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On-Board Closed-Loop Congestion Control for Satellite Based Packet Switching Networks

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Abstract

NASA Lewis Research Center is currently investigating a satellite architecture that incorporates on-board packet switching capability. Because of the statistical nature of packet switching, arrival traffic may fluctuate and thus it is necessary to integrate congestion control mechanism as part of the on-board processing unit. This study focuses on the closed-loop reactive control. We investigate the impact of the long propagation delay on the performance and propose a scheme to overcome the problem. The scheme uses a global feedback signal to regulate the packet arrival rate of ground stations. In this scheme, the satellite continuously broadcasts the status of its output buffer and the ground stations respond by selectively discarding packets or by tagging the excessive packets as low-priority. The two schemes are evaluated by theoretical queuing analysis and simulation. The former is used to analyze the simplified model and to determine the basic trends and bounds, and the later is used to assess the performance of a more realistic system and to evaluate the effectiveness of more sophisticated control schemes. The results show that the long propagation delay makes the closed-loop congestion control less responsive. The broadcasted information can only be used to extract statistical information. The discarding scheme needs carefully-chosen status information and reduction function, and normally requires a significant amount of ground discarding to reduce the on-board packet loss probability. The tagging scheme is more effective since it tolerates more uncertainties and allows a larger margin of error in status information. It can protect the high-priority packets from excessive loss and fully utilize the downlink bandwidth at the same time.

Key Words: packet switching networks, fast packet switch, propagation delay, congestion control, reactive control.

1 Introduction

Future communication satellites are expected to support a wide variety of services, including text, data, voice, image and video, as well as ISDN (Integrated Services Digital Network)/B-ISDN (Broadband ISDN) compatible traffic [4, 5, 7]. To accommodate these diversified services and the

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inherent traffic fluctuation, a network with packet switching capability is desired. Packet switching is a scheme that divides user information into fixed-length units known as packets and then statistically multiplexes these packets through the link. For bursty traffic, it is more efficient than circuit switching, in which the bandwidth is assigned according to the peak rate. NASA Lewis Research Center is currently investigating a geostationary communication satellite MCSPS (Multi-Channel Signal Processing Satellite), which can support the required packet switching capability and provide direct-to-the-user services [17].

In a conventional satellite based network, the satellite only relays the broadband signal and is essentially a "virtual pipe". It has no access to the information inside the packets. From the computer network's point of view, the satellite is simply a physical medium. All the processing beyond physical layer is performed in ground stations. To achieve the packet switching capability, we need either to employ a contention protocol or to use a master ground station [31]. The former uses satellite link as a multiple-access channel for the ground stations to contend. The later relays the signal to a master ground station, which extracts baseband information and performs switching. Two extra hops are required to achieve this goal. The block diagrams and layer models for the two schemes are shown in the Figure 1 and Figure 2 respectively. The contention protocol is complex and inherently inefficient, and the master ground station doubles the delay and reduces the bandwidth by half. Thus, neither scheme is effective.

As technology advances, more on-board processing capability can be incorporated in satellites, such as ACTS (Advanced Communication Technology Satellite) [22] and European Space Agency TST (Time-Space-Time) prototype [1]. These satellites can demodulate the aggregated input signals, perform circuit switching, and then modulate and distribute the signal to downlink beams. MCSPS intends to extend the on-board capability by incorporating a packet switch in satellite. It can convert the broadband signal to baseband, extract packet header information, and automatically route the packet to its destination . The satellite now essentially performs some functionalities in the datalink layer and network layer. The diagram and layer model are shown in Figure 3. Because of the high switching speed, the satellite switch looks more like a fast packet switch or an ATM (Asynchronous Transmission Mode) switch and thus we use the FPR (Fast Packet Relay) layer rather than the conventional datalink layer [6].

One of the functionalities in the upper layer is congestion control [27, 31]. This is required because the bandwidth for the packet switching networks is allocated on demand. Statistical fluctuation or network malfunction can occur and may cause the traffic exceeding the buffer capacity. Thus, it is necessary to incorporate congestion control mechanism to regulate the input traffic. Since the expected traffic is bursty and correlated, and its characteristic is extremely complex, the fast packet switching network needs a very sophisticated congestion control scheme. This topic has been studied extensively by the current B-ISDN research community [2, 12, 18, 23, 29, 16, 28]. However, most of them are focusing on the preventive control. This study is mainly concentrated on the reactive control, which is less understood.

The most unique characteristic of the satellite link is its long propagation delay between the earth stations and the satellite. The long delay makes the closed-loop control very difficult. This study investigates the impact of propagation delay on the performance of reactive congestion control, and proposes a congestion control scheme to overcome this problem. The proposed congestion control scheme uses a global feedback signal to regulate the packet arrival rate of ground stations. The satellite continuously broadcasts the status of its output buffer and the ground stations respond accordingly. When a ground station receives the status information and detects the congestion, it will either reduce the arrival rate by discarding packets or start to tag the excessive packets as low-priority. These low-priority packets will be discarded on board if congestion actually occurs. These schemes are evaluated by theoretical queuing models and simulation. The former is used to analyze the simplified model and to determine the basic trends and bounds, and the later is used to assess the performance of a more realistic system and to evaluate the effectiveness of more sophisticated control schemes.

The remaining article is organized as follows: section 2 gives an overview on congestion control; section 3 describes the need for the reactive control and the proposed rate adjusting scheme; section 4 develops two queuing models to investigate the impact of long propagation delay; section 5 discusses the analytical and simulation results; and the last section concludes the study.

2 Overview on Congestion Control

To achieve flexibility and efficiency, packet switching systems allocate resources on demand; i.e., no bandwidth will be consumed if the connected link is idle. This feature is essential for bursty traffic, in which the packet arrival rate fluctuates significantly and the peak arrival rate is much larger than the average arrival rate. If the allocated bandwidth is fixed, as in the circuit switching, it has to be equal to the peak rate to accommodate the worst case. On the other hand, in the packet switching networks the allocated bandwidth only needs to be roughly equal to the average rate of the incoming traffic. Therefore, system resource can be better utilized in packet switching networks. Due to the statistical fluctuation, a packet switching network may suffer potential congestion problem. The volume of total incoming traffic may occasionally exceed the capacity of outgoing link, even the outgoing link can accommodate incoming traffic statistically (i.e., in average). Without proper control, the buffer may overflow and certain packets will be lost. This in turn will reduce the effective throughput and introduce long delay. The purpose of congestion control is to provide a mechanism to smooth out fluctuation by regulating the incoming traffic and to prevent severe performance degradation [2, 9, 27].

Congestion control can be divided into reactive control and preventive control, depending whether a feedback information (from the destination node or network) is used in control. Reactive control is closed-loop control, in which the source node traffic is regulated by the destination node and/or the network. In this method, the destination node or the network transmit a special control/status information to the source node. The source node examines this information and responds accordingly. At the onset of congestion, reactive control instructs the source node to throttle its traffic by sending feedback to the source node. It is important to observe that the reactive control reacts to the congestion *after* it happens and tries to bring the degree of network congestion to an acceptable level. Two representative schemes are the sliding window scheme, in which the destination node uses "permits" to control the packet departure from the source node, and the choking packet scheme, in which the network uses a special control packet to slow down the transmission of the source nodes [27].

Preventive control is open-loop control, in which no feedback information is provided. Unlike the reactive control where control is invoked upon the detection of congestion, preventive control tries to prevent the network from reaching an unacceptable level of congestion (i.e., to prevent congestion *before* it happens). Preventive control is normally performed by the combination of admission control and bandwidth enforcement [2]. Admission control decides whether to accept or reject a new connection at the time of call setup. The decision is based on the new connection's service requirements and the traffic characteristic (which is also known as the traffic descriptor, and may include peak rate, average rate, burstiness and burst interval) as well as the current load status of the network. Bandwidth enforcement monitors individual connection to ensure that the actual traffic flow from the connection conforms with the parameters specified at call establishment.

Selection between the two methods depends on the inherent characteristic of the network. Two parameters, *bit-length* and *congestion-period-to-propagation-delay-ratio*, are of particularly importance. Bit-length is defined as the product of end-to-end propagation delay and link bandwidth. It represents the maximal number of outstanding bits that can exist between the source node and the destination node. For example, the bit-lengths of a 2 km 10 Mbps LAN segment, a 200 mile 1.544 Mbps T1 line and a 100 km 1 Gbps optical fiber line are 100 bits, 2500 bits and 1.6 Mbits respectively. Congestion-period-to-propagation-delay is defined as the ratio between the "burst period", in which excessive traffic arrives, and the propagation delay. In general, reactive becomes less effective when the bit-length increases and congestion-period-to-propagation-delay decreases, due to the large transient traffic and sluggish response time. Conventional terrestrial networks normally use reactive control because of the relative small bit-length, and optical-fiber based networks tend to use preventive control.

3 Closed-Loop Rate-Adjusting Control

3.1 Reactive Congestion Control for a Satellite Based Switch

The MCSPS network can be thought as a packet switching network with a single gigantic switch on the sky [17]. The most unique characteristic of the network is the long propagation delay of the link. The geostationary orbit is approximately 22,000 miles away from the surface of the earth and causes a one-way propagation delay (ground station to satellite) of 125 ms. This delay is much larger than any terrestrial link (the delay for a cross-continental link is about 20 ms). The long propagation delay makes the bit-length extremely large. It is 8000 bits for a single 64 Kbps channel and is 64 Mbits for the entire uplink (which has a capacity of 512 Mbps). Because of the large bit-length, it is necessary to incorporate certain preventive mechanisms to regulate short-term fluctuation, similar to that of B-ISDN networks [2, 16, 28].

A major problem with the preventive control is that the network has no control after the connection is established. The control is completely based on a priori information and cannot react to the changing traffic characteristic or the network load. This control is far from precise because the traffic descriptor is not exact and the bandwidth enforcement is not ideal. Furthermore, the exact characteristic of traffic and traffic mix of B-ISDN are too complex and are largely unknown. Since it is not possible to accurately predict the future condition by just using limited priori information, preventive control scheme needs to consider the worst case and tends to reserve more resource than actually required. Therefore, preventive control tends to under-utilize the system resource. For ATM based networks, it is a less problem because of the high bandwidth provided by the underlying optical fiber link. But on the other hand, the satellite bandwidth is still a precious resource and needs to be efficiently used.

