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Multiclass Information Based Deflection Strategies for the Manhattan Street Network

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Abstract

Delay sensitive and loss sensitive classes of traffic are introduced simutaneously on the Manhattan Street Network (MSN) in conjuction with alternate routing strategies. Results are presented from simulating an 8×8 MSN with input buffers. It is shown that static priority assignment with age deflection will improve both classes delay performance. The choice of routing strategy also depends on the desired quality of service (QOS) requirement.

1. Introduction

One of the aspects of the rapid evolution in the field of telecommunication is the use of fiber optics. The use of fiber optics causes the processing speed at the network switching nodes, rather than the channel transmission speed, to become a bottleneck for network performance. This is because the nodes still use electronic devices for processing information.

One way to increase the processing speed so that it can match that of optics is using parallelism and hardware protocol processors. The Manhattan street network (MSN) proposed by N. F. Maxemchuk [1, 2], originally for use as a metropolitan area network backbone, is one of such kind of network.

The MSN is a directed two-dimensional mesh with toroidal boundaries (Figure 1). It uses packet switching without storing packets at nodes; hence, the processing at nodes becomes fast and can match the speed of optical links. In the MSN, each node operates in a discrete, time slotted fashion and has two input links two output links and a local input buffer. At each time slot a node receives at most two packets from its neighbors. When no transiting packet or only one transiting packet enters a node or at least one of two incoming packets is destinated to the node in a time slot, a locally generated packet inside the input buffer can enter the node.

Several routing methods have been studied for the MSN [3, 4, 5, 6]. However, those results are based on the assumption of a single class of traffic on the network. But the future broadband network trend is for networks to carry a mixture of voice, data, video and graphics informations. Several papers [8, 9] have introduced the study of multiple classes of traffic on some networks in order to find the improvement in performance necessary to meet the quality of service (QOS) constraints for each class of traffic. For example, real-time voice requires rapid transfer through a network while the loss of small amounts of voice information is tolerable. On the other hand in data applications real-time transfer is not of primary importance, but strict error control and high throughput are more important.

In this paper, a delay-sensitive class and a loss-sensitive class of traffic are introduced. Voice and video are treated as delay-sensitive while data is loss-sensitive. Although there are some services that require both rapid transfer and error-free transmission [10], this can be achieved by introducing a third class traffic on the network. The main purpose of this paper is to study the performance trade off between these two classes of traffic under various routing strategies on the MSN. For more than two classes of traffic on the network, the results can be extended.

The paper is organized as follows. In section 2, the models for the simulated network and the traffic are proposed. In section 3, different routing strategies which will be applied in the simulation are explained. The performance results are presented in section 4. Finally, in section 5, a brief conclusion is given.

2. Description of Simulated Network

An 8 × 8 Manhattan Street Network with local input buffers at each node is used for the simulation model. Each input buffer can hold up to 70 packets. The network is packet switched and time slotted. That is each switching and transmission process take place on a time slotted basis and all arrivals and departures occur at slot boundaries.

In the model, several assumptions are made concerning the network. First, the communication channels are assumed to be ideal. This means that no packet will be lost or corrupted during transmission. At most one packet per time slot can be transmitted on each link. Secondly, nodes operate synchronously. A node will send its stored packets to its neighboring output nodes and receive packets from its input neighbors. Finally, the local traffic source can generate up to one packet for each class of traffic, according to the arrival rate of each class, in a time slot. This means that the arrival process is analogous to a Poisson arrival process in a discrete distribution manner, i.e. the geometric distribution [11]. The arrival processes of two classes of traffic are assumed to be uncorrelated. The destination of each newly generated packet is assumed to be uniformly distributed in the network and independent between successive packets.

The initial laxity for a newly arrived packet in the Maximum Laxity Threshold strategy, which will be explained later, is generated as follow. Once the destination of the new packet is known, the shortest distance between its destination node and its arriving node can be calculated. Then the initial laxity will be set to be 150 percent of that shortest distance. The additional 50 percent is included because that not every packets can reach its destination by its shortest path and an allowance for delay is expected.

Simulation results are produced by fixing the arrival rate for one class and varying the arrival rate of other class. The model is simulated for 100,000 slots while discarding the data for the first 1,000 slots as transient.

3. Routing Strategy

In [6], the routing events in a node are classified into seven possible events. From table 1, when packets in a node have the same preferred output links, which is event 3, contention occurs. Maxemchuk first proposed deflection routing as a solution for this case [1, 2]. The routing strategies used in this paper are also based on deflection but with different decision rules.

There are three different kinds of routing strategies used in our study. They are Static Priority Deflection, Age Deflection, and Maximum Laxity Threshold. They will be briefly described below:

Static Priority Deflection (SPD): When two different classes of packets in a node prefer the same output link, the delay-sensitive packet will always be sent to its preferred output link and the loss-sensitive packet will be deflected to the other output link. The strategy always gives priority to the delay-sensitive packets. If the conflict occurs when two packets of the same class are inside the node, a random decision will be used to decide which packet will be sent to its preferred output link.

Age Deflection: This strategy uses the same algorithm as that of SPD except it uses age based decisions instead of random decisions when the same class of packets in a node have the same preferred output link. In other words, when a conflict occurs for the case of two packets of the same class in a node, the older packet (in the sense of total hop count) will be sent to its preferred output link while the one with the lower hop number history will be deflected to the other output link.

Maximum Laxity Threshold (MLT): Laxity is defined as the number of time slots (or hops) remaining before a packet's delivery deadline expires. When there are two different classes of packets in a node having the same preferred output link, the laxity of the delay-sensitive class packet will be checked first. If the laxity is larger than a specific threshold value, the priority will be given to the the loss-sensitive packet. Otherwise, the delay-sensitive packets will have priority. If contention occurs with two loss-sensitive packets, then a decision based on packet age will be used. On the other hand, if contention occurs with two delay-sensitive packets, the one with smaller laxity will be sent to its preferred output link and the other one will be deflected. If both of them have the same laxity, random decisions will be applied.

