packet as $TP = \frac{S}{t_r - t_s}$, where S is the size of the packet, t_r is the time the ACK is received and t_s is the time that the packet is ready at the MAC layer. The time interval $t_r - t_s$ includes the channel busy and contention time. We keep separate throughput estimates to different neighbors because the channel conditions may be very different to each one.

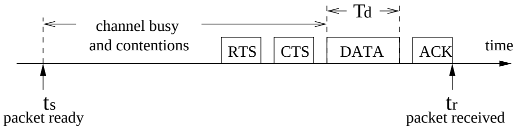

Fig. 1. IEEE 802.11 unicast packet transmission sequence.

This link layer measurement mechanism captures the effect of contention on available bandwidth. If contention is high, $t_r - t_s$ will increase and the throughput TP will decrease. This mechanism also captures the effect of fading and interference errors because if these errors affect the RTS or DATA packets, they have to be re-transmitted. This increases $t_r - t_s$ and correspondingly decreases available bandwidth. Our available bandwidth measurement mechanism thus takes into account the phenomena causing it to decrease from the theoretical maximum channel capacity. It should be noted that the available bandwidth is measured using only *successful* link layer transmissions of an ongoing data flow.

It is clear that the measured throughput of a packet depends on the size of a packet. Larger packet has higher measured throughput because it sends mre data once it grabs the channel. To make the throughput measurement *independent* of packet size, we normalize the throughput of a packet to a pre-defined packet size. In Figure 1, $T_d = S/BW_{ch}$ is the actual time for the channel to transmit the data packet, where BW_{ch} is the channel's bit-rate. Here we assume the channel's bit-rate is a pre-defined value. The transmission times of two packets should differ only in their times to transmit the DATA packets. Therefore, we have:

$$(t_{r1} - t_{s1}) - \frac{S_1}{BW_{ch}} = (t_{r2} - t_{s2}) - \frac{S_2}{BW_{ch}} \quad (1)$$

$$= \frac{S_2}{TP_2} - \frac{S_2}{BW_{ch}} \quad (2)$$

where S_1 is the actual data packet size, and S_2 is a pre-defined standard packet size. By Equation (2), we can calculate the normalized throughput TP_2 fr the standard size packet. To verify the validity of this equation, we simulated a group of mobile wireless hosts within a single-hop ad hoc network using the *ns-2* network simulator. We sent CBR traffic from one host to another, and varied the packet size from 64 bytes to 640 bytes during the course of the simulation. The measured raw throughput is normalized against a standard size, picked as 512 bytes. Figure 2 shows the result of the measured raw throughput and its corresponding normalized thorughput. Obviously, the raw throughput depends on the packet size; larger packet size leads to higher measured throughput. The normalized throughput, on the other hand, does not depend on the data packet size. Hence, we use the normalized throughput to represent the bandwidth of a wireless link, to filter out the noise introduced by the measured raw throughput from packets of different sizes.

Another important issue is the *robustness* of the MAC layer bandwidth measurement. We measure the bandwidth of a link in discrete time intervals by averaging the throughputs of the recent packets in the past time window and use it to estimate the bandwidth

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[1] A neighbor of a wireless host is defined as any other wireless host within its transmission range.

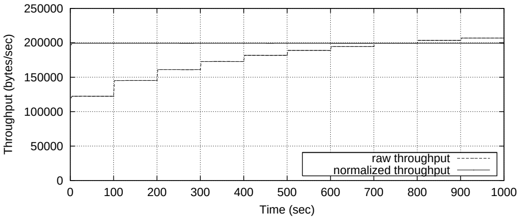


Fig. 2. Raw and normalized throughput at MAC layer.

in the current time window. Obviously, this estimation may not be accurate because the channel condition may have changed. To evaluate the estimation error, we run a CBR flow using UDP with data rate 160 kbps from a node to another in a 10 node one-hop environment. Background traffic consists of 1 greedy TCP flow in the light channel contention case, and 7 TCP flows in the heavy contention case. Here we use TCP only to generate bursty cross-traffic to the UDP flow. We measure and normalize the throughput of the CBR flow every 2 seconds using the average of packet throughputs in the past time window. Our results show that under light channel contention, over 97% of the estimates are within 20% of error; under heavy contention, still over 80% of the estimates are within 20% of error. We thus conclude that using average throughput of past packets to estimate current bandwidth is feasible and robust.