Several recent studies suggest that the arriving traffic characteristic can be described by a hierarchical model and the control should be designed accordingly [14, 8, 24, 26]. The hierarchy is divided into three layers[1], according to the active time period. The highest one is the call layer, representing the length of a connection, which may range from seconds to several minutes or even hours. The middle one is the burst layer, representing an active interval in a connection, which may last from a fraction of second to several seconds. And the lower one is the packet layer, representing the transmission time of a packet, which only lasts a few micro-seconds. The effective control should be a hybrid of several mechanisms, each one targeting at a different layer. In the packet layer, the time scale involved is much smaller than the propagation delay and thus only

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[1] The term "layer" here is used to describe the traffic characteristic and is not related to the "layer" in the ISO layered network model.

pure preventive control can be implemented. Schemes similar to bandwidth enforcement need to be applied. Clearly, reactive control will not be effective for packet layer fluctuation since its period is much smaller than the propagation delay. On the other hand, it is possible to use reactive control in the burst layer whose active period can last up to several seconds [26, 30], which is much larger than satellite's propagation delay. The reactive control lets the network be able to react to the changing load and traffic characteristic, and to adapt new situation. It will complement the preventive control and make the overall control more effective.

In the reactive control scheme, the user stations need a mechanism to obtain the current network status. This can be done implicitly by using a sliding-window scheme between the user station and the switch, or explicitly by letting the switch "inform" the user stations about its status. In the sliding-window typed schemes, there is a large amount of overhead associated with each connection, and thus these schemes are not feasible for the high bandwidth packet switch. Furthermore, it will be very demanding for the on-board processor to handle up to 10,000 connections simultaneously. Therefore, these schemes should be only employed by end-to-end control (i.e., ground station to ground station) rather than by link-by-link control (i.e., satellite switch to ground station).

Letting the switch inform the user station is more appropriate for the fast packet switch. The packet switch can send an explicit control packet for a connection, such as the choke packet scheme [27], or add extra congestion information to the passing packets, such as the proposed FECN (Forward Explicit Congestion Notification) and BECN (Backward Explicit Congestion Notification) fields in the ATM cell [10, 4]. This scheme is particularly appealing for a satellite based network because of its inherent broadcasting capability. When the satellite is sending its status information to one station, *all* the active ground stations covered by the same beam can obtain the same information. In a short time (after the spot beam scans all the dwells), all the ground stations will have this information and can respond accordingly.

3.2 The Proposed Scheme

The proposed congestion control scheme uses a global feedback signal to regulate the packet arrival rate of ground stations. The satellite broadcasts the status of its output buffer, either by using an explicit chock packet or by piggybacking on a regular packet. When a ground station receives the status information and detects the congestion in satellite switch, it will initiate the rate control by either discarding packets or tagging the excessive packets as low-priority.

The scheme largely releases the responsibility from the space based segment. The satellite only needs to estimate the network load, which is reflected from the buffer status, and then broadcast this information. In the discarding scheme, the ground station determines the fraction to be reduced, if required, and the method to execute the reduction (e.g., selectively discarding the packets [30, 33] or changing coding scheme [32]). In the tagging scheme, the ground station determines the fraction to be tagged, and which portion to be tagged. Essentially, this scheme pushes the buffer overflow problem from the satellite to the ground station. Since the ground station has more knowledge about its traffic and can house more sophisticated hardware and software, letting it make decision will be more effective than letting satellite blindly drop packets.

3.2.1 Rate Reduction by Discarding

In this scheme, if congestion occurs, the ground station reduces the arrival rate by discarding portion of the arrival traffic. The relation between controlled and uncontrolled arrival rate of a ground station can be described as $\bar{\lambda}_k = f(k) * \lambda$, where $f(\cdot)$ is the rate reduction function, k is the status received from the satellite broadcasting, and $\bar{\lambda}_k$ and λ are the controlled arrival rate and original arrival rate respectively. If the status is below some pre-defined threshold, there will be no rate adjustment (i.e., $f(k) = 1$). Otherwise, the arrival rate will be reduced (i.e., $f(k) < 1$) according to the value of k. The difference between the original arrival rate and the controlled rate, $\lambda * (1 - f(k))$, represents the rate of the packets that needs to be discarded.

3.2.2 Tagging the Excessive Packets

The previous scheme uses ground discarding to reduce the on-board loss. In general, low on-board loss requires more conservative buffer management policy, which usually causes low resource utilization and increases the ground discarding probability. Because of the inaccurate status and long propagation delay, this phenomena will be further magnified. An alternative is to use a "tagging" scheme [2]. In this scheme, packets are divided into two priorities and are processed differently in the presence of congestion. The priority scheme comes from the observation that arrival packets may have different service requirements and some packets are less "vital". Normally, the non-delay-sensitive traffic, and certain portion of the voice and layer-coded video traffic can be marked as low-priority. Losing these packet has less impact because they can be recovered later (by the protocols in the upper layers) or they do not contain the vital information. The tagging scheme allows a larger margin of error in the status information as well as the uncertainty in the traffic characteristic. It can fully utilize the system resource and at same time reduce the on-board loss probability for high-priority packets.

When there is no congestion, the packets are processed as there is no priority control (alternatively, we can think all of them are designated as high-priority). When congestion occurs, certain portion of the arriving packets is tagged as low-priority (and the untagged ones are implicitly designated as high-priority). Both high-priority and low-priority packets will be sent to satellites, but they are treated differently on board. The low priority packet will be processed only if enough buffer space is available. If congestion does occur on board satellite, the low-priority packets will be discarded to make room for high-priority packets. Various buffer management algorithms have been proposed [15]. Push-out algorithm, in which the high-priority packets will always be inserted ahead of the low-priority packets, is used in this study. The number of tagged packets is determined by a "tagging function". The relation between the untagged rate (high-priority) and the original rate is $\bar{\lambda}_k = f(k) * \lambda$, similar to the discarding scheme. However, now the function $f(\cdot)$ is the tagging function and the expression $\lambda * (1 - f(k))$ represents the rate of the packets tagged as low-priority

3.2.3 Choice of Status Information and Reduction/Tagging Function

If there is no feedback delay, instantaneous buffer occupancy can be used as the status information. The ground stations can obtain the most accurate information and re-adjust the rate immediately. As the round-trip delay increases, this information becomes less valuable since it only reflects the buffer occupancy one propagation delay ago. A short-term average will be more effective because it filters out fluctuation and gathers information over a period of time. This also fits naturally to the satellite model, which can periodically broadcast the status information.

The simplest reduction function is a step function. There are two levels, representing congestion and no-congestion. When the status exceeds a threshold, the ground stations assume the congestion occurs and start to reduce the arrival rate. This is conceptually similar to the choke packet scheme, in which the network can slow down the arrival rate by using one status bit. Since the broadcasted status information can incorporate more than a single bit, it is possible to use more sophisticated reduction function, such as multiple-level stair function. A relevant issue for the function selection is the potential oscillation due to the non-negligible propagation delay. Consider a system with heavy incoming traffic. The heavy traffic causes the buffer occupancy exceeding the threshold, and triggers the rate reduction, which forces the traffic to return to the normal level. At this point, the buffer occupancy returns to normal, making the ground stations turn off the rate reduction. This, in turn, causes the system to go back to the original congested state, and to repeat the cycle again. To prevent oscillation, some "memory" element is required to record the current system state so that the rate control can react accordingly. We implement this memory element by adding hysteresis loop in the reduction function. The step function with hysteresis is shown in Figure 4(a). There are two thresholds: N_2 is the threshold from non-congested state to congested state and N_1 is the threshold from congested state to non-congested state. The same principle can be applied to multiple-level stair function. In this function, each level represents a congestion state and has its own reduction curve. Once the system reaches a new level, it follows the reduction curve in that particular level. A four-level reduction function is shown in Figure 4(b). Since the reduction function and tagging function play similar role in the control, previous discussion also applies to the tagging function.

4 Queueing Analysis

Two theoretical queuing models are developed to study the impact of the propagation delay and to evaluate the performance of the proposed reactive control schemes. Following subsections first review the switch model and then discuss the models for the discarding scheme and tagging scheme. Instantaneous buffer occupancy is used as the status information.

4.1 The Basic Switch Model

The proposed MCSPS architecture employs an eight-by-eight contention-free switch (since there are eight up-beams and eight down-beams) with output buffering capability [17]. Figure 5 shows the system block diagram from congestion control's point of view. It has been shown that the arrival process for one particular output buffer can be modeled as Poisson process when the size of the switch size approaches infinite large [13, 19]. It is difficult to consider incoming traffic of every ground station. Instead, we employ a single virtual incoming traffic stream, which lumps the individual incoming traffic together, for each uplink beam. If the individual traffic is independent Poisson process, the lumped traffic is also a Poisson process whose arrival rate is the summation of the individual arrival rates. If we further assume that the length of the packet is exponentially distributed, an output buffer can be modeled as an M/M/1 queue with finite waiting room [3]. Figure 6(a) and Figure 6(b) show the simplified block diagrams for the closed-loop rate control with discarding scheme and tagging scheme respectively.

4.2 Queuing Model for Discarding

Modeling constant propagation delay in a communication network is very difficult. To make analysis tractable, we assume that the delay is not constant but exponentially distributed. Based on the renewal property of the exponential distribution, it is possible to incorporate the delay into the Markov model. Basically, the original birth-death Markov chain is expanded to multiple phases [32]. A phase represents the ground operation mode experienced by the satellite. Within a phase, the chain evolves as a regular birth-death process. When the buffer reaches a new congestion status, the chain may switch to a phase corresponding to the new operation mode. The rate of change τ is $(2 * t_d)^{-1}$, where t_d is the one-way propagation delay.

Figure 7 shows the state transition diagram of a network with the step reduction function shown in Figure 4(a). K, N_1 and N_2 are the size of the buffer plus 1 (to include the packet currently being transmitted), the threshold from congested condition to non-congested condition and the threshold from non-congested condition to congested condition respectively. The state diagram represents the buffer condition on board. There are two phases representing the operation modes experienced by the satellite. For clarity, we use the two-tuple (s, i), where $s \in \{0, 1\}$ and $0 \leq i \leq K$, to represent a particular state in the state diagram. s and i represent the phase and the number of packets on the output buffer (including the one currently being transmitted) respectively. When s is 0, the satellite "feels" that the ground stations are in normal (non-congested) mode. Since no rate adjustment is performed, the mean arrival rate and mean service rate (which is defined as $\frac{\textit{mean packet length}}{\textit{downbeam speed}}$) are the original ones, denoted by λ and μ respectively. When s is 1, the satellite "feels" that the ground stations are in the discarding (congested) mode. In this mode, the ground stations reduce the arrival rate to λ_r, where $\lambda_r = \lambda * r$. Because of the propagation delay, it takes one propagation delay for the ground stations to obtain the information and takes another delay for the satellite to experience the traffic adjustment. The system cannot jump from one phase to another phase instantaneously; it has to stay in the same phase for one round-trip delay after reaching the trigger point (N_1 or N_2), and then switches to a new phase. This phenomena is modeled by the transition between two phases, which has a rate of τ. If τ is small (i.e., the propagation delay t_d is large), the probability of switching to another phase is very small and has to stay in the same phase longer. On the other hand, if τ is large (i.e., the propagation delay t_d is small), the probability of switching to another phase is large and the switching can occur very quickly. In the extreme case of zero delay, τ becomes infinite large and the system will switch to a new phase once it reaches the triggering states $(0, N_2)$ and $(1, N_1)$.

