Performance Evaluation of an Integrated Access Scheme in a Satellite Communication Channel[1]

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Performance Evaluation of an Integrated Access Scheme in a Satellite Communication Channel

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Abstract—**A method for realizing a circuit and packet integrated access scheme in a satellite communication channel is considered. Two kinds of terminals are assumed, namely, bursty terminals for handling bursty traffic and heavily loaded terminals for long-holding-time message traffic. In this method, the channel frame is divided into two subframes: one is for bursty terminals, and the other is for heavily loaded terminals. The subframe for heavily loaded terminals is further divided into two subchannels, a reservation subchannel (consisting of small slots) and a message subchannel. The bursty terminals transmit their packets in their dedicated subframes on the slotted ALOHA protocol. The heavily loaded terminal having a message transmits, first of all, a reservation packet in a randomly selected small slot of the reservation subchannel to reserve slots in the coming message subchannels. One slot in the same position of each of the succeeding message subchannels is reserved for the terminal until the end-of-use flag, transmitted from the terminal, is received by the satellite.**

Mean transmission delays for both kinds of traffic in this method are analytically obtained. We show that there exists an optimal frame length which minimizes mean transmission delay for one kind of traffic while keeping mean transmission delay for the other kind under some permissible value.

I. INTRODUCTION

THE satellite communication system offers flexible and homogeneous service to a large number of geographically spread users of various kinds because of its multiaccess capabilities, and hence, various multiple-access protocols for application in satellite communication channels, e.g., random access, demand assignments, fixed assignments, etc., have been presented and analyzed in recent years. In general, random access techniques (ALOHA protocols) can be said to give the best performance with bursty traffics. Demand assignments give better performance as the channel load increases. Fixed assignments are the best schemes for heavy loads. References [1]-[4] give clear and concise explanations of these protocols and show their relative performance characteristics through representation of the mean response time in each protocol as a function of the channel loads.

Most of the access protocols proposed are for homogeneous users, i.e., for users having the same traffic characteristics, and none of those but the PODA protocol is efficient for mixed traffic conditions. However, in most actual satellite communication networks, the traffic will have various characteristics according to different utilization forms. It would therefore be desirable for a satellite communication network to have an access scheme that could handle varying kinds of traffic [5]-[8]. With this view, we analyze the following integrated access scheme based upon both slotted ALOHA and packet reservation protocols.

We assume two kinds of terminals (i.e., computer terminals) in the satellite communication system, namely, bursty terminals for handling bursty data traffic, and heavily loaded terminals for long-holding-time message traffic or stream traffic (circuit-switched voice traffic). The former, for example, corresponds to the terminals operated by the interactive mode, and the latter to the terminals which transmit file, facsimile, digitized voice, and so on. In our integrated access scheme, the channel frame is divided into two subframes; one is for bursty terminals, which is used on a contention basis with the slotted ALOHA protocol, and the other is for heavily loaded terminals. The subframe for heavily loaded terminals is further divided into two subchannels, a reservation subchannel and a message subchannel. The reservation subchannel is for reservation packet transmissions on the slotted ALOHA basis to reserve slots in the coming message subchannels. If a reservation is successful once, one slot in the same position of each of the succeeding message subchannels is reserved for the terminal until an end-of-use flag is received by the satellite. The heavily loaded terminal can then use this slot in each of the succeeding message subchannels without contention until it transmits an end-of-use flag. For this reason, the channel for heavily loaded terminals will support traffic requiring transparency in the channel, for example, circuit-switched voice traffic. Furthermore, this scheme can avoid exclusive possession of the channel over a long period of time caused by one user having a long message. The satellite is assumed to have an on-bo...d processing capability and assigns slots to each successful reservation.

Mean transmission delays for both kinds of traffic in this integrated access scheme are analytically obtained. We show that there exists an optimal frame length which minimizes the mean transmission delay for one kind of traffic, while keeping the mean transmission delay for the other kind under some permissible value.

