Abstract—The use of deadline based channel scheduling in support of real time delivery of application data units (ADU’s) is investigated. Of interest is priority scheduling where a packet with a smaller ratio of delivery deadline over number of hops to destination is given a higher priority. It has been shown that a variant of this scheduling algorithm, based on head-of-the-line priority, is efficient and effective in supporting real time delivery of ADU’s. In this variant, packets with a ratio smaller than or equal to a given threshold are sent to the higher priority queue. We first present a technique to select this threshold dynamically. The effectiveness of our technique is evaluated by simulation. We then study the performance of deadline based channel scheduling for large networks, with multiple autonomous systems. For this case, accurate information on number of hops to destination may not be available. A technique to estimate this distance metric is presented. The effectiveness of our algorithm with this estimated distance metric is evaluated. In addition, we study the performance of a multi-service scenario where only a fraction of the routers deploy deadline based channel scheduling.

I. INTRODUCTION

Many applications running on the Internet require timely delivery of real time data. Examples include delivery of audio and video data, state update in a distributed multi-user game, and transmission of urgent data in an alarm application. Also, some electronic commerce applications require business documents to be delivered on time. To ensure timely delivery, quality of service (QoS) support at the transport network is required. Techniques for QoS support include fair queueing and buffer management at routers [3], [5], integrated services and resource reservation [2], [7], and differentiated services [1]. These strategies are based on the notion of a flow, and QoS support is provided on a per flow basis. However, they may not be appropriate for certain types of real time data transfer. An example is the delivery of a small document (or a short message). In this case, it is difficult to specify a flow with given bandwidth requirements because data will not be presented to the network for a significant period of time.

In [8], a deadline based approach to managing network resources in support of real time document delivery is proposed. A document may correspond to a file (with a range of sizes) or a frame in audio or video transport. Each real time document or application data unit (ADU) is associated with a delivery deadline, which is a time-of-day measure that represents the absolute time at which this ADU should be delivered at the receiver. This application layer deadline is mapped onto a network layer deadline, which is carried by packets and used by routers for channel scheduling purpose. Deadline based channel scheduling was investigated by the authors in [8], and shown to be superior to FCFS (first-come-first-serve) in terms of the percentage of ADU’s that are delivered on time.

The channel scheduling algorithm of interest is based on the ratio T/H, where T is the time left (or delivery deadline — current time) and H is the number of hops to destination [8]. T/H is calculated when a packet arrives at a router; it can be viewed as the urgency of a packet. Specifically, a packet with a smaller T/H means that it is more urgent. In terms of implementation, T can readily be calculated because the delivery deadline is carried with a packet and the current time can be obtained by reading the clock at the router (Note that clock synchronization among senders, receivers and all routers along the path is assumed). The value of H is readily available if a router has complete knowledge of the path to the packet’s destination.

There are two variants of the algorithm: T/H and T/H-L.

- T/H - the packet with the smallest value of T/H is given the highest priority, in other words, the most urgent packet in queue is serviced first.
- T/H-L - this is a head-of-the-line priority queuing system [4]. A threshold parameter L is defined, packets with T/H value less than or equal to L are transmitted before those with T/H larger than L.

In [8], it was shown that both T/H and T/H-L are superior to FCFS in terms of the percentage of ADU’s that are delivered on time. Between these two schemes, T/H has slightly better performance, but its implementation complexity is higher, especially when the backlog is large.

An important issue for the T/H-L algorithm is the selection of the threshold L. The results reported in [8] are preliminary in nature because they are based on static values of L, and the same value of L is used at all channels. In this paper, the issue of how one may select L is addressed in detail. In general, different routers may use different values for L for any of its outgoing channels, based on traffic condition seen by the router. A technique to select L dynamically is presented. The performance of this technique is evaluated by simulation.

We also study the effectiveness of our algorithm for large networks, with multiple autonomous systems (AS’s) [6]. For this case, accurate information on distance to destination for a given packet may not be available. This is due to the fact that the various autonomous systems may be administrated by different network service providers. A technique to estimate the total number of hops for packets that traverse multiple AS’s is presented. The performance of our algorithm when using this technique is also evaluated by simulation. In addition, we consider a multi-service scenario where some routers in a network use deadline based channel scheduling, while others use FCFS. Performance results for this scenario provide valuable insight into QoS support in a heterogeneous network environment.

The remainder of this paper is organized as follows. In section II, we present our technique of selecting L for the T/H-L algorithm. Performance results on the effectiveness of our technique are discussed. Section III considers the case of large networks. Our technique to estimate the number of hops is described, and simulation results on the performance of T/H.
and T/H-L are presented. Section IV is concerned with the performance of deadline based channel scheduling for a multisevice scenario. Finally, section V contains a summary of our findings.