From the transition state diagram, we can determine the transition rate. Let $q_{(m,i)\to(n,j)}$ be the transition rate from state (m, i) to (n, j). The transition rate within normal mode is

$$q_{(0,i)\to(0,j)} = \begin{cases} \lambda & \text{if } j = i+1,\ 0 \leq i \leq K-1 \\ \mu & \text{if } j = i-1,\ 1 \leq i \leq K \end{cases}$$

and transition rate within discarding mode is

$$q_{(1,i)\to(1,j)} = \begin{cases} \lambda_r & \text{if } j = i+1,\ 0 \leq i < K-1 \\ \mu & \text{if } j = i-1,\ 1 \leq i \leq K \end{cases}$$

and the transition rate between the two modes is

$$q_{(m,i)\to(n,j)} = \begin{cases} \tau & \text{if } m = 0, n = 1, j = i,\ N_2 \leq i \leq K \\ \tau & \text{if } m = 1, n = 0, j = i,\ 0 \leq i \leq N_1 \end{cases}$$

and the "self transition rate" is

$$q_{(m,i)\to(m,i)} = \begin{cases} -\lambda & \text{if } m = 0,\ i = 0 \\ -\lambda - \mu & \text{if } m = 0, 1 \leq i \leq N_2 - 1 \\ -\lambda - \mu - \tau & \text{if } m = 0,\ N_2 \leq i \leq K-1 \\ -\mu - \tau & \text{if } m = 0,\ i = K \\ -\lambda_r - \tau & \text{if } m = 1,\ i = 0 \\ -\lambda_r - \mu - \tau & \text{if } m = 1,\ 1 \leq i \leq N_1 \\ -\lambda_r - \mu & \text{if } m = 1,\ N_1 + 1 \leq i \leq K-1 \\ -\mu & \text{if } m = 1,\ i = K \end{cases}$$

and $q_{(m,i)\to(n,j)} = 0$ for all other transitions.

For computation purpose, we can enumerate (s,i) into a one-dimension variable x (where x can be determined by $s*(K+1)+i$), and can write $q_{(m,k)\rightarrow(n,l)}$ as q_{uv}. Let the equilibrium probability of the buffer in state (s,i) be $p_{(s,i)}$ (or simply p_x). Define the transition rate matrix $\mathbf{Q} \equiv [q_{uv}], 0 \leq u,v \leq 2K+1$, probability vector $\mathbf{P} \equiv [p_u]$, $0 \leq u \leq 2K+1$ and null vector $\mathbf{0} \equiv [0,0,\cdots,0]$. We can obtain p_x [20] by solving:

$$\mathbf{PQ} = \mathbf{0} \text{ and } \sum_{x=0}^{2K+1} p_x = 1$$

In the satellite switch, an arrival packet will be lost if the buffer is full (i.e., in state $(0,K)$ and state $(1,K)$). Thus, the packet loss probability on board satellite is

$$P_{loss\ on\ board} = \frac{\lambda p_{(0,K)} + \lambda_r p_{(1,K)}}{\sum_{i=0}^{K} \lambda p_{(0,i)} + \sum_{i=0}^{K} \lambda_r p_{(1,i)}}$$

For the ground station, the average arrival rate of the controlled system $\bar{\lambda}$ is

$$\bar{\lambda} = \sum_{i=0}^{K} \lambda p_{(0,i)} + \sum_{i=0}^{K} \lambda_r p_{(1,i)}$$

The difference $\lambda - \bar{\lambda}$ represents the average rate of packets discarded by the ground station due to the rate control, and the loss probability on ground is

$$P_{loss\ on\ ground} = \frac{\lambda - \bar{\lambda}}{\lambda} = 1 - \frac{\sum_{i=0}^{K} \lambda p_{(0,i)} + \sum_{i=0}^{K} \lambda_r p_{(1,i)}}{\lambda}$$

4.3 Queuing Model for Tagging

The basic queuing model for the tagging scheme is very similar to that of the discarding scheme, using phases to represent the operation modes experienced by the satellite and using the transition between the two phases to model propagation delay. However, the birth-death process within a phase now is expanded into a two-dimension process, with each dimension representing a class (tagged or untagged) of packets. The two-tuple (h,l) represents that there are h high-priority (untagged) packets and l low-priority (tagged) packets buffered/processed in an output buffer.

Figure 8 shows the state transition diagram of a system with the step tagging function shown in Figure 4(a). In the upper part, the satellite feels that the ground stations are in regular mode. Since no tagging is performed, all the arriving packets are considered as high-priority packets. Thus, the arrival rates for high-priority packets and low-priority packets are λ and 0 respectively. In the lower part, the satellite feels that the ground stations are in the tagging mode. In this mode, the ground station divides the arriving packets into two priorities and tags $(1-r)$ portion of them as low priority. The arrival rates for high-priority packets and low-priority packets are λ_h (which is equal to $r\lambda$) and λ_l (which is equal to $(1-r)\lambda$) respectively. The transition shows that the high-priority packets will be inserted ahead of low-priority packets, and the low-priority packets will be served only when there is no high-priority packet left. When the system is full (i.e., $h+l=K$) and a new high-priority packet arrives, satellite will remove one low-priority packet to make room for the high-priority one. The state diagram also shows the transition from the tagging mode to normal mode. When the total number of packets (i.e., $h+l$) shrinks below the threshold N_1, the system may switch back to the normal mode with a rate of τ. During the transition, all the packets will covert to high-priority packets and proceed as in normal mode.

For clarity, we use the three-tuple (s,h,l) to represent a state in the state diagram. The s represents the phase of the state diagram, with 0 for the normal mode and 1 for tagging mode. From the transition state diagram, we can determine the transition rate. Let $q_{(m,i,k)\rightarrow(n,j,l)}$ be the transition rate from state (m,i,k) to (n,j,l). The transition rate within normal mode is

$$q_{(0,i,0)\rightarrow(0,j,0)} = \begin{cases} \lambda & \text{if } j = i+1,\ 0 \le i \le K-1 \\ \mu & \text{if } j = i-1,\ 1 \le i \le K \end{cases}$$

and transition rate within tagging mode is

$$q_{(1,i,k)\rightarrow(1,j,l)} = \begin{cases} \lambda_h & \text{if } j = i+1, l = k, 0 \le i \le K-1, 1 \le k \le K, 0 \le i+k \le K-1 \\ \lambda_h & \text{if } j = i+1, l = k-1, 0 \le i \le K-1, 1 \le k \le K, i+k = K \\ \lambda_l & \text{if } j = i, l = k+1, 0 \le i \le K-1, 1 \le k \le K-1, 0 \le i+k \le K-1 \\ \mu & \text{if } j = i-1, l = k, 1 \le i \le K, 0 \le k \le K-1, 1 \le i+k \le K \\ \mu & \text{if } j = i = 0, l = k-1, N_1+1 \le k \le K \end{cases}$$

and the transition rate between the two modes is

$$q_{(m,i,k)\rightarrow(n,j,l)} = \begin{cases} \tau & \text{if } m = 0, n = 1, j = i, l = k = 0, N_2 \le i \le K \\ \tau & \text{if } m = 1, n = 0, 1 \le i \le N_1, 0 \le k \le N_1, 0 \le i+k \le N_1 \end{cases}$$

and the self transition rate is

$$q_{(m,i,k)\rightarrow(m,i,k)} = \begin{cases} -\lambda & \text{if } m = 0, i = 0, k = 0 \\ -\lambda-\mu & \text{if } m = 0, 1 \le i \le N_2-1, k = 0 \\ -\lambda-\mu-\tau & \text{if } m = 0, N_2 \le i \le K-1, k = 0 \\ -\mu-\tau & \text{if } m = 0, i = K, k = 0 \\ -\lambda_l-\lambda_h-\tau & \text{if } m = 1, i = 0, 0 \le k \le N_1 \\ -\lambda_l-\lambda_h-\mu & \text{if } m = 1, i = 0, N_1+1 \le k \le K-1 \\ -\lambda_l-\lambda_h-\mu-\tau & \text{if } m = 1, 1 \le i \le N, 0 \le k \le N_1-1, 1 \le i+k \le N_1 \\ -\lambda_l-\lambda_h-\mu & \text{if } m = 1, 1 \le i \le K-1, 0 \le k \le K-1, N_1+1 \le i+k \le K-1 \\ -\lambda_h-\mu & \text{if } m = 1, 1 \le i \le K-1, 0 \le k \le K-1, i+k = K \\ -\mu & \text{if } m = 0, i = K, k = 0 \end{cases}$$

and $q_{(m,i,k)\rightarrow(n,j,l)} = 0$ for all other transitions.

For computation purpose, we can enumerate (s,h,l) into a one-dimension variable x (since the chain is finite), and can write $q_{(m,i,k)\rightarrow(n,j,l)}$ as q_{uv}. Let the equilibrium probability of the buffer in state (s,h,l) be $p_{(s,h,l)}$(or simply p_x). Define $\mathbf{Q} \equiv [q_{uv}], 0 \le u, v \le \frac{(K+1)(K+4)}{2}$, $\mathbf{P} \equiv [p_u]$, $0 \le u \le \frac{(K+1)(K+4)}{2}$, and $\mathbf{0} \equiv [0, 0, \cdots, 0]$. We can obtain p_x by solving

$$\mathbf{PQ} = \mathbf{0} \text{ and } \sum p_u = 1$$

Once $p_{(s,h,l)}$ is obtained, we can determine the quantities of interest. The loss probability of high-priority packets is

$$P_{loss\ of\ high\ priority\ packets} = \frac{\lambda p_{(0,K,0)} + \lambda_h p_{(1,K,0)}}{\lambda}$$

and the loss probability of low-priority packets is

$$P_{loss\ of\ low\ priority\ packets} = \frac{\sum_{h=0}^{K-1} \lambda p_{(1,h,K-h)} + \lambda_l p_{(1,K,0)}}{\lambda}$$

and the overall packet loss probability is

$$P_{total\ loss} = P_{loss\ of\ high\ priority\ packets} + P_{loss\ of\ low\ priority\ packets}$$

Since there is no discarding on ground, all the loss occurs in satellite. Thus, the total loss is identical to the loss of a system with no congestion control and is also independent of the propagation delay.