II. MODEL

The number of bursty and heavily loaded terminals are assumed to be finite, and are designated as N_B and N_H, respectively. At each bursty terminal, constant bit length packets (packet having a length equal to a fixed number of bits) are

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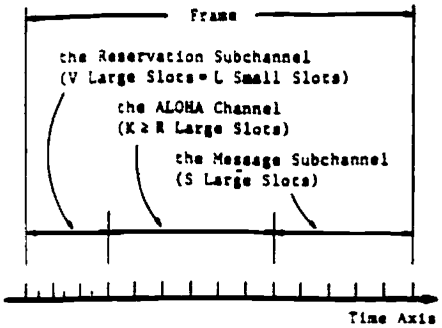

Fig. 1. Frame configuration.

assumed to arrive according to a Poisson distribution with parameter λ_B (packets/slot). At each heavily loaded terminal, messages generating a number of packets are assumed to arrive according to a Poisson distribution with parameter λ_H (messages/slot). The number of packets in a message is assumed to obey a geometric distribution with parameter q, that is, the probability that a message generates i packets is $(1-q)^{i-1}\cdot q$.

Our frame configuration is shown in Fig. 1. Channel time is divided into frames, and each frame consists of (large) time slots, the duration of which is equal to one data packet transmission time. It is assumed that all terminals are operated synchronously and that each terminal can transmit its packet only at the beginning of the time slot. The assigned time interval for the bursty terminals in each frame, the ALOHA channel, consists of constant K successive (large) time slots. The residual (large) time slots are for the heavily loaded terminals, and are partitioned into two subchannels, namely, a reservation subchannel and a message subchannel, each consisting of constant V and S (large) slots, respectively. V large slots in the reservation subchannel are further divided into L small slots, the duration of which is equal to the transmission time of a reservation packet. Here, K is assumed to be greater than or equal to a round trip propagation delay R (in large slots).

A bursty terminal having a packet (or packets) to transmit at the beginning of the ALOHA channel chooses one time slot from this time interval according to a uniform distribution, and transmits its packet in the selected slot. After a round-trip propagation delay R, the terminal will know whether its transmitted packet has been successfully received at its destination or not. If collision of the packet is detected, the packet will be retransmitted in the succeeding ALOHA channel, again according to a uniform distribution. The terminal will not begin transmission of the next packet until it knows that the previous packet has been successfully received by its destination. Each bursty terminal is assumed to have infinite buffer capacity for storing packets arriving while the terminal is in a transmission mode. Arriving packets are transmitted according to the first-come first-served discipline.

For the message transmission procedure at the heavily loaded terminals, the following contention-based reservation scheme is employed. A terminal divides an arriving message into constant bit length packets, the length of which is equal to that of a data packet arriving at the bursty terminals, and creates a reservation packet containing the identification of the terminal. A terminal having a message (or messages) to transmit at the beginning of the frame transmits, first of all, a reservation packet in a randomly selected one of L small slots in the reservation subchannel. The reservation is for acquiring time slots in the message subchannels for transmission of the message. Upon receiving the noncollided reservation packet, the satellite assigns a slot in the message subchannel for the terminal. If there are any nonreserved slots in the message subchannel, the satellite randomly assigns one of them to the originating terminal of the reservation packet. If all slots in the message subchannel are reserved, the reservation is rejected. The terminal is informed of the success or failure of the reservation by the control packet generated at the satellite. The length of the control packet is assumed to be equal to that of the reservation packet.

Once the reservation is successful, the slot in the same position in each of the coming message subchannels is reserved for the terminal. From the assumption that K is greater than or equal to a round-trip propagation delay R, the terminal will know whether the reservation of time slots was successful or not before the beginning of the message subchannel in the frame. In case of collision of the reservation packet at the up-link, or reservation failure at the satellite, the terminal retransmits the reservation packet in a randomly selected small slot in the next reservation subchannel. Here, we should notice that, in case of $K < R$, the terminal cannot know the position of the assigned slots before the beginning of the message subchannel. Therefore, some of the assigned slots will be kept empty until the terminal transmits the first message packet. This leads to inefficiency in the channel. This is the reason why we assume that $K \geq R$. With regard to buffer capacity at the heavily loaded terminals, we consider two cases, the case of infinite buffer capacity and the case of one message buffer capacity. In the infinite buffer capacity case, messages arriving at a terminal in a transmission mode are stored in its buffer, and are transmitted according to the first-come first-served discipline. Each terminal is assumed not to send the reservation packet for a newly arrived message until it has completely transmitted all the messages that have arrived previously. In the case of buffer capacity for only one message, a terminal will be "locked" for new message arrivals on the condition that a prior message at the terminal has not been transmitted, that is, the system in this case corresponds to the blocked calls cleared system.