II. THE T/H-L CHANNEL SCHEDULING ALGORITHM

In this section, we present our technique to select the threshold L for the T/H-L channel scheduling algorithm. We consider two types of ADU's: real time and best effort. Each real time ADU has an associated delivery deadline, as mentioned previously. Best effort traffic, on the other hand, has no delivery deadline; they can be considered as having a delivery deadline of infinity.

In our investigation, the delivery deadline of a real time ADU is modeled as follows. Let \( x \) be the end-to-end latency when there is no queuing and no segmentation of ADU into packets. Also let \( x_d \) be the end-to-end propagation delay, \( y \) the size of the ADU, and \( c_j \) the capacity of the \( j \)-th channel along the path. Then \( x \) can be estimated by \( x = x_d + \sum_j y/c_j \). The allowable delay is assumed to be proportional to \( x \). Hence, the delivery deadline for the ADU is given by \( \text{arrival time} + kx \), where \( k \) is a “deadline parameter” \( (k > 1) \). In general, a smaller \( k \) means that the ADU has a tighter deadline.

When an ADU is segmented into packets, each of these packets will carry the same deadline information as that for the ADU.

A. Preliminary Observation

For the T/H-L algorithm, each communication channel can be represented by the single server queue model shown in Fig. 1. This is a head-of-the-line priority system with three queues [4]. A real time packet is sent to the high priority queue if its T/H value is less than or equal to the threshold \( L \); otherwise it is sent to the medium priority queue. Best effort packets are always sent to the low priority queue.

Let \( MQ \) and \( HQ \) be the number of packets that are sent to the medium and high priority queues respectively. Also let \( R = MQ/HQ \) and \( U \) be the channel utilization by real time traffic.

We first note that if \( k \) is large, the advantage of deadline based disciplines such as T/H or T/H-L is minimal unless the channel is heavily utilized by real time traffic. We also note that when \( U \) is small, the choice of \( L \) is not expected to have a significant impact on the percentage of real time ADU’s that are delivered on time. This is due to the fact that the channel is not heavily utilized by real time traffic. There is not much queuing in either the high or medium priority queue, and packets are serviced quickly regardless of the value of \( L \) used.

Based on the above observations, we place emphasis on small values of \( k \) \((k \leq 2.0)\), and moderate to large values of \( U \). For T/H-L, the threshold \( L \) used would affect the ratio \( R \). \( L \) also determines the fraction of real time packets that are considered as being urgent, and are sent to the high priority queue. Note that this fraction should not be very small or very large because for both of these cases, the queueing discipline used for real time packets tends to behave like FCFS, which is inferior to T/H and T/H-L.

Our algorithm to select \( L \) is based on the premise that its best value is affected by \( U \), \( R \), and the urgency of packets seen by the router. For our purpose, the urgency of a packet is defined by its normalized per hop slack which is equal to \( T/(H \times (P_t + P_s)) \), where \( T \) is the time left (or delivery deadline − current time), \( H \) is the number of hops to destination, \( P_t \) is the packet transmission time, and \( P_s \) is the propagation delay to next node. Let \( S \) be the mean normalized per hop slack over all packets routed to the channel. Note that \( U \), \( R \), and \( S \) can all be readily measured.

To characterize the relationship between these parameters, extensive simulation is performed for the single channel model shown in Fig. 1, with real time traffic only. In the simulation experiments, we assume that the channel capacity is 155 Mbit/sec and the maximum packet size is 1500 bytes (the maximum ethernet frame size, which is widely used on the Internet). The interarrival time of ADU’s is exponentially distributed, the size of each ADU is assumed to belong to one of two ranges: [500, 1500], and [1500, 500000], in bytes. The first range reflects the sizes of small ADU’s, i.e., one packet per ADU. The proportion of small ADU’s is kept at 25%. ADU size is assumed to be uniformly distributed within each of these two ranges. The deadline parameter \( k \) is assumed to be 1.0 plus an exponentially distributed random variable.

Each arriving ADU is segmented into packets before being entered to the high or medium priority queues. The percentage of on-time ADU’s is collected after packet re-assembly. Different combinations of ADU arrival rate and deadline parameter \( k \) have been investigated. For each combination, the value of \( L \) that yields the highest percentage of on-time ADU’s is determined. The corresponding values of \( U \), \( R \), and \( S \) are also recorded. Using these results, we found that these three parameters are related as follows:

\[
R = 4.4 - 2.6U - 0.03S \quad (1)
\]

We conclude from this relationship that \( S \) does not have a significant impact on the value of \( R \) (or the best value of \( L \)). The reason is that its impact is small when the deadline is tight (small \( S \)), and that the value of \( L \) used is not important when the deadline is loose (large \( S \)). In any case, (1) will be used as the basis for our algorithm to select \( L \).