The tagging probability is defined as the percentage of packets that is tagged (or has been forced to designated as low-priority). It can be obtained by

$$P_{tagging} = \frac{\sum_{h=0}^{K} \sum_{l=0}^{K-h} \lambda_l p_{(1,h,l)}}{\lambda}$$

5 Results and Observations

This section shows the numerical results from theoretical queuing analysis, with emphasis on the impact of propagation delay, and the results from the simulation, with the emphasis of using average queue length as the status. Mathematica[2], a mathematical software package is used to obtain the numerical results, and BONES Designer[3], a network simulation package, is used to perform simulation. The major criteria for performance evaluation is the on-board packet loss probability due to the buffer overflow. In the original MCSPS design, the required on-board packet loss probability is around 10^{-9} at the load ($\frac{\lambda}{\mu}$) of 0.8. This can be done by using a buffer with a size of 125 packets. To achieve this extremely low loss probability, the Monte Carlo technique (used in BONES) needs to simulate a large number of packets (10^{12} to 10^{14} packets). This in turn requires a significant amount of computation time and cannot be done by today's workstation. Instead, we choose a much larger loss probability, 10^{-3}, at the load of 0.8, which can be achieved by a buffer with a size of 25 packets. This configuration makes the simulation manageable and allows us to experiment with various combinations, to evaluate their performance and to identify the basic trend. We also assume that the average size of the packet is 53 bytes, similar to the size of an ATM cell, and the down-link rate is 150 Mbps. The average service time (μ^{-1}) is 53*8/150M.

5.1 Queueing Analysis Results

5.1.1 Impact of Propagation Delay on Discarding Scheme

Figure 9(a) and Figure 9(b) illustrate the effect of propagation delay on the discarding scheme, showing the on-board packet loss probability due to buffer overflow and the ground loss probability due to the voluntary discarding. The N_1 and N_2 are chosen to be 18 and 20 respectively. The round-trip propagation delay is represented in term of average packet transmission time t ($t = \mu^{-1}$), ranging from $0.001t$ to $1000t$. The two figures clearly show the impact of the long propagation delay. The on-board loss probabilities for $0.001t$ and $1t$ are extremely small, and all the excessive packets are voluntarily discarded on ground. As the propagation delay increases, the on-board loss probability increases. There are significant gaps between $1t$ and $10t$, and between $10t$ and $100t$. As the propagation delay reaches $1000t$, the loss probability continuously increases, although the gap is not that significant.

The figures show that the ground discarding probabilities for various delays are very close, even the on-board loss probabilities vary significantly. This indicates that the amount of ground reduction for various delays is very similar. When the propagation delay is small, this reduction

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[2] Mathematica is a registerd trademark of Wolframe, Inc.

[3] BONES Designer is a registered trademark of Comdisco Systems, Inc.

can be done in a timely manner and prevent further on-board loss. As the delay increases, the response becomes sluggish and the on-board loss increases. When the propagation delay becomes extremely large, as in $100t$ and $1000t$, the system is no longer responsive and the feedback status can only be used as some kind of "statistical information" rather than the instantaneous buffer status. This also explains the small gap between $100t$ and $1000t$. More and less, the system has reached a "statistical steady state", and continuously increasing the propagation delay will not significantly change the system behavior.

Figure 10(a) and Figure 10(b) compare the difference between the exponential delay and the constant delay. The later is obtained by simulation. The figures show that the behaviors of the two systems are very close, with similar curves and trends. The curve with exponential delay always performs better than its counterpart. This may be due to the former is random and may contains both short delays and extremely large delays. Since the extremely large delays are not heavily penalized, the average performance becomes better.

5.1.2 Impact of Propagation Delay on Tagging Scheme

Figure 11(a) and Figure 11(b) show the performance of the tagging scheme and the effect of propagation delay. The N_1 and N_2 are chosen to be 10 and 15 respectively. Figure 11(a) shows the on-board high-priority packet loss probability as well as the total packet loss probability under various propagation delays. Since there is no packet physically discarded on ground stations, the total packet loss probability will be independent of the propagation delay and is identical to the packet loss probability of a system with no congestion control. The tagging scheme essentially protects the "vital" packets by giving them preferential treatment and sacrificing the performance of less important packets. Figure 11(a) shows that the high-priority packet loss probability is rather "flat" under heavy loads, and is much smaller than that of the discarding scheme. Also, the performance is less sensitive to the propagation delay. Propagation delay still has a negative impact on the performance. As the propagation delay increases, the system suffers more high-priority packet loss and has to tag more arriving packets as low-priority.

Figure 12(a) and Figure 12(b) compare the difference between the exponential delay and the constant delay. The later is obtained by simulation. The results are very similar to those in discarding scheme. Again, the behaviors of the two systems have similar curves and trends, but the set with exponential delay always performs better.

In general, the theoretical results faithfully reflect the behaviors of the actual system and thus can be used as a good approximation for the system. The computation involved in the theoretical analysis demands much more less CPU time (which is required for solving a set of linear equations) and thus can be used to obtain the results when the simulation is not feasible.

5.2 Simulation Results

Previous results show that the buffer occupancy only has statistical significance for large propagation delay. Instead of instantaneous status, using the short-term average of buffer occupancy will be more effective because it filters out fluctuation, gathers data over a period of time and provides more statistical information. Since theoretical queuing analysis is not able to model averaging occupancy, it is necessary to use simulation to evaluate the performance. Simulation also can be used to study system with constant propagation delay and complex reduction/tagging functions.

The 125 ms propagation delay needs a large number of packets to fill the "pipe" and requires a large amount of simulation time before the system can reach steady state. Therefore, we assume that the propagation delay is 1000 average service time. This ratio is large enough and its effect is close to 125 ms propagation delay.

5.2.1 Effect of Averaging Period on Buffer Occupancy

Figure 13 illustrates the effect of averaging period. A step reduction function is used. The ground discarding probabilities of three different averaging periods, with values of $10t$, $200t$ and $20000t$ respectively, are plotted. In the ideal case, there should be no discarding when the load is smaller than 0.8. When load exceeds this value, the reduction mechanism should become active and bring the load back to 0.8. A significant discarding will occur (up to 20%) during this part. The plot with $20000t$ illustrates the effect of long-term average. It clearly shows the onset of the reduction mechanism. The onset of the $200t$ plot is less clear, however, there is a noticeable slope change near 0.75. The $10t$ plot is almost a linear curve and there is no clear onset point. Although the long-term average gives an accurate estimation, it cannot quickly respond to the time-varying traffic. In the remaining subsection, we choose to use an averaging period of $200t$, which is a fraction of propagation delay and gives a reasonable estimation. The $20000t$ plot also clearly shows the impact of oscillation since the reduction rate is about 9% when the ideal one should be close to 20%.

5.2.2 Effect of Reduction Function

Figure 14(a) and Figure 14(b) illustrate the effect of different reduction functions for the discarding scheme, showing the on-board packet loss probability and the ground discarding probability respectively. Three functions are used: a step function f_1, a step function with hysteresis f_2 and a multi-level stair function with hysteresis f_3. f_2 and f_3 are similar to the functions in Figure 4(a) and Figure 4(b). To determine the exact values of thresholds (N_1, N_2 etc.) is difficult. We use the formula for long-term M/M/1/K average $\sum_{k=1}^{K} k \frac{1-\frac{\lambda}{\mu}}{1-(\frac{\lambda}{\mu})^{K+1}}(\frac{\lambda}{\mu})^k$ as the approximated values.

Comparing the plots for f_1 and f_2, we can see that the hysteresis causes a shaper curve and makes the reduction closer to ideal. Both f_1 and f_2 experience a high level of undesired ground discarding near the load of 0.8. f_3 has better resolution for reduction levels. It improves the discarding probability near 0.8 and still can maintain a high reduction rate at heavy load (≥ 0.9). Figure 14(a) shows the on-board loss can be reduced significantly, although the loss is still high (larger than the desired 10^{-3}) for heavy load. Figure 14(b) clearly shows that price paid for this scheme. Ground stations need to discard a large number of packets to obtain improvement on board. This cannot be avoided because of the inherent long propagation delay of the satellite link.

5.3 Effect of Tagging

Figure 15(a) and Figure 15(b) illustrate the effect of tagging. The identical f_1, f_2 and f_3 are used as tagging functions. Figure 15(a) shows the total on-board loss probability as well as loss probability of the high-priority packets. Since there is no packet discarding on ground, the total loss probability will be the same for either function and is also identical to the loss probability of no congestion control. The plot indicates that the on-board loss of high-priority packets can be significantly reduced. The curves are "flat" even for heavy loads. For f_2 and f_3, the loss probabilities are extremely small and is within 10^{-3}. Figure 15(b) shows the portion of arriving traffic tagged as low-priority. Again, f_3 has the best performance. It can accurately detect the onset of the congestion near the load of 0.8 and maintain a high tagging rate for heavy loads.

6 Conclusions

This study investigates reactive congestion control schemes for satellite based packet switching networks and the impact of long propagation delay. The proposed scheme uses a global feedback signal to regulate the packet arrival rate of ground stations. The satellite continuously broadcasts the status of its output buffer. When ground stations detect the congestion in satellite switch, they either reduce the arrival rate by discarding packets or start to tag the excessive packets as low-priority.

Both analytical and simulation results show that the long propagation delay makes the closed-loop congestion control less responsive. The broadcasted information cannot be used as the instantaneous status to prevent immediate on-board loss. However, it can be used to extract statistical information and to perform congestion control, possibly in the burst layer. Using short-term average as the status will further enhance the performance. In the discarding scheme, it normally needs a large amount of ground discarding to achieve low on-board packet loss probability. Although the carefully-chosen status information and reduction function can improve the performance, the discarding is still significant. This inevitably decreases the utilization of the downlink beam. The tagging scheme is an attractive alternative since it can tolerate uncertainty and inaccuracy caused by the long propagation delay. Tagging can protect the high-priority packets from excessive loss and fully utilize the downlink bandwidth at the same time. It is the most promising scheme and should be used for the services containing priority information.

The study shows that it is possible and beneficial to incorporate reactive congestion control to regulate the incoming traffic for satellite based packet switching networks. However, the analysis and simulation is performed around a simplified satellite model. Future study should extend the current model to emulate a system with more realistic switch configuration and more sophisticated arrival process. Areas worth the further study include the schemes for priority/buffer management, the impact of multicasting, and the effect of a more realistic eight-by-eight switch and correlated arrival process (such as Modulated Markov Poison Process).