4. Results and Discussion:

In the simulated results, class 1 will represent the delay-sensitive class and class 2 will represent the loss-sensitive class. Since the performance results depend on the arrival rates of both classes of packets, as well as the routing strategy the node uses, one can write:

$$\begin{aligned} Performance &= Function(\lambda_1, \lambda_2, routing\ \ strategy) \\ where\ \ \lambda_1 &: arrival\ \ rate\ \ of\ \ class\ 1\ \ packet \\ \lambda_2 &: arrival\ \ rate\ \ of\ \ class\ 2\ \ packet \end{aligned}$$

In the following, the performance will be given and discussed when only one of the function variables are varied while the others are fixed.

4.1 Network Delay:

4.1.1 Holding the routing strategy fixed:

SPD Deflection: As mentioned before, event 3 is the only event that will cause contention to occur. In event 3, one of the packets will be deflected and the shortest distance to its destination will increase by at most 4 hops. The deflection in event 3 will increase the mean hop delay.

Contention may occur between two packets of the same class or different classes. For class 2 traffic, both cases will increase its mean hop delay. When two class 2 packets prefer the same output link, one will be deflected by random decision. If the contention is between a class 1 packet and a class 2 packet, the packet of the second class will lose its priority to be sent to its preferred output link. For class 1 traffic, contention only occurs when two class 1 packets prefer the same output link and one of them is deflected, thus increasing mean hop delay. The more often that a deflection occurs for a packet of a specific class, the greater the increase in the mean hop delay of that specific class of packets. A deflection involving two different classes of packets will only increase the mean hop delay of class 2 packets. Two cases will be discussed below.

Case I: Arrival rate of class 1 packets is fixed and the arrival rate of class 2 packets is varied

As more class 2 traffic arrives into the network, it will decrease the probability of deflection occurring for two class 1 packets meeting in a node. The mean hop delay of class 1 traffic is thus decreased. This can be seen in table 2.b and 2.c when class 1 packets have a medium and a heavy arrival rate. However, the mean hop delay of class 1 traffic under light load approaches a constant. The mean number of hops for a single class of traffic under uniform loading and shortest path routing for an 8×8 MSN is 5.08 which is close to the result in table 2.a. This means that when $\lambda_1 = 0.01$ the probability of two class 1 packets in a same node preferring the same output link is almost zero. Increasing class 2 traffic will not have much influence on the probability of this event and the mean hop delay of class 1 traffic will approach the constant of 5.08.

When the arrival rate of class 2 traffic increases, the mean hop delay of class 2 traffic will increase due to the increase in the probability of deflection occurring. However , an exception can be seen in table 2.c when λ_2 varies from 0.12 to 0.15 under the load of $\lambda_1 = 0.1$. This is because the throughput saturates when the total arrival rate of both classes of traffic is larger than 0.22 for an 8×8 MSN. When saturation occurs, the throughput of class 1 packets will decrease from 0.10 to 0.89 while the arrival rate of class 2 packets increases from 1.2 to 1.5. The decrease of the throughput of class 1 traffic will decrease the probability of deflection for class 2 packets meeting class 1 packets in the same node. Although the increase of class 2 traffic will increase the probability of deflection for two packets of the second class, this effect is not stronger than the previous effect of decreasing the probability of being deflected by class 1 packets. For this reason the mean hop delay of class 2 packets decreases.

Case II: Arrival rate of class 2 packets is fixed and the arrival rate of class 1 packets is varied

From table 3 the mean hop delay of both classes of traffic is increased when more class 1 packets are present in the network.

Age Deflection: The relation between the mean delay and arrival rates is the same as the SPD case.

MLT Deflection: Intuitively, this routing method lets a class 2 packet have the chance to have the priority to be sent to its preferred output link when it meets a class 1 packet and conflicts occur. This chance for class 2 packets to be given priority depends on a preset threshold value for the laxity of class 1 packets.

Consider two extreme cases. Firstly, when the threshold value is infinite, the laxity will always be smaller than the threshold value. Class 2 packets will not have the chance to get the preferred output link priority when contending with class 1 packets and MLT deflection acts like Age deflection. The second case occurs when the threshold value is zero. Then as long as the laxity is positive class 2 packets will have priority in a conflict situation. Once the laxity of class 1 packets becomes negative then the class 1 packets will have priority. The effect of this is that many class 1 packets will miss their deadlines if the initial laxity is considered to be the deadline of the packet. In this paper only one threshold value, which is 6 hops, is assigned and simulated. Table 4 gives the percentage of class 1 packets which reach their destination before their laxity becomes zero under different loads. For different threshold values, the trend of the distribution curve of the hop delay for MLT can be predicted when compared with the hop delay distribution curves from Age and SPD deflection cases. For example, if the threshold value of hop number is increased, the curves of MLT in figures 2 and 3 will move in appearance toward the Age curve. If the threshold value is set to be smaller than 6, the tails of the MLT curves in these two figures will move away in appearance from the tails of the Age curves. Consider now two cases:

Case I: Arrival rate of class 1 packets is fixed and the arrival rate of class 2 packets is varied

As more class 2 traffic enters the network, more deflection events involving class 1 packets meeting class 2 packets in a same node occur which increases the probability of deflection for class 1 packets. At the same time, the probability of a deflection event for two class 1 packets in the same node will decrease. The former effect has much more influence on the mean hop delay of class 1 packets than the latter one does, increasing the mean hop delay of class 1 packets when increasing the arrival rate of class 2 packets. Table 2.a and 2.b illustrate this point.

The probability of a deflection event occurring for two class 2 packets will increase as more class 2 packets arrive. Thus, the mean hop delay of class 2 packets will increase when the arrival rate of class 2 packets increases.

In table 2.c the above result is not valid when $\lambda_1 = 0.1$ and λ_2 varies from 0.13 to 0.15. The reason for the decrease of mean hop delay for class 2 packets is the same as that in the SPD case. For class 1 packets the decrease of throughput of class 1 packets will cause the decrease of the occurrence of a deflection event for two class 1 packets. This will decrease the mean hop delay of class 1 packets. The presence of more class 2 packets in the network will increase the probability of class 1 packets losing priority. However, the effect of throughput decreasing is stronger than that of increasing the arrival rate of class 2 packets. Thus in table 2.c η_1 is decreasing while

λ_2 is still increasing.