B. Algorithm to Select \( L \)

We first note from (1) that \( R \) is a decreasing function of \( U \). This observation implies that when the level of real time traffic increases, \( L \) should be increased also so that more packets are sent to the high priority queue.
We now present our algorithm. First, L is set to an initial value \( L_0 \). Measurement data are obtained for \( R, U \) and \( S \) at regular intervals (of duration \( Q \)). At the end of each interval, let the measured data be \( R_m, U_m \) and \( S_m \) respectively. Using \( U_m, S_m \) and (1), a desirable target for \( R \) (denoted by \( R_t \)) is obtained. If \( R_m > R_t \) then \( L \) is incremented by \( \Delta(L) \) so that more real time packets are sent to the high priority queue, thus reducing \( R \), otherwise \( L \) is decremented by \( \Delta(L) \). \( \Delta(L) \) is a tunable parameter. Our experience shows that its value should be \( O(10^5 P_t) \) where \( P_t \) is the mean packet transmission time. Note that our algorithm is dynamic in the sense that the value of \( L \) is adjusted according to the measured values of \( R, U \) and \( S \).

The measurement interval \( Q \) is also a tunable parameter. In general, a small interval may quickly improve the value of \( L \) but is more costly in terms of overhead. A long measurement interval incurs less overhead, but may be too slow in reacting to changing conditions.

Finally, any value can be used for \( L_0 \), the initial value of \( L \), because the algorithm is adaptive, and the value of \( L \) should improve as more measurement data become available. However, \( L \) would reach its best value faster if a good starting value is used. Our experience shows that a reasonable choice of \( L_0 \) is \( O(100^5 P_t) \).

C. Performance Evaluation

In this subsection, a performance model is developed to evaluate the effectiveness of our technique for selecting \( L \). The performance measure of interest is the percentage of real time ADU’s that are delivered on time.

At the sender, segmentation of an ADU into packets is performed before the packets are admitted to the source node. The maximum packet size at the network layer is 1500 bytes. These packets are routed through the network until they reach their destination node. They are then delivered to the receiver where packet re-assembly is performed. We assume that fixed shortest-path routing is used, no packets are lost due to error or buffer overflow, and that packet transmissions are not delayed by any flow or congestion control mechanism. We further assume that each router has complete knowledge of the path (and hence the hop count) to every destination. For simplicity, the processing time at the sender to prepare the packets for transmission and the processing time to receive a packet are not included in our model.

The network topology used in our simulation experiments is depicted in Fig. 2. The capacity of each channel is assumed to be 155Mbit/sec. ADU’s may be generated from any point in the network. The interarrival time of ADU’s is assumed to be exponentially distributed, and the aggregate arrival rate is \( \lambda \) (in number of ADU’s per second). All ADU’s are of type real time. For each arriving ADU, the source node and destination node are selected at random. The deadline parameter \( k \) is assumed to have a mean of 2.0.

At the network layer, all system and router clocks are assumed to be perfectly synchronized; it follows that deadline information is accurate at all the routers.

As to our algorithm for selecting \( L \), the following parameter values are used: the measurement interval \( Q \) is 0.5 second and \( \Delta(L) \) is 0.002 second. Two values of \( L_0 \) are simulated; they are 0.03 and 0.04 seconds. To evaluate the effectiveness of T/H-L, we compare its performance with T/H and FCFS. In Fig. 3, the percentages of ADU’s that are delivered on time is plotted against the arrival rate \( \lambda \) for these three algorithms. We make the following observations:

- The results for T/H-L are close to those for T/H. The difference between T/H-L and T/H ranges from 0.9% when \( \lambda = 400 \) to 6.1% when \( \lambda = 1200 \).
- For T/H-L, the choice of \( L_0 \) has a small impact on the performance. The results for \( L_0 = 0.03 \) and \( L_0 = 0.04 \) are very close to each other.
- Both T/H and T/H-L perform better than FCFS by a noticeable margin, especially when ADU arrival rate is high. The difference between FCFS and T/H-L ranges from 2.8% when \( \lambda = 400 \) to 17% when \( \lambda = 1200 \).

We conclude from the above observations that our technique for selecting \( L \) yields good results.