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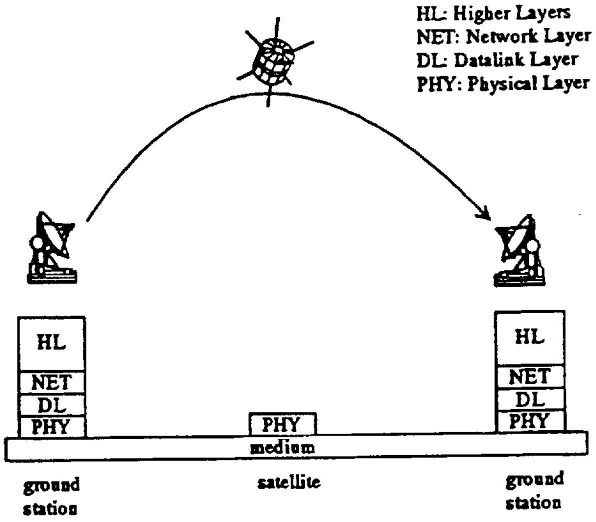


Figure 1. A "Bent-Pipe" Satellite Switching Network

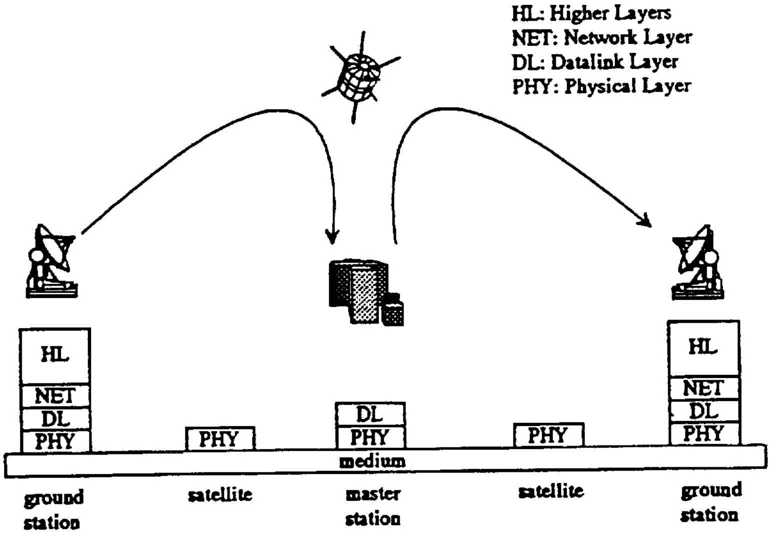


Figure 2. A Two-Hop Satellite Switching Network

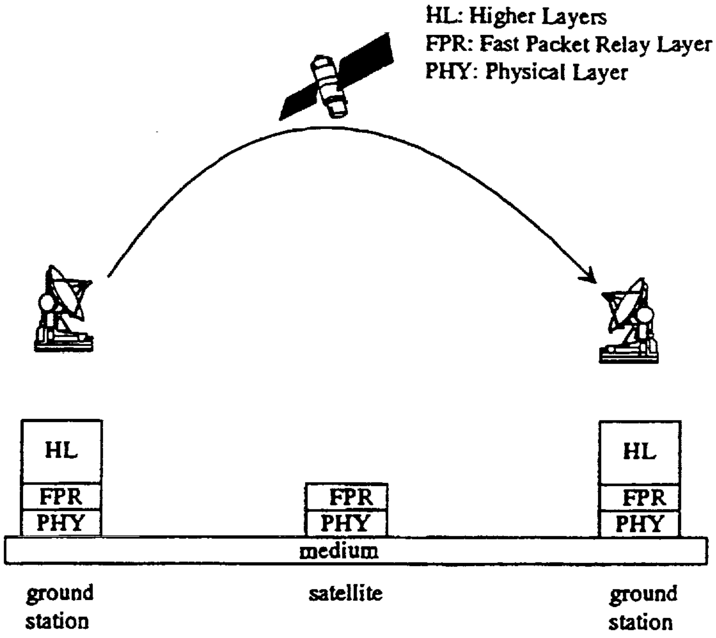
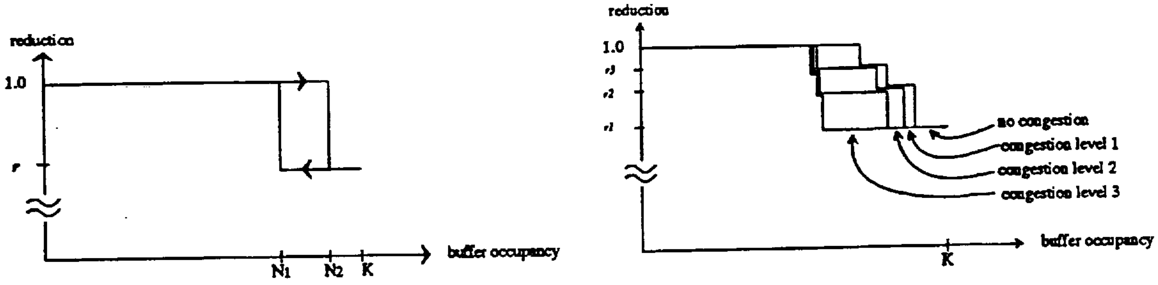


Figure 3. A Packet Switching Network with OBP Satellite



(a). step function with hysteresis

(b) multi-level stair function with hysteresis

Figure 4. Two Reduction Functions

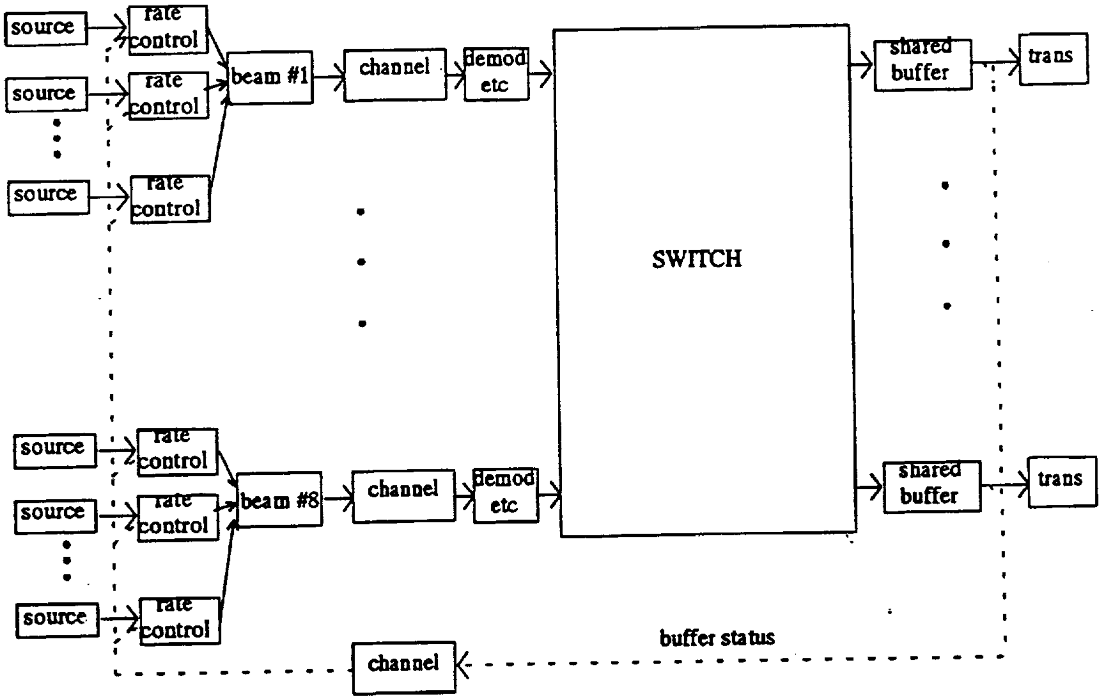
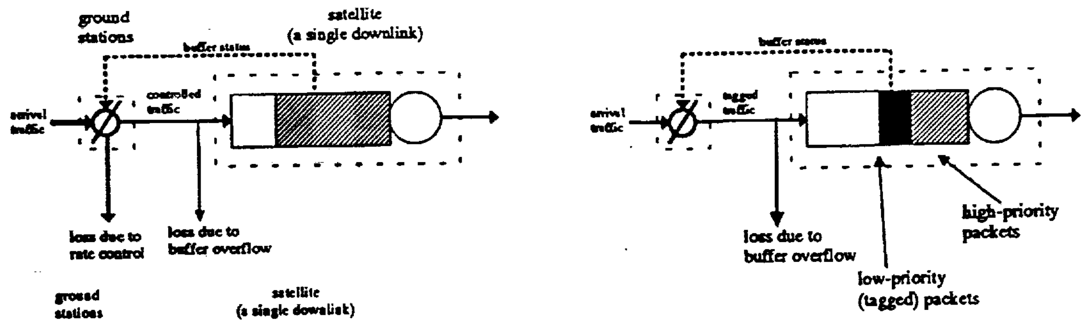


Figure 5. System Block Diagram (From CongestionControl's Point of View)