Case II: Arrival rate of class 2 packets is fixed and the arrival rate of class 1 packets is varied

From table 3 the mean hop delay of both classes traffic is increased when more class 1 packets are in the network.

4.1.2 Holding traffic load fixed

Table 2 & 3 also shows the mean delay of two classes of packets when different contention solution methods are used. From figure 2 to 7, the tail of the delay probability density function for class 1 & 2 packets under age deflection decreases much more steeply than that of SPD does and this decreases the mean delay. This is because under age deflection the older packets are forced to go to their preferred output link when conflicts occur and will reach their destination sooner than under the SPD case which uses a random decision when two packets of the same class are in the same node. Thus the Age strategy has a better performance in this regard over SPD.

In the MLT case, since there is a trade off of priority assignment between two classes of packets, it is not surprising to have a better result for class 2 and a worse result for class 1 compared with the Age and the SPD cases.

4.2 Input buffer delay

4.2.1 Holding the routing strategy fixed

The larger the mean delay experienced by packets in the network, the higher the probability of a node having two packets inside it. This will increase the probability of blocking experienced by the packets in the head of local input buffers that are trying to get on the network. This will cause the input buffer delay to become larger. Finally, the blocking probability seen by packets arriving to the input buffers will be increased.

From the previous results, we know that when the traffic load becomes heavier, at least one of the classes of packets will stay longer on the network, increasing the input buffer mean delay. Simulation results shown on table 5 & 6 illustrate this point.

A model of a single queue with service rate related to arrival rate can be used to show the relation between the input buffer mean hop delay and packet arrival rate. Figure 8 shows a model of a single queue with one server. The packet at the head of the input buffer can only be sent to the buffer in a node when at least one of the node buffers is empty. Thus the service rate depends on the probability of having an empty node buffer. The higher the probability of having an empty node buffer, the faster the service rate. In addition, the probability of an empty buffer is related to the network mean hop delay. A larger network hop delay means packets will stay much longer on the network and occupy node buffers more frequently. This will cause the service rate to become slower. From the previous discussion, the network mean hop delay is a function of λ_1 and λ_2 , $\eta = f(\lambda_1, \lambda_2)$. So the service rate, μ, will be related to $f(\lambda_1, \lambda_2)$. For a given pair of arrival rates of both classes, the queueing system will act like an Geom/Geom/1/N queueing system.

When one of the arrival rates increases, the service rate will be decreased as mentioned above. The longer service times lead to more congestion, i.e. longer hop delay.

The dramatic increase in the input hop delay in table 5.c & 6.c can be explained as follows:

From Little's law we know:

$$\overline{n} = \lambda \overline{\tau}$$

In our case $\overline{n}$ will be the mean number of packets in the input buffer and $\overline{\tau}$ represents the input buffer mean hop delay.

The smallest input buffer mean hop delay of one of the two classes of packets will be achieved if the arrival rate of the other class packets is assumed to be zero. For an Geom/Geom/1/N queue, using Little's law, the mean hop delay will be

$$\overline{\tau} = \frac{\overline{n}}{throughput}$$

When one of the arrival rates increases, throughput will eventually reach the network saturation throughput, which is about 0.22 [6]. However, the mean number of packets, $\overline{n}$, in the buffer still increases, making the delay, $\overline{\tau}$, suddenly become large. It can be seen that the change always occurs when the total throughput ,which will be discussed later, rises above the saturation value of 0.22 for an 8×8 MSN.

A final point is that although the 0.22 throughput is a low value, the operating speed of the MSN will be several hundred Mbps due to the use of optical fibers and this will allow the throughput to be several Mbps. This is high compared with a T1 channel.

4.2.2 Holding the traffic load fixed

The performance of the input buffer mean hop delay will be better when using the Age routing strategy compared to that under SPD routing. This is because the mean network hop delay of the two classes of packets are lower when the Age strategy is applied. From the previous queueing model, the server will have a faster service rate and this will make the delay smaller.

From table 5 & 6, the results show that the MLT dynamic priority assignment routing strategy has the best performance result for the input buffer delay, though the difference is small at light to medium loads.

Although in our study the MLT shows the best performance, this does not mean that it will always have this superiority. The performance of MLT strongly depends on the preset threshold value for the maximum laxity for the network and definition of the initial laxity in the network. This will influence the result of network mean hop delay, and the input buffer delay (as explained by using the previous queueing model).

4.3 Input Buffer Blocking Probability

Since the input buffer length is finite, theoretically there will always be a blocking probability when there is any traffic load. However, the value will be very small under very light load or for a very long input buffer size and this causes simulation difficulty due to the difficulty of simulating rare events. Table 7 thus only shows the simulated results under heavy load.

By comparing the table with the input buffer delay, it can be shown that the larger the delay, the higher the blocking probability that would be expected. The previous input buffer delay result shows that the smallest mean delay simulated occurs under the MLT routing method with a preset laxity threshold value of 6 hops. Table 7 illustrate the point that the MLT strategy gives the smallest blocking probability.

4.4 Throughput

The throughput under different traffic loads is listed in table 8 & 9. As we know from queueing theory:

$$\begin{array}{rrl} \gamma & = & \lambda(1-P_b) \\ where & \gamma : & throughput \\ & \lambda : & arrival\ rate \\ & P_b : & blocking\ probability \end{array}$$

P_b is very small under light load; thus, the throughput of each class of packet will be close to its arrival rate. The simulated results shown in table 8 & 9 demonstrates this. The tiny difference is due to the discarding of the transient period of the simulation.

As mentioned before, the saturated value of the throughput for an 8 × 8 MSN is around 0.22. This can be easily verified if one just takes the summation of throughput of both classes under heavy load.

5. Conclusion

Performance results for the MSN with two classes of traffic under different routing strategies are shown in this paper. The performance results of the network under the strategy of age deflection is better than those when static priority deflection routing method is used.