III. LARGE NETWORKS

In this section we study the performance of the T/H-L algorithm in large networks, with multiple autonomous systems (AS’s). As mentioned in the introduction, accurate information on hop count for this case may not be available. A mechanism is therefore needed to estimate \( H \) in order to utilize the T/H-L algorithm.

![Fig. 2. Network model](image)

![Fig. 3. Performance of technique to select L](image)
A. Estimation of Hop Count

In general, a packet initiated at a source AS may traverse a number of forwarding AS’s before reaching its destination AS. This is illustrated in Fig. 4.

Our technique for estimating H is based on the assumption that each router has complete knowledge of the hop count to every destination within the same AS. It also has the following information regarding other AS’s in the entire network:

- AS level connectivity information, together with the corresponding ingress and egress routers between connected AS’s.
- AS level routing information, i.e., a router knows which transit AS’s and destination AS a packet must traverse before it reaches its destination node.
- The average number of hops in each AS, for packets to be forwarded, and for packets with destination in that AS.

With the above assumption, a router can estimate the number of hops to a destination as follows. It first determines the destination AS of the packet. If the destination is in the same AS, then accurate information on the number of hops is available. On the other hand, if the destination is in a different AS, the router checks the AS level routing information to identify all forwarding AS’s along the way. Let $I$ be the set of forwarding AS’s. H can be estimated by:

$$
H' = H_s + \sum_{i \in I} (1 + H_i) + (1 + H_d) \quad (2)
$$

where $H_s$ is the number of hops to the egress router that leads to the first forwarding AS, $H_i$ is the average hop count in forwarding AS $i$, for packets to be forwarded, and $H_d$ is the average hop count in the destination AS. We assume that two neighboring AS’s are one hop away from each other.

B. Performance Results

We have evaluated the performance of T/H and T/H-L when an estimated hop count, as given in (2), is used. We also compare their performance with FCFS under similar conditions.

Fig. 5 depicts the network model used in our simulation. All links have a capacity of 155 Mbit/sec, except the highlighted links, which have a capacity of 622 Mbit/sec. We assume that 50% of the ADU’s are of type real time. The deadline parameter $k$ is based on the estimated H, and follows the same distribution as described in Section II, with a mean of 2.0. All the other assumptions are the same as those described in Section II.

Simulation results on the percentage of ADU’s that are delivered on time are presented in Table I. These results are for two values of $\lambda$: 800 and 1200, corresponding to moderate and heavy load respectively. For T/H-L algorithm, $L_0$, the initial value of $L$, is 0.04.

We observe that for the example network under consideration, the performance of T/H and T/H-L is not significantly affected when an estimated hop count is used. We also observe that the performance of T/H-L is close to that of T/H, and is better than that for FCFS by a noticeable margin. We thus conclude that our T/H-L algorithm is effective for the case of large networks.

IV. Multi-service Scenario

Our discussion so far is based on network configurations where deadline based scheduling is used in every channel in the network. Another configuration of interest is a multi-service scenario where some routers in an AS employ deadline based scheduling while the others use FCFS. In this section, we evaluate the performance of such a multi-service scenario.

The 13 node network depicted in Fig. 2 is used in our simulation experiments. Let $m$ be the number of routers that deploy deadline based scheduling (T/H or T/H-L). $m = 0$ and $m = 13$ correspond to the use of FCFS and deadline based scheduling in every router respectively. In our experiments, the model parameters are identical to those used in Section II, when we evaluated our algorithm for selecting $L$. The initial value for $L$, or $L_0$, is 0.04. In Fig. 6, the percentage of on-time ADU’s as a function of $m$ is presented for $\lambda = 800$ and $\lambda = 1200$. For
deadline based scheduling, the results are shown for the cases where T/H or T/H-L is used. Our results show that the performance improves as the number of routers that deploy deadline based scheduling increases. This further supports the merit of deadline based scheduling because noticeable performance improvement can be realized even when it is used in a relatively small number of routers.

In addition to the results presented in Fig. 6, we observe that the performance gains are more significant if deadline based scheduling is used in more heavily utilized channels.

V. Conclusion

Deadline based channel scheduling is a relatively new approach to supporting real time data transfer in packet-switched networks. In this paper, we investigated the T/H-L algorithm with respect to how the threshold $L$ should be selected, its effectiveness when deployed in large networks, and its effectiveness in a multi-service scenario. In all cases, it is found that T/H-L is superior to FCFS in terms of the percentage of ADU’s that are delivered on time. It is also found that its performance is slightly worse than T/H. Taking into consideration that the implementation complexity of T/H is higher, T/H-L is the preferred scheme.

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Fig. 6. Performance results for multi-service scenario

References