(a). Discarding Scheme (b). Tagging Scheme

Figure 6. Simplified Block Diagram

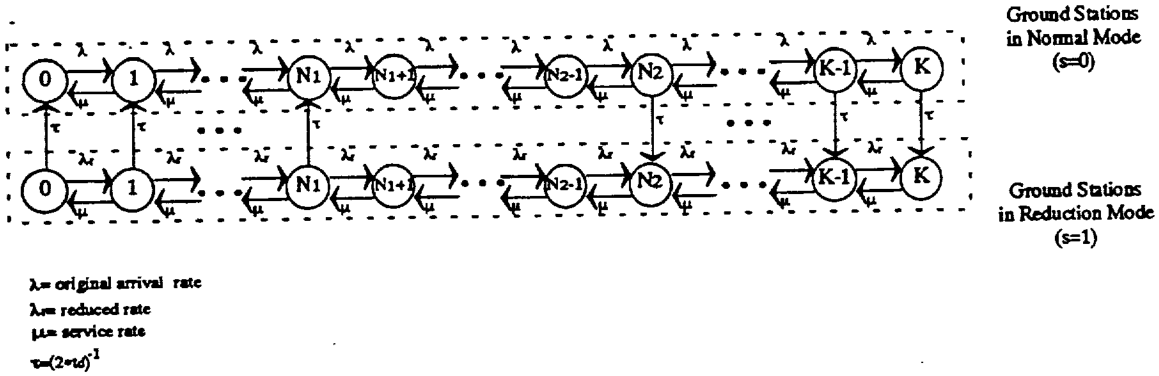


Figure 7. State Transition Diagram of Discarding Scheme

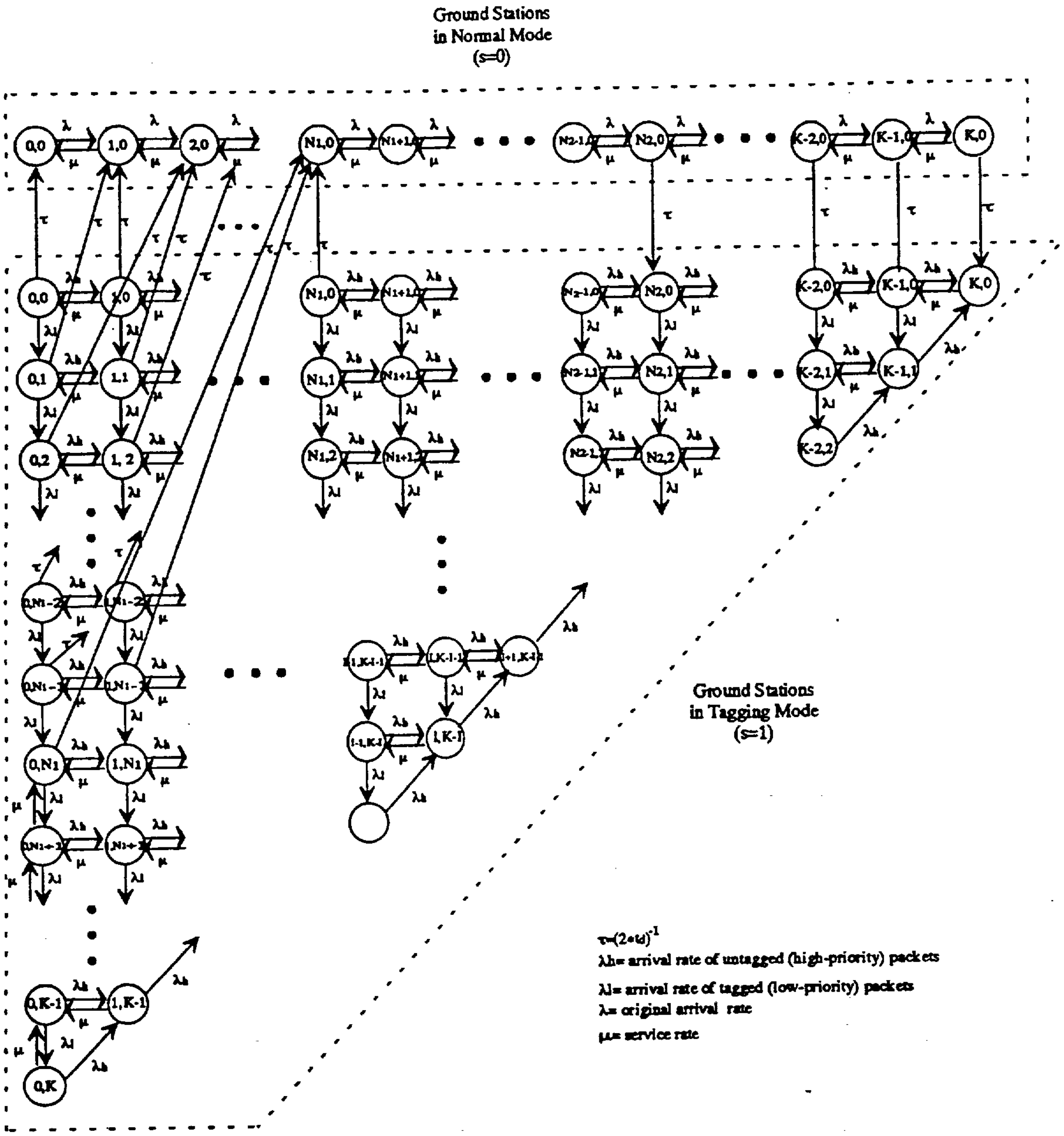
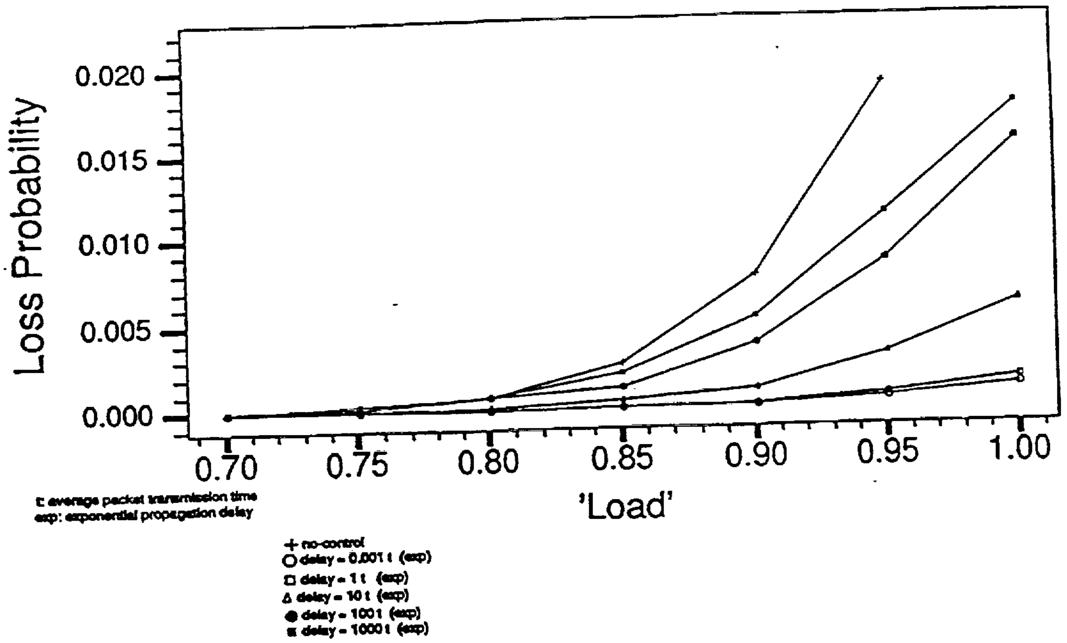
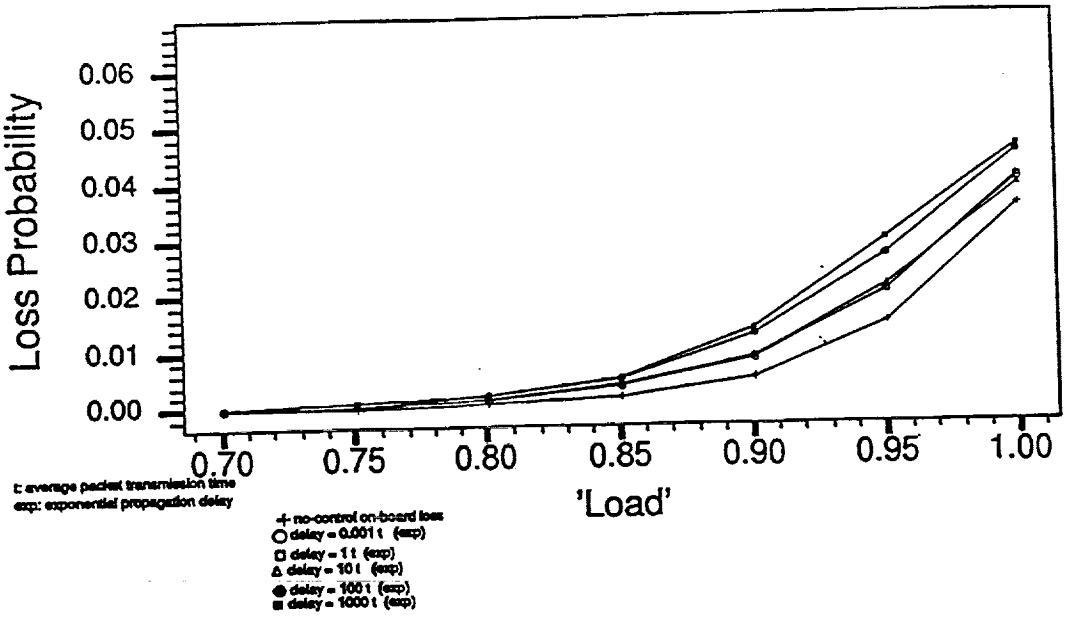