Although we call class 2 the loss-sensitive class, this does not mean that the class 2 packets can endure very long hop delay. If the network uses age deflection routing, the mean hop delay of the loss-sensitive class packets will be larger than that when the MLT method is applied. So, the choice between the Age strategy and the MLT strategy depends on what QOS constraints are imposed on the network.

It should be noted that the performance of MLT is sensitive to the preset threshold value. Thus, choosing a threshold value will depend on the QOS requirement imposed on the network.

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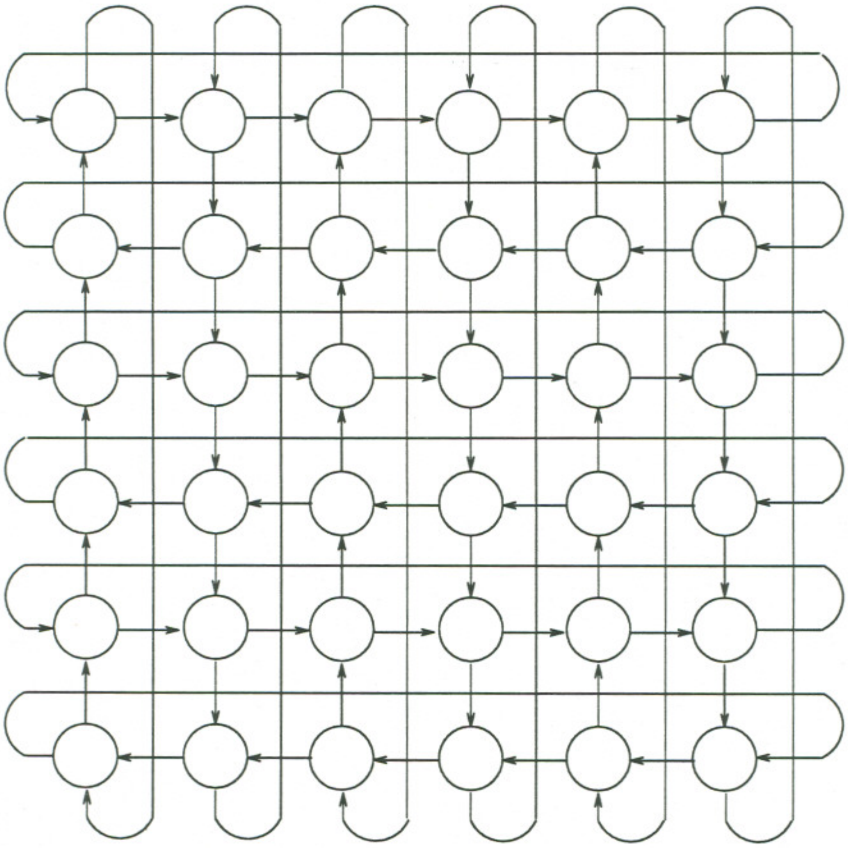

Figure 1: A 6 × 6 Network Structure of Manhattan Street Network

Table 1: Routing Events

Event 0	No packets
Event 1	1 packet, 1 preferred output link
Event 2	1 packet, 2 equally good output links
Event 3	2 packets, 1 preferred output link each, same link
Event 4	2 packets, 1 preferred output link each, different links
Event 5	2 packets, 1 preferred link for one packet, 2 links for other
Event 6	2 packets, 2 equally good output links for each packet

Table 2.a: Mean Hop Delay of Class 1 & 2 Packets

λ_1=0.01

	SPD		Age		MLT	
λ_2	η_1	η_2	η_1	η_2	η_1	η_2
0.05	5.10	5.67	5.10	5.68	5.25	5.64
0.06	5.11	5.80	5.09	5.78	5.32	5.74
0.07	5.09	5.91	5.09	5.90	5.33	5.86
0.08	5.09	6.04	5.10	6.01	5.37	5.98
0.09	5.10	6.17	5.10	6.13	5.40	6.10
0.10	5.10	6.31	5.08	6.27	5.42	6.22
0.11	5.09	6.48	5.10	6.40	5.46	6.37
0.12	5.11	6.64	5.10	6.56	5.48	6.52
0.13	5.09	6.83	5.08	6.70	5.53	6.67
0.14	5.09	7.00	5.11	6.89	5.58	6.84
0.15	5.10	7.22	5.10	7.07	5.61	7.02

Table 2.b: Mean Hop Delay of Class 1 & 2 Packets

λ_1=0.05

	SPD		Age		MLT	
λ_2	η_1	η_2	η_1	η_2	η_1	η_2
0.05	5.46	6.68	5.46	6.65	5.64	6.41
0.06	5.45	6.83	5.45	6.79	5.66	6.56
0.07	5.45	7.00	5.45	6.95	5.71	6.71
0.08	5.45	7.18	5.43	7.12	5.74	6.87
0.09	5.45	7.35	5.43	7.28	5.77	7.04
0.10	5.44	7.58	5.43	7.49	5.80	7.22
0.11	5.43	7.81	5.42	7.68	5.85	7.42
0.12	5.43	8.07	5.42	7.92	5.88	7.63
0.13	5.43	8.36	5.41	8.16	5.92	7.88
0.14	5.42	8.70	5.42	8.44	5.96	8.13
0.15	5.41	9.03	5.41	8.71	6.00	8.42

Table 2.c: Mean Hop Delay of Class 1 & 2 Packets

λ_1=0.10

	SPD		Age		MLT	
λ_2	η_1	η_2	η_1	η_2	η_1	η_2
0.05	6.02	8.55	5.98	8.44	6.18	7.85
0.06	6.01	8.81	5.98	8.69	6.23	8.06
0.07	6.00	9.11	5.97	8.97	6.25	8.31
0.08	5.98	9.44	5.95	9.25	6.30	8.57
0.09	5.97	9.83	5.94	9.57	6.34	8.87
0.10	5.96	10.24	5.93	9.95	6.39	9.19
0.11	5.95	10.73	5.92	10.34	6.43	9.55
0.12	5.93	11.31	5.90	10.79	6.46	9.98
0.13	5.89	11.31	5.88	11.03	6.50	10.33
0.14	5.84	11.18	5.84	10.91	6.47	10.27
0.15	5.80	11.07	5.80	10.80	6.43	10.19