Our satellite is assumed to have the on-board processing capability to interrogate the up-link reservation packet and to create the down-link control packet. Furthermore, processing time of this capability is assumed to be small enough to neglect in the following analysis.

In our scheme, bursty terminals are not allowed to use the excess capacity for heavily loaded terminals, even if it is not used, and vice versa. That is, our scheme is the so-called "fixed boundary" integrated access scheme. Bursty terminals, however, cannot know the usage status of the next message subchannel because of a long propagation delay between earth terminals and the satellite. It should be noticed that, hence, straightforward extension of our scheme to the "movable boundary" scheme is quite difficult.

In the following, the proposed scheme is analyzed and mean transmission delays are obtained.

III. ASSUMPTIONS

The following assumptions are made in our analysis.

Assumption 1: The terminal state independence assumption where the state of one terminal is independent of the state of the other terminals.

Assumption 2: The stationary assumption where the system has a stationary probability distribution.

In the following analysis, we take one large slot duration as the unit time; hence, transmission delays to be obtained are in number of large slots.

IV. ANALYSIS FOR BURSTY TERMINALS

Mean packet transmission delay D_B for bursty terminals is defined here as the time interval from when a data packet arrives at a terminal until it is successfully received at its destination, which interval includes not only the time required for packet transmission but also waiting time in a terminal buffer. The probability S_B of successful transmission of a data packet is necessary to obtain this D_B, and is considered in the next subsection.

A. Probability of Successful Transmission

Here the notation S_B is defined as the probability of successful transmission of a data packet given that a bursty terminal has transmitted a data packet.

We first consider the case $S + V \geqslant R$. In this case, all the terminals that have transmitted their packets in the previous ALOHA channel can know whether the transmission was successful or not before the beginning time of the next ALOHA channel. Therefore, each terminal accesses to a slot in the ALOHA channel with probability $1/K$ when it has one or more packets to transmit. From this fact and Assumption 1, S_B is expressed as follows.

$$S_B = \sum_{i=0}^{N_B-1}\left[{}_{N_B-1}C_i\rho_B{}^i(1-\rho_B)^{N_B-1-i}\cdot\left(1-\frac{1}{K}\right)^i 1^{N_B-1-i}\right] = \left(1-\frac{\rho_B}{K}\right)^{N_B-1} \quad (1)$$

where ρ_B is the utilization factor at each bursty terminal, that is, $\rho_B = \lambda_B \cdot E[X_B]$, where $E[X_B]$ is the mean packet service time to be obtained in the next subsection.

Next we consider the case $S + V < R$. Here, the time interval between two successive ALOHA channels is smaller than the round-trip propagation delay R. Therefore, some terminals will not know whether their data packet transmissions have been successful or not at the beginning time of the next ALOHA channel. This means that there are some terminals which will not access to the time slots in the ALOHA channel, even if they have packets to transmit. This fact makes the analysis quite difficult; hence, the following assumption is employed in the analysis.

Assumption 3: Every terminal is assumed to access to a slot in the ALOHA channel with probability $1/K$ when it has one or more packets to transmit at the beginning of the ALOHA channel.

Under this assumption, it is easy to see that S_B in this case is expressed by (1). Furthermore, it should be noticed that, in the case of $S + V < R$, S_B obtained by (1) gives the lower bound, and the mean packet transmission delay to be obtained in the following gives the upper bound.

In the next subsection, mean service time of a data packet is expressed as a function of S_B.

B. Mean Packet Service Time

With regard to a packet arriving at an idle terminal, the service time of that packet $X_B{}^I$ is defined to be the time interval from its arrival to the end of its transmission (i.e., time instant when the packet is successfully received by its destination). For a packet arriving at a terminal in the transmission mode, its service time $X_B{}^T$ is defined to be the time interval from the end of transmission of the prior packet in the terminal buffer to the end of its own transmission.

We consider the service time $X_B{}^I$. The service time $X_B{}^I$ consists of the following three time intervals (see Fig. 2).

1) Time interval from its arrival to the beginning of the ALOHA channel (α).
2) Time interval required for retransmissions (β).
3) Time interval required for a successful transmission (γ).