Figure 8. State Transition Diagram of Tagging Scheme

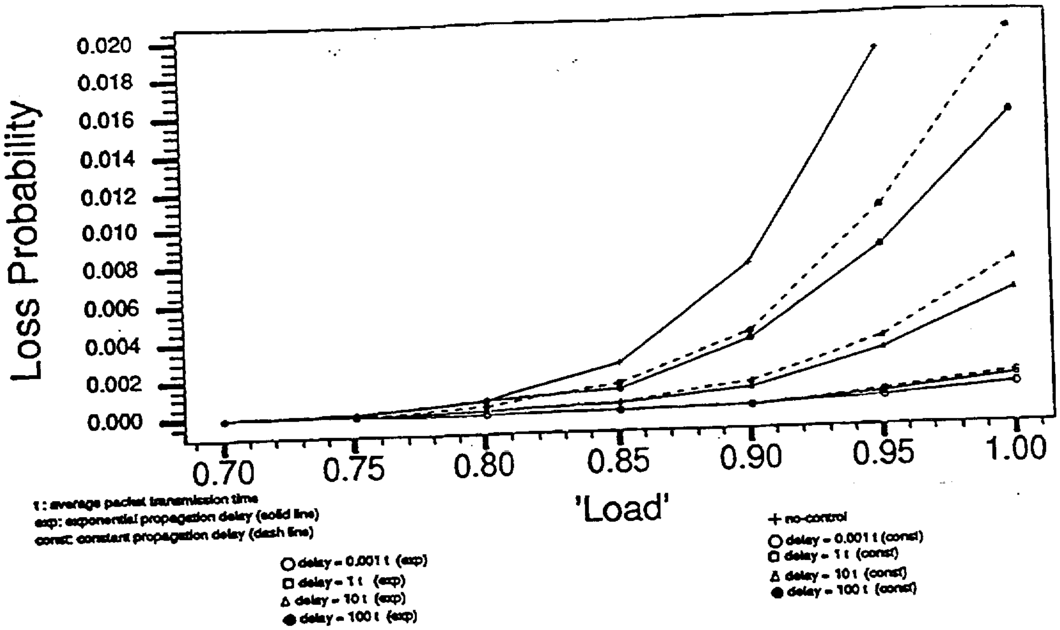


(a) On-board Loss Probability

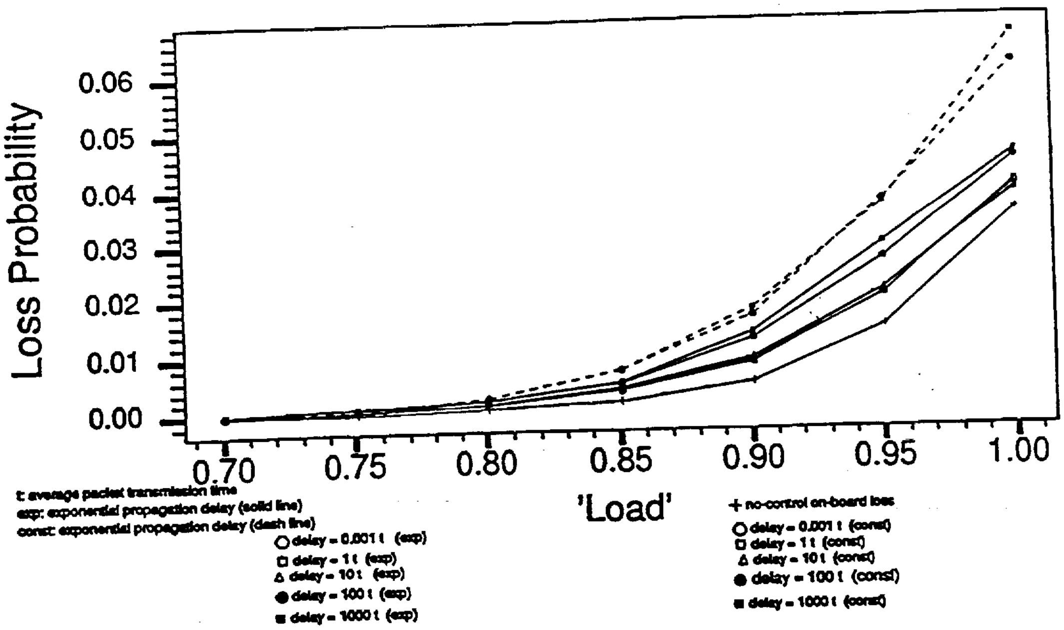


(b). Ground Loss Probability

Figure 9. The Effect of Propagation Delay on Discarding Scheme

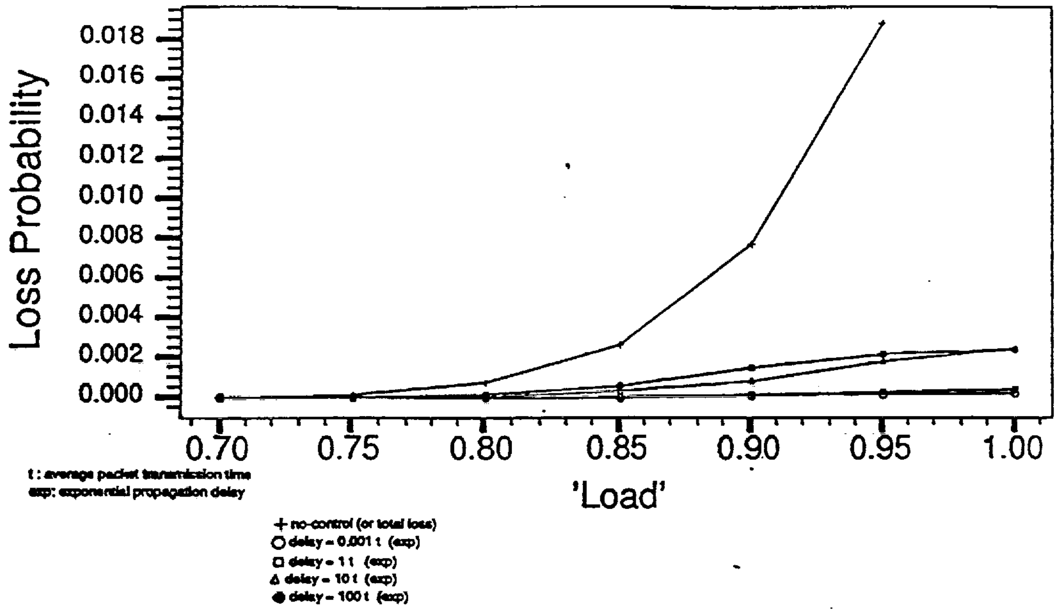


(a). On-board Loss Probability

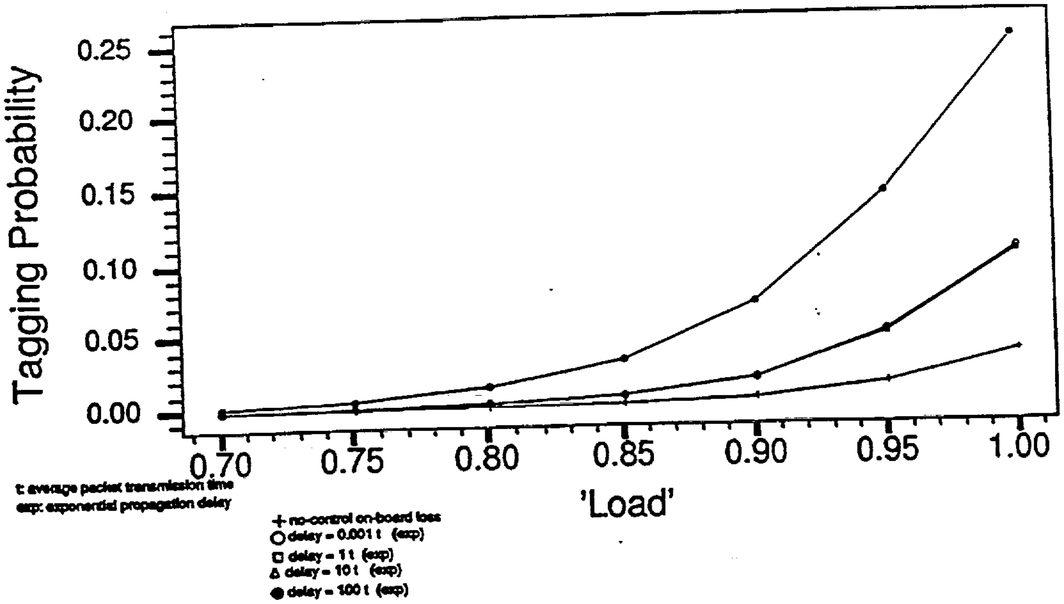


(b). Ground Loss Probability

Figure 10. Comparison Between Exponential and Constant Delays

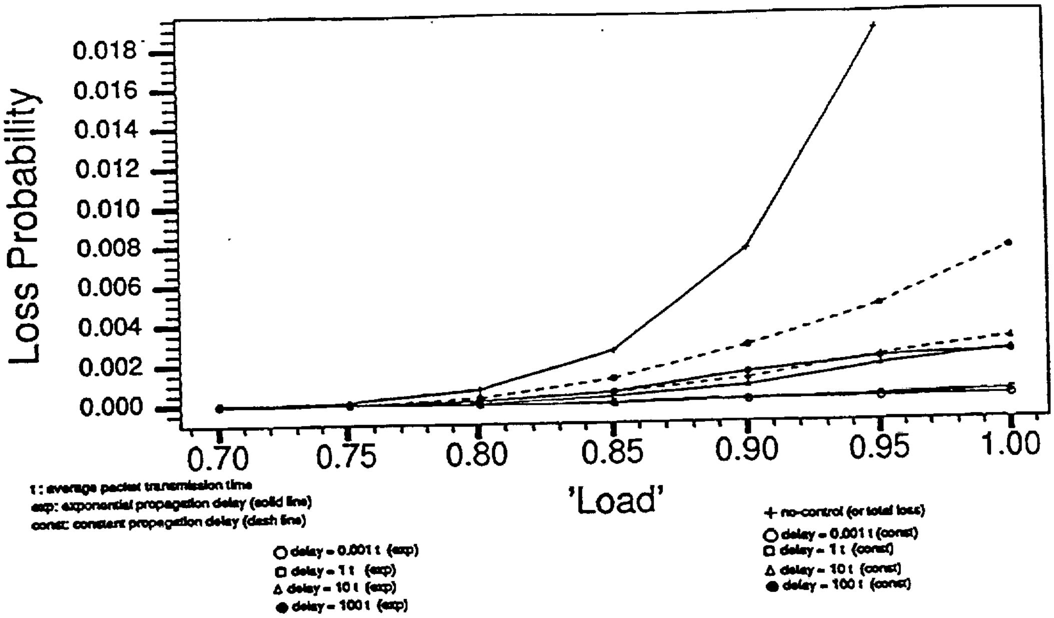


(a). On-board Loss Probability for High-Priority Packets

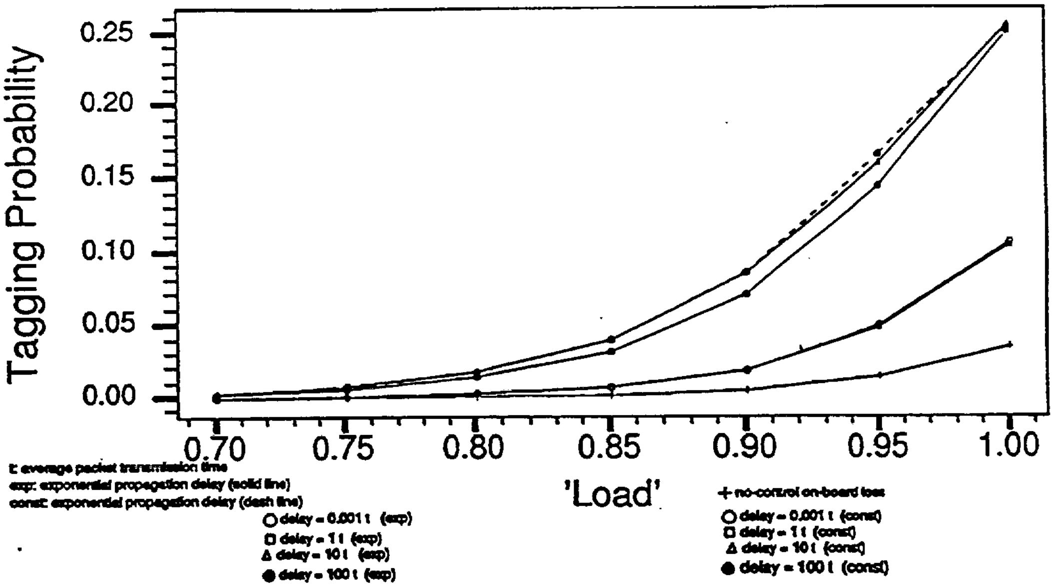


(b). Ground Tagging Probability

Figure 11. The Effect of Propagation Delay on Tagging Scheme



(a). On-board Loss Probability for High-Priority Packets



(b). Ground Tagging Probability

Figure 12. Comparison Between Exponential and Constant Delays

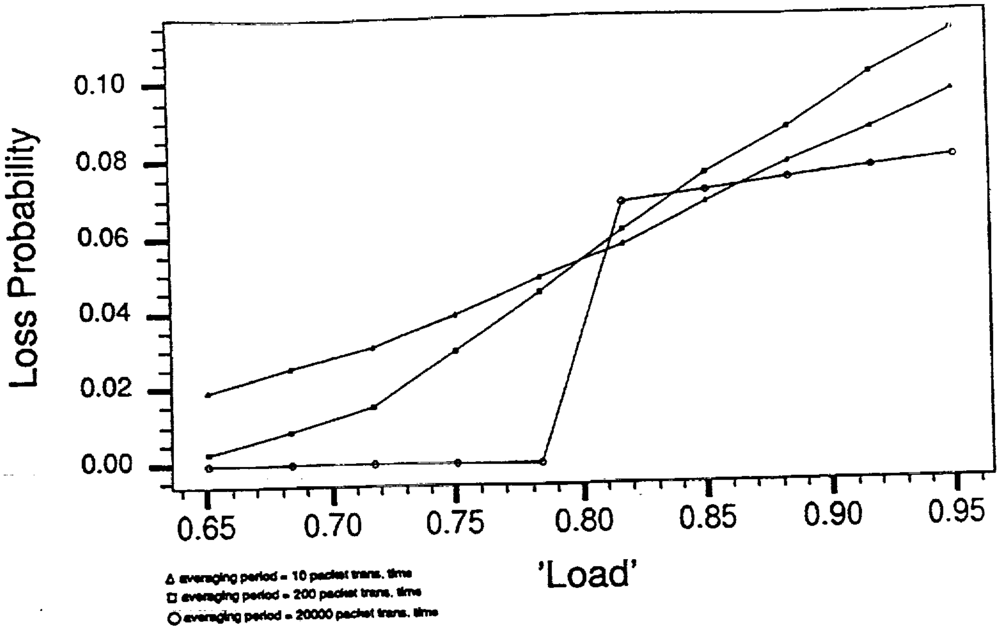
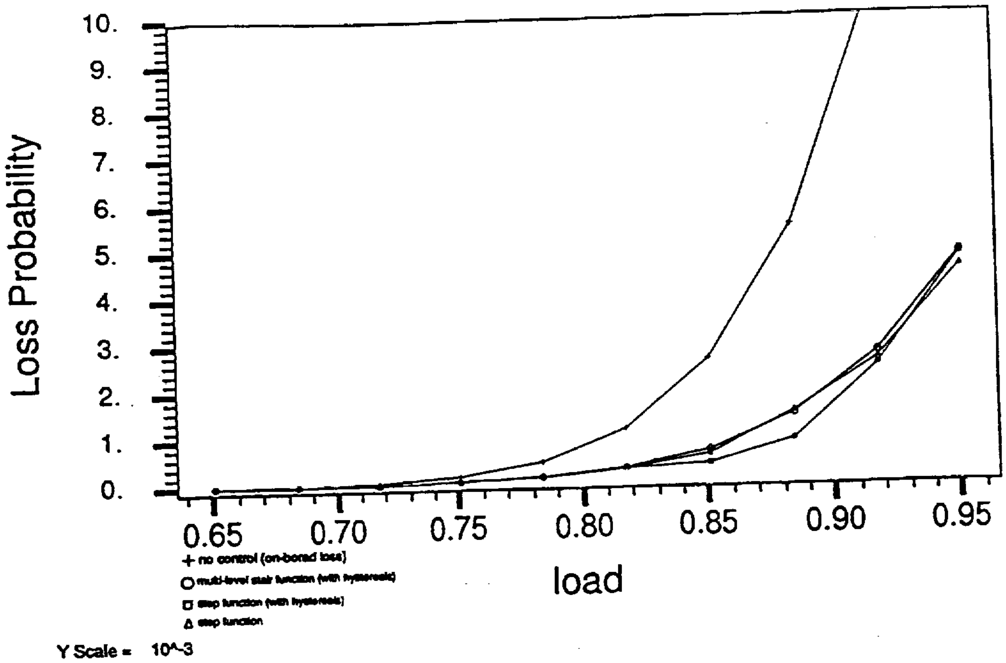
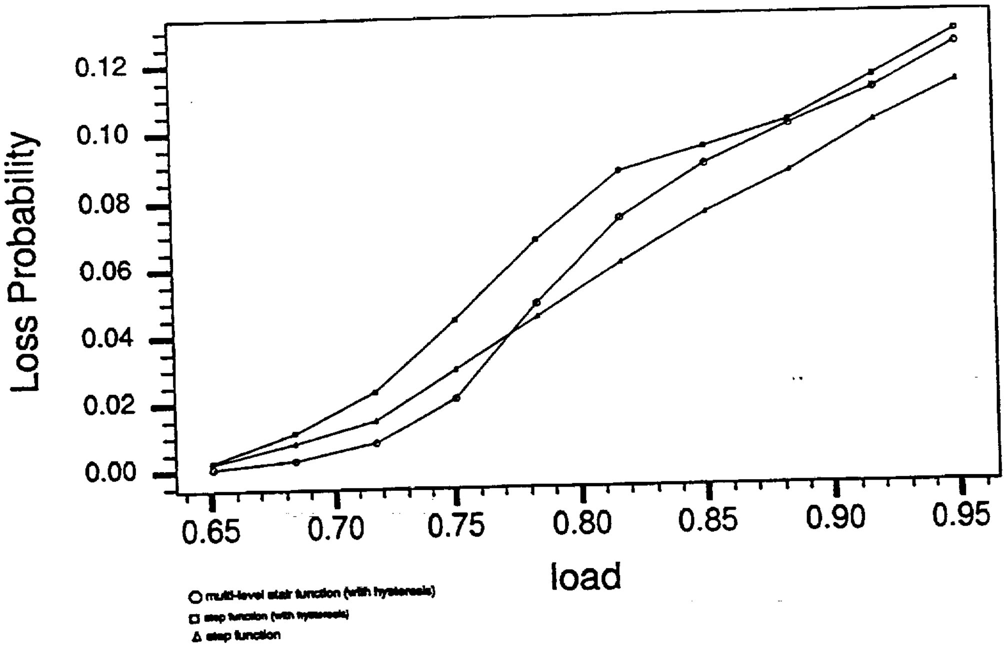


Figure 13. The Effect of the Averaging Period

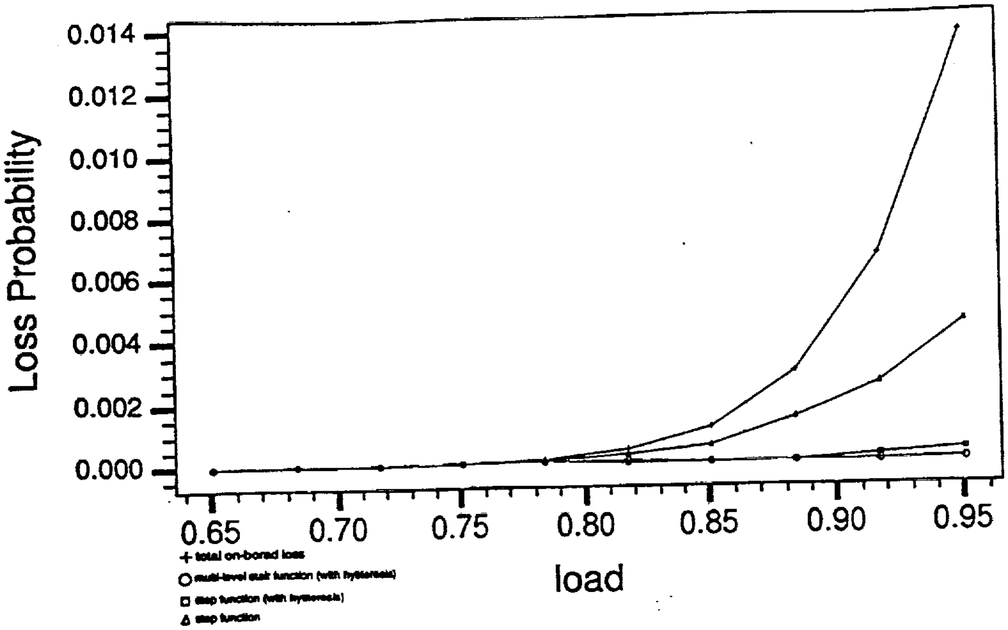


(a). On-board Loss Probability

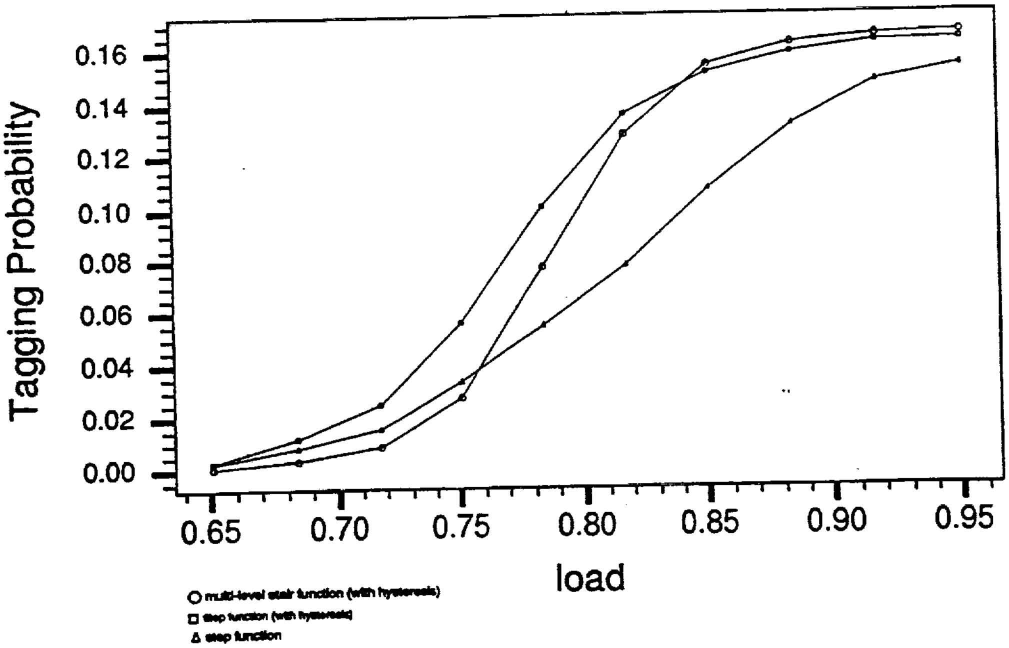


(b). Ground Loss Probability

Figure 14. The Effect of Reduction Function



(a). On-board Loss Probability for High-Priority Packets



(b). Ground Tagging Probability

Figure 15. The Effect of Tagging with Various "Tagging" Functions

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13. ABSTRACT ***(Maximum 200 words)***