Table 3.a: Mean Hop Delay of Class 1 & 2 Packets

λ_2=0.01

	SPD		Age		MLT	
λ_1	η_1	η_2	η_1	η_2	η_1	η_2
0.05	5.48	6.12	5.47	6.11	5.50	5.91
0.06	5.58	6.40	5.56	6.38	5.59	6.12
0.07	5.69	6.68	5.67	6.62	5.70	6.31
0.08	5.80	6.99	5.79	6.94	5.82	6.55
0.09	5.93	7.33	5.90	7.27	5.92	6.79
0.10	6.06	7.68	6.02	7.58	6.04	7.08
0.11	6.20	8.10	6.14	8.01	6.17	7.39
0.12	6.34	8.61	6.28	8.45	6.30	7.73
0.13	6.51	9.10	6.42	8.91	6.43	8.05
0.14	6.67	9.69	6.58	9.50	6.59	8.51
0.15	6.87	10.41	6.74	10.09	6.74	8.95

Table 3.b: Mean Hop Delay of Class 1 & 2 Packets

λ_2=0.05

	SPD		Age		MLT	
λ_1	η_1	η_2	η_1	η_2	η_1	η_2
0.05	5.43	6.66	5.45	6.63	5.63	6.42
0.06	5.57	6.97	5.54	6.94	5.74	6.65
0.07	5.66	7.30	5.65	7.26	5.85	6.91
0.08	5.78	7.67	5.76	7.63	5.95	7.19
0.09	5.89	8.07	5.86	8.01	6.07	7.50
0.10	6.02	8.58	5.99	8.45	6.19	7.84
0.11	6.14	9.07	6.10	8.94	6.31	8.21
0.12	6.29	9.68	6.22	9.47	6.45	8.65
0.13	6.43	10.37	6.36	10.08	6.59	9.12
0.14	6.60	11.21	6.51	10.85	6.75	9.65
0.15	6.76	12.09	6.65	11.63	6.91	10.27

Table 3.c: Mean Hop Delay of Class 1 & 2 Packets

λ_2=0.10

	SPD		Age		MLT	
λ_1	η_1	η_2	η_1	η_2	η_1	η_2
0.05	5.44	7.58	5.43	7.50	5.80	7.23
0.06	5.54	8.00	5.52	7.87	5.91	7.54
0.07	5.63	8.45	5.62	8.28	6.02	7.88
0.08	5.74	8.99	5.73	8.78	6.14	8.27
0.09	5.85	9.56	5.82	9.30	6.26	8.70
0.10	5.96	10.24	5.93	9.95	6.38	9.19
0.11	6.08	11.05	6.04	10.60	6.52	9.76
0.12	6.20	11.99	6.15	11.49	6.65	10.38
0.13	6.29	12.35	6.25	12.10	6.79	11.05
0.14	6.36	12.56	6.32	12.28	6.83	11.22
0.15	6.42	12.77	6.37	12.47	6.89	11.37

	λ_1		
λ_2	0.01	0.05	0.10
0.05	95.4%	87.6%	76.9%
0.06	94.6%	87.2%	76.2%
0.07	94.2%	86.4%	75.7%
0.08	93.4%	85.6%	75.0%
0.09	92.9%	85.2%	74.3%
0.10	92.5%	84.8%	73.6%
0.11	91.7%	83.9%	72.9%
0.12	91.2%	83.2%	72.2%
0.13	90.6%	82.6%	71.7%
0.14	89.8%	81.8%	72.3%
0.15	89.1%	81.2%	73.0%

Table 4.a: Percentage of class 1 packets arriving at destinations before their initial laxities expire

	λ_2		
λ_1	0.01	0.05	0.10
0.05	90.0%	87.6%	84.6%
0.06	88.0%	85.6%	82.5%
0.07	85.9%	83.4%	80.3%
0.08	83.7%	81.2%	78.1%
0.09	81.6%	79.2%	75.9%
0.10	79.4%	76.9%	73.7%
0.11	76.9%	74.6%	71.2%
0.12	74.6%	72.2%	68.9%
0.13	72.2%	69.6%	66.5%
0.14	69.6%	67.1%	65.8%
0.15	67.0%	64.6%	65.0%

Table 4.b: Percentage of class 1 packets arriving at destinations before their initial laxities expire

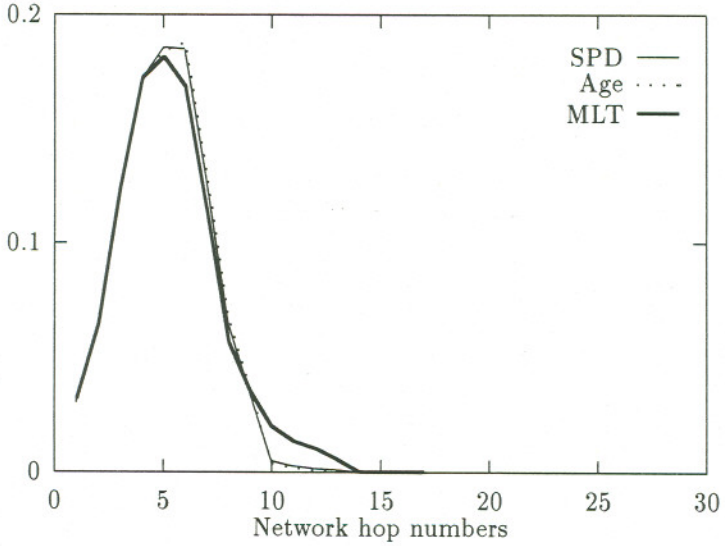

Figure 2: Network Delay distribution for class 1 packets when $\lambda_1 = 0.01$ & $\lambda_2 = 0.05$