Figure 3(b) shows the performance of the bandwidth estimation scheme in a static multi-hop scenario 3(a). The plot shows the throughput observed out of the same interface (host 0) to different neighbors can be different based on different levels of contention. The interference flow from host 3 to host 4 is 200 kbps and starts 90 seconds into the simulation. It lies within the interference range of host 2 and hence contends with the flow from host 0 to host 2, but is out of range of host 0 and host 1 and hence does not affect the available bandwidth from 0 to 1. A smoothing factor has been applied to the estimated available bandwidth plots.

Simulation of channel errors due to physical objects such as walls, doors, etc. is not possible in ns-2. However, we have used our bandwidth estimation scheme in indoor and outdoor testbed environments in conjunction with a single-hop bandwidth management and a multi-hop flow control scheme. We briefly summarize these approaches in the Case Studies section IV and refer the interested reader to the details in [2], [5].

III. CHANNEL TIME PROPORTION AND ADMISSION CONTROL

We use the bandwidth estimation mechanism outlined in the previous section for admission control in single- and multi-hop wireless networks. We first introduce the concept of *channel time proportion* (CTP), using a simple example. Assume that the throughput TP over a particular wireless link is 10 MAC frames of a particular size S per second, based on the level of contention and physical error experienced on this link. Assume that a particular flow requires 3 frames over this link between neighbor. It thus needs to be active on the sending host's interface for 30% of unit time, on average. This leaves only 70% of unit time available to other flows out of this interface, which directly affects their admission. We can then extend this logic to bits per second also. If k bits can be transmitted over a wireless link in a second, given a certain level of contention and physical errors, and a user requires a minimum throughput of l bits per second, then in effect the user requires $\frac{l}{k}$ of unit time on the source interface. The CTP requirement of a flow can thus be obtained by simply dividing its bandwidth requirement in bits per second by the estimated available bandwidth. The CTP requirement is a fraction. Admission control divides up 100% of channel time on an interface among the different flows based on their requirements and certain fairness criterion.

IV. CASE STUDIES

We have used our MAC layer bandwidth estimation scheme as an essential component in the construction of: (a) a dynamic bandwidth management scheme for single-hop mobile ad hoc networks [5], and (b) an explicit rate-based flow control scheme for multi-hop mobile ad hoc networks [2]. We briefly describe both of these in this section.

A. Dynamic Bandwidth Management in Single-hop Ad hoc Networks

Our admission control and dynamic bandwidth management scheme provides fairness and rate guarantees in the absence of distributed link layer fair scheduling. The scheme is especially suited to smart-rooms where peer-to-peer multimedia transmissions need to adapt their transmission rates co-operatively. We mapped minimum and maximum bandwidth requirements of a flow to the respective CTP requirements. The center piece of the scheme, a Bandwidth Manager (BM), allots each flow a share of the channel depending on its requirements relative to those of other flows. The BM uses a max-min fair algorithm with minimum CTP guarantees. Admitted flows co-operatively control their transmission rates so they only occupy the channel for the fraction of time allotted to them. As available bandwidth in the network changes and traffic characteristics change, the BM dynamically re-allocates the channel access time to each individual flow. Simulations showed that, at a very low cost and with high probability, every flow in the network will receive at least its minimum requested share of the network bandwidth. We also conducted testbed experiments with our scheme using a real-time audio streaming application running between Linux laptops equipped with standard IEEE 802.11b network cards. The bandwidth estimation procedure was embedded in the device driver of the Lucent IEEE 802.11b network card.