NASA Lewis Research Center is currently investigating a satellite architecture that incorporates on-board packet switching capability. Because of the statistical nature of packet switching, arrival traffic may fluctuate and thus it is necessary to integrate congestion control mechanism as part of the on-board processing unit. This study focuses on the closed-loop reactive control. We investigate the impact of the long propagation delay on the performance and propose a scheme to overcome the problem. The scheme uses a global feedback signal to regulate the packet arrival rate of ground stations. In this scheme, the satellite continuously broadcasts the status of its output buffer and the ground stations respond by selectively discarding packets or by tagging the excessive packets as low-priority. The two schemes are evaluated by theoretical queuing analysis and simulation. The former is used to analyze the simplified model and to determine the basic trends and bounds, and the later is used to assess the performance of a more realistic system and to evaluate the effectiveness of more sophisticated control schemes. The results show that the long propagation delay makes the closed-loop congestion control less responsive. The broadcasted information can only be used to extract statistical information. The discarding scheme needs carefully-chosen status information and reduction function, and normally requires a significant amount of ground discarding to reduce the on-board packet loss probability. The tagging scheme is more effective since it tolerates more uncertainties and allows a larger margin of error in status information. It can protect the high-priority packets from excessive loss and fully utilize the downlink bandwidth at the same time.

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