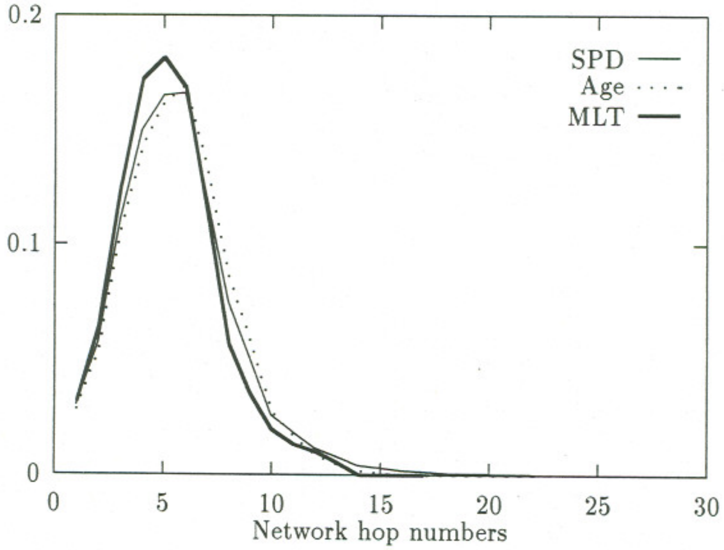

Figure 3: Network Delay distribution for class 2 packets when $\lambda_1 = 0.01$ & $\lambda_2 = 0.05$

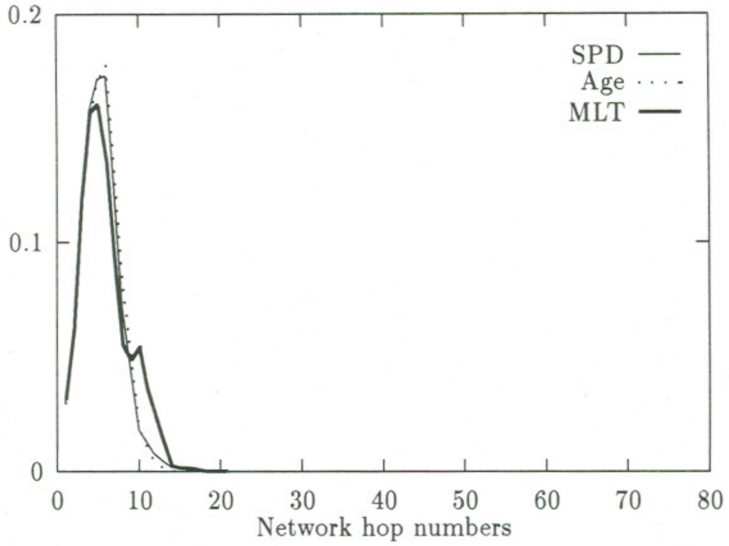

Figure 4: Network Delay distribution for class 1 packets when $\lambda_1 = 0.05$ & $\lambda_2 = 0.10$

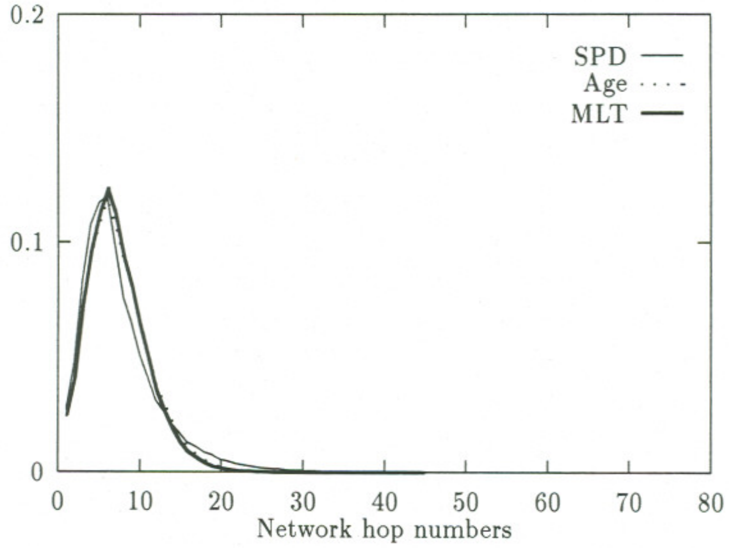

Figure 5: Network Delay distribution for class 2 packets when $\lambda_1 = 0.05$ & $\lambda_2 = 0.10$

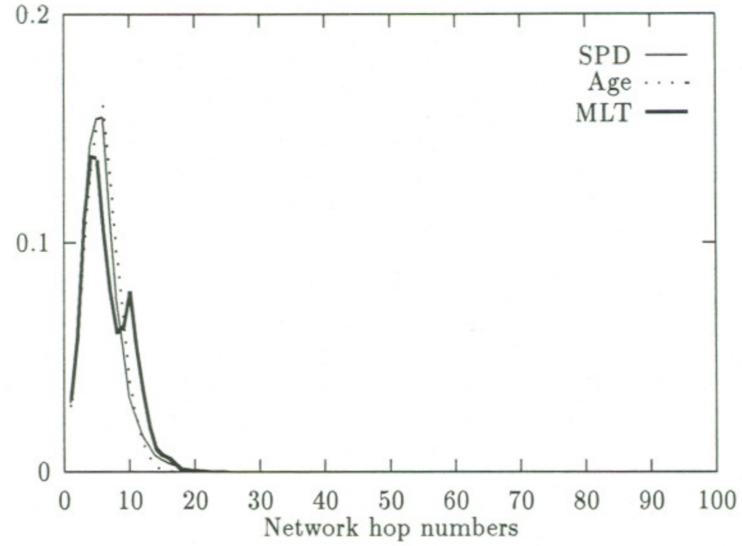

Figure 6: Network Delay distribution for class 1 packets when $\lambda_1 = 0.10$ & $\lambda_2 = 0.11$