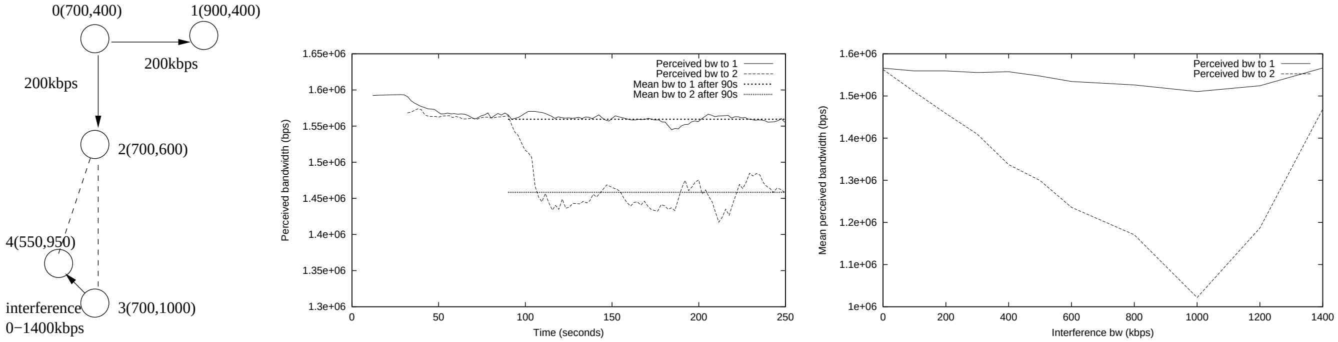
B. EXACT

EXACT is a rate-based *explicit* flow control scheme designed for the multi-hop ad hoc network scenario. It EXACT, each router determines the data rates of the flows that are currently passing the router, based on the measured bandwidth of the outgoing wireless links. The request of each flow in bandwidth is converted into a request for channel time proportion, and the total channel time is allocated to the competing flows using the max-min fairness criterion. Our results show that the explicit rate allocation scheme can effectively utilize the bandwidth resource of the wireless links.

V. LIMITATIONS

The following are the two major limitations of our link layer available bandwidth estimation mechanism.

First, the link layer available bandwidth estimation may lead to inaccurate admission control because it is impossible to gauge



(a) Scenario.

(b) Different throughput to different neighbors on the same interface.

(c) Accuracy of available bandwidth estimation.

Fig. 3. Bandwidth estimation in a static multi-hop wireless network.

beforehand the effect, due to medium contention, that a new 500 kbps data flow will have on the available bandwidth of previously existing flows in the neighborhood. We may admit a 500 kbps flow based on its CTP requirements, but once it begins operation, it *may* increase contention and cause a substantial decrease in available bandwidth of the neighboring flows (other flows sharing the channel). Since the CTP allotted remains constant in the BM scheme, the decrease in available bandwidth causes a decrease in raw throughput available to the neighboring flows, causing a degradation in their quality. However, they can then request more CTP to compensate for the drop in available bandwidth. Hence, the problem of inaccurate admissions in the BM scheme is solved by having dynamic re-negotiation in the presence of changed conditions brought on by inaccurate admission control. In general, in wireless networks, one-time admission control is insufficient. Conditions are dynamically varying, so a provision must be present to allow flows to modify reservations. By default, in the BM scheme, flows re-negotiate their CTP if their available bandwidth varies by 15% since the last re-negotiation.

The second limitation of the link layer available bandwidth estimation scheme occurs only in a multi-hop environment and is illustrated in Figure 3(c). (The simulation scenario for this experiment is shown in Figure 3(a).) As the bit-rate of the flow from 3 to 4 increases, the available bandwidth measurement of the flow from 0 to 2 decreases until it reaches a knee. After this, the available bandwidth appears to increase with an increase in contention! This is obviously an anomaly. When the bit-rate of the flow from 3 to 4 increases, this flow practically captures the channel. RTS transmissions from node 0 to 2 are not acknowledged with a corresponding CTS, because the host 2 can sense the continuous transmission from 3 to 4 within its interference range. After several RTS re-transmissions, node 0 gives up and drops the packet [2]. Although a few packets might still manage to get through, they yield an inaccurate available bandwidth reading, seen after the knee in the curve. This anomaly can be alleviated when mobility is present. With mobility, the location of the nodes are constantly changing, which avoids persistant channel capturing by a flow. This situation can be further improved with a MAC layer distributed fair scheduling scheme (e.g. [3], [4]), which aims to improve medium access fairness between contending nodes. Our result of the EXACT scheme in a multi-hop mobile network scenario shows that, despite this difficulty in bandwidth measrumement, it still achieves our flow control goal in EXACT. Therefore, we consider it a feasible solution in practice.

VI. CONCLUSION

The aim of available bandwidth estimation is to serve as a basis for admission control and rate control of flows sharing the network. We have developed a per-neighbor available bandwidth estimation scheme for IEEE 802.11-based wireless networks, in which we leverage the protocol's mechanisms to deal with contention and physical channel errors, to gauge how much these phenomena affect the available channel bandwidth. We utilized the available bandwidth so obtained, and the concept of channel time proportion (CTP), in (a) a dynamic bandwidth management framework for single-hop mobile ad hoc networks, and (b) an explicit rate-based flow control scheme for multi-hop mobile ad hoc networks.

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[2] This problem does not occur in a single-hop scenario because, in such a case, node 0 will also be able to sense the continuous transmission from 3 to 4 and will not send an RTS to begin with during this time.