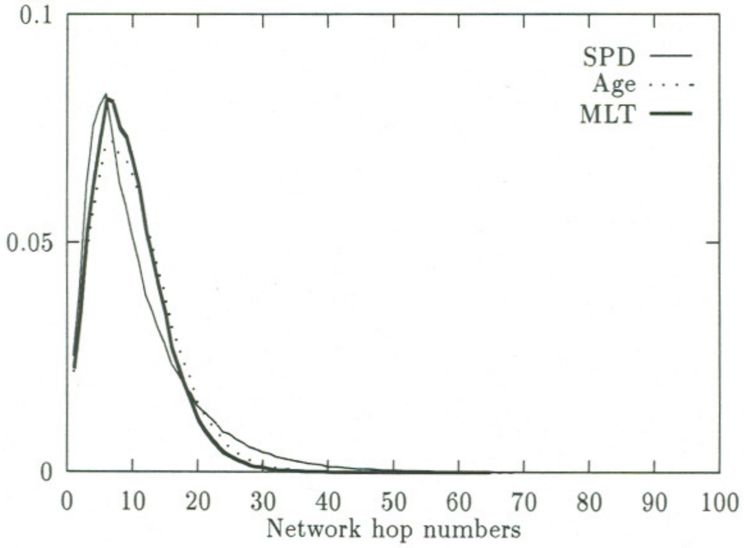

Figure 7: Network Delay distribution for class 2 packets when $\lambda_1 = 0.10$ & $\lambda_2 = 0.11$

Table 5.a: Input Buffer Mean Hop Delay of Class 1 & 2 Packets

λ_1=0.01

	SPD		Age		MLT	
λ_2	η_{i1}	η_{i2}	η_{i1}	η_{i2}	η_{i1}	η_{i2}
0.05	0.02	0.03	0.02	0.03	0.02	0.03
0.06	0.03	0.04	0.03	0.04	0.03	0.04
0.07	0.04	0.05	0.04	0.05	0.04	0.05
0.08	0.06	0.07	0.06	0.07	0.06	0.07
0.09	0.08	0.09	0.08	0.09	0.07	0.09
0.10	0.11	0.12	0.10	0.11	0.10	0.11
0.11	0.14	0.15	0.14	0.15	0.13	0.14
0.12	0.18	0.19	0.18	0.19	0.17	0.19
0.13	0.23	0.25	0.23	0.24	0.22	0.24
0.14	0.31	0.32	0.30	0.31	0.30	0.31
0.15	0.42	0.44	0.40	0.41	0.39	0.40

Table 5.b: Input Buffer Mean Hop Delay of Class 1 & 2 Packets

λ_1=0.05

	SPD		Age		MLT	
λ_2	η_{i1}	η_{i2}	η_{i1}	η_{i2}	η_{i1}	η_{i2}
0.05	0.08	0.14	0.08	0.14	0.08	0.13
0.06	0.11	0.16	0.10	0.16	0.10	0.16
0.07	0.14	0.20	0.14	0.20	0.14	0.19
0.08	0.19	0.24	0.18	0.24	0.18	0.24
0.09	0.24	0.30	0.24	0.29	0.23	0.29
0.10	0.32	0.38	0.31	0.37	0.30	0.37
0.11	0.43	0.49	0.40	0.47	0.40	0.46
0.12	0.59	0.66	0.55	0.62	0.53	0.60
0.13	0.84	0.92	0.77	0.85	0.74	0.82
0.14	1.30	1.39	1.15	1.23	1.07	1.16
0.15	2.17	2.27	1.77	1.87	1.67	1.77

Table 5.c: Input Buffer Mean Hop Delay of Class 1 & 2 Packets

λ_1=0.10

	SPD		Age		MLT	
λ_2	η_{i1}	η_{i2}	η_{i1}	η_{i2}	η_{i1}	η_{i2}
0.05	0.32	0.44	0.31	0.43	0.30	0.42
0.06	0.43	0.56	0.42	0.55	0.40	0.53
0.07	0.59	0.73	0.56	0.70	0.53	0.67
0.08	0.84	0.99	0.78	0.93	0.74	0.89
0.09	1.28	1.46	1.15	1.32	1.06	1.24
0.10	2.17	2.37	1.87	2.08	1.68	1.87
0.11	4.82	5.08	3.63	3.87	2.99	3.21
0.12	38.81	39.22	12.01	12.35	7.90	8.19
0.13	220.04	219.92	177.31	177.42	122.21	122.40
0.14	263.44	263.42	246.95	246.97	229.49	229.58
0.15	282.64	282.63	271.70	271.66	263.82	263.87

Table 6.a: Input Buffer Mean Hop Delay of Class 1 & 2 Packets

λ_2=0.01

	SPD		Age		MLT	
λ_1	η_{i1}	η_{i2}	η_{i1}	η_{i2}	η_{i1}	η_{i2}
0.05	0.02	0.07	0.02	0.07	0.02	0.07
0.06	0.03	0.09	0.03	0.09	0.03	0.09
0.07	0.04	0.12	0.04	0.12	0.04	0.11
0.08	0.06	0.15	0.06	0.14	0.06	0.14
0.09	0.08	0.17	0.08	0.17	0.08	0.17
0.10	0.10	0.22	0.10	0.21	0.10	0.21
0.11	0.14	0.26	0.13	0.26	0.13	0.26
0.12	0.18	0.32	0.17	0.31	0.17	0.31
0.13	0.24	0.40	0.23	0.38	0.22	0.37
0.14	0.31	0.49	0.30	0.47	0.29	0.47
0.15	0.42	0.62	0.39	0.60	0.37	0.58

Table 6.b: Input Buffer Mean Hop Delay of Class 1 & 2 Packets

λ_2=0.05

	SPD		Age		MLT	
λ_1	η_{i1}	η_{i2}	η_{i1}	η_{i2}	η_{i1}	η_{i2}
0.05	0.08	0.13	0.08	0.13	0.08	0.13
0.06	0.11	0.17	0.11	0.17	0.11	0.17
0.07	0.14	0.22	0.14	0.22	0.14	0.22
0.08	0.18	0.28	0.18	0.28	0.18	0.27
0.09	0.24	0.35	0.24	0.34	0.23	0.34
0.10	0.32	0.45	0.31	0.44	0.30	0.42
0.11	0.42	0.57	0.41	0.55	0.40	0.54
0.12	0.59	0.75	0.55	0.71	0.53	0.69
0.13	0.83	1.04	0.76	0.96	0.73	0.93
0.14	1.28	1.54	1.13	1.37	1.04	1.28
0.15	2.11	2.43	1.79	2.08	1.59	1.86

Table 6.c: Input Buffer Mean Hop Delay of Class 1 & 2 Packets

λ_2=0.10

	SPD		Age		MLT	
λ_1	η_{i1}	η_{i2}	η_{i1}	η_{i2}	η_{i1}	η_{i2}
0.05	0.32	0.38	0.31	0.37	0.30	0.37
0.06	0.43	0.51	0.41	0.49	0.41	0.48
0.07	0.59	0.69	0.56	0.65	0.54	0.64
0.08	0.85	0.97	0.79	0.92	0.74	0.86
0.09	1.28	1.45	1.15	1.30	1.06	1.22
0.10	2.16	2.38	1.89	2.09	1.67	1.85
0.11	4.64	4.93	3.65	3.93	2.96	3.21
0.12	30.66	31.13	12.32	12.75	7.41	7.76
0.13	210.91	211.18	117.59	117.85	117.08	117.65
0.14	261.00	261.15	246.53	246.68	224.12	224.02
0.15	281.48	281.39	270.03	269.92	260.88	260.79

Figure 8: A queueing system with one server

Table 7.a: Blocking Probability

$\lambda_1=0.10$

	SPD		Age		MLT	
λ_2	P_{b1}	P_{b2}	P_{b1}	P_{b2}	P_{b1}	P_{b2}
0.12	0.0001	0.0001	0.00[1]	0.00	0.00	0.00
0.13	0.033	0.036	0.018	0.020	0.008	0.009
0.14	0.068	0.076	0.053	0.059	0.042	0.047
0.15	0.10	0.12	0.088	0.099	0.078	0.087

Table 7.b: Blocking Probability

$\lambda_2=0.10$

	SPD		Age		MLT	
λ_1	P_{b1}	P_{b2}	P_{b1}	P_{b2}	P_{b1}	P_{b2}
0.12	0.00002	0.00003	0.00	0.00	0.00	0.00
0.13	0.03	0.03	0.018	0.021	0.006	0.007
0.14	0.066	0.076	0.053	0.062	0.040	0.046
0.15	0.10	0.12	0.088	0.10	0.076	0.089

[1] A 0.00 in the table indicates no blocking event during the length of the simulation

Table 8.a: Throughput of Class 1 & 2 Packets

λ_1=0.01

	SPD		Age		MLT	
λ_2	γ_1	γ_2	γ_1	γ_2	γ_1	γ_2
0.05	0.01	0.05	0.01	0.05	0.01	0.05
0.06	0.01	0.06	0.01	0.06	0.01	0.06
0.07	0.01	0.07	0.01	0.07	0.01	0.07
0.08	0.01	0.08	0.01	0.08	0.01	0.08
0.09	0.01	0.09	0.01	0.09	0.01	0.09
0.10	0.01	0.11	0.01	0.11	0.01	0.11
0.11	0.01	0.11	0.01	0.11	0.01	0.11
0.12	0.01	0.12	0.01	0.12	0.01	0.12
0.13	0.01	0.13	0.01	0.13	0.01	0.13
0.14	0.01	0.14	0.01	0.14	0.01	0.14
0.15	0.01	0.15	0.01	0.15	0.01	0.15

Table 8.b: Throughput of Class 1 & 2 Packets

λ_1=0.05

	SPD		Age		MLT	
λ_2	γ_1	γ_2	γ_1	γ_2	γ_1	γ_2
0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.06	0.05	0.06	0.05	0.06	0.05	0.06
0.07	0.05	0.07	0.05	0.07	0.05	0.07
0.08	0.05	0.08	0.05	0.08	0.05	0.08
0.09	0.05	0.09	0.05	0.09	0.05	0.09
0.10	0.05	0.10	0.05	0.10	0.05	0.10
0.11	0.05	0.11	0.05	0.11	0.05	0.11
0.12	0.05	0.12	0.05	0.12	0.05	0.12
0.13	0.05	0.13	0.05	0.13	0.05	0.13
0.14	0.05	0.14	0.05	0.14	0.05	0.14
0.15	0.05	0.15	0.05	0.15	0.05	0.15

Table 8.c: Throughput of Class 1 & 2 Packets

λ_1=0.10

	SPD		Age		MLT	
λ_2	γ_1	γ_2	γ_1	γ_2	γ_1	γ_2
0.05	0.10	0.05	0.10	0.05	0.10	0.05
0.06	0.10	0.06	0.10	0.06	0.10	0.06
0.07	0.10	0.07	0.10	0.07	0.10	0.07
0.08	0.10	0.08	0.10	0.08	0.10	0.08
0.09	0.10	0.09	0.10	0.09	0.10	0.09
0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.11	0.10	0.11	0.10	0.11	0.10	0.11
0.12	0.10	0.12	0.10	0.12	0.10	0.12
0.13	0.096	0.125	0.098	0.128	0.100	0.129
0.14	0.093	0.129	0.095	0.130	0.096	0.133
0.15	0.089	0.133	0.091	0.135	0.092	0.137

Table 9: Throughput of Class 1 & 2 Packets

λ_2=0.10

	SPD		Age		MLT	
λ_1	γ_1	γ_2	γ_1	γ_2	γ_1	γ_2
0.05	0.05	0.10	0.05	0.10	0.05	0.10
0.06	0.06	0.10	0.06	0.10	0.06	0.10
0.07	0.07	0.10	0.07	0.10	0.07	0.10
0.08	0.08	0.10	0.08	0.10	0.08	0.10
0.09	0.09	0.10	0.09	0.10	0.09	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.11	0.11	0.10	0.11	0.10	0.11	0.10
0.12	0.12	0.10	0.12	0.10	0.12	0.10
0.13	0.126	0.097	0.128	0.098	0.130	0.100
0.14	0.131	0.092	0.133	0.094	0.134	0.095
0.15	0.135	0.088	0.137	0.090	0.138	0.091