Therefore, we have

$$X_B{}^I = \alpha + \beta + \gamma. \quad (2)$$

Because α, β, and γ are independent, the mean and second moment of $X_B{}^I$ become

$$E[X_B{}^I] = E[\alpha] + E[\beta] + E[\gamma] \quad (3)$$

$$E[(X_B{}^I)^2] = E[\alpha^2] + E[\beta^2] + E[\gamma^2] + 2\cdot(E[\alpha]\cdot E[\beta] + E[\beta]\cdot E[\gamma] + E[\gamma]\cdot E[\alpha]). \quad (4)$$

The mean and second moment of each term [illegible] the above equations are obtained as follows. Because [illegible]. Poisson arrival stream of new packets, the mean and second moment of the random variable α become [9].

$$E[\alpha] = (V + K - S)/2 \quad (5)$$

$$E[\alpha^2] = (V + K + S)^2/3. \quad (6)$$

The probability P_A that the acknowledgment of the packet transmitted in the previous ALOHA channel is received before the beginning of the next ALOHA channel becomes

$$P_A \begin{cases} = (S + V + K - R)/K & (S + V < R) \\ = 1 & (S + V \geqslant R) \end{cases} \quad (7)$$

Using this, and noting that the probability of a packet requiring exactly i retransmissions to be successfully received is S_B

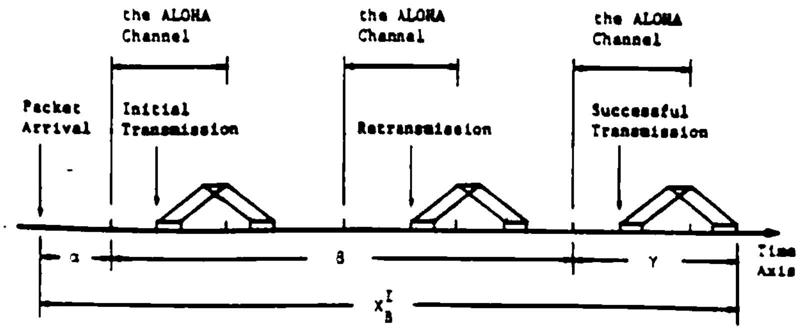

Fig. 2. Packet service time $X_B{}^I$.

$(1 - S_B)^i$, the mean and second moment of β become

$$E[\beta] = \sum_{i=0}^{\infty} \left\{ \sum_{j=0}^{i} {}_iC_j P_A{}^j (1 - P_A)^{i-j} \cdot [j \cdot (V+K+S) + (i-j) \cdot 2(V+K+S)] \right\} \cdot (1 - S_B)^i S_B = (2 - P_A)(V+K+S)(1 - S_B)/S_B \quad (8)$$

$$E[\beta^2] = \sum_{i=0}^{\infty} \left\{ \sum_{j=0}^{i} {}_iC_j P_A{}^j (1 - P_A)^{i-j} \cdot [j \cdot (V+K+S) + (1-j) \cdot 2(V+K+S)]^2 \right\} \cdot (1 - S_B)^i S_B = (V+K+S)^2 (P_A - 2)^2 (1 - S_B)(2 - S_B)/(S_B{}^2) + (V+K+S)^2 P_A (1 - P_A)(1 - S_B)/S_B. \quad (9)$$

Packet transmission occurs in a randomly selected slot of K slots in the ALOHA channel, and it takes a round-trip propagation delay R for the transmitted packet to reach the destination. Hence, the mean and second moment of γ become

$$E[\gamma] = \sum_{i=0}^{K-1} (i + R + 1) \cdot \frac{1}{K} = (K-1)/2 + R + 1 \quad (10)$$

$$E[\gamma^2] = \sum_{i=0}^{K-1} (i + R + 1)^2 \cdot \frac{1}{K} = \frac{(K-1)(2K-1)}{6} + (R+1)(K-1) + (R+1)^2. \quad (11)$$

On the other hand, the service time $X_B{}^T$ consists of the following three time intervals.

1) Time interval from the end of transmission of the last packet in the terminal buffer to the beginning of its own transmission (δ).
2) Time interval required for retransmissions (β).
3) Time interval required for a successful transmission (γ).

Therefore, we have

$$X_B{}^T = \delta + \beta + \gamma \quad (12)$$

Because δ, β, and γ are independent, the mean and second moment of $X_B{}^T$ become

$$E[X_B{}^T] = E[\delta] + E[\beta] + E[\gamma] \quad (13)$$

$$E[(X_B{}^T)^2] = E[\delta^2] + E[\beta^2] + E[\gamma^2] + 2(E[\delta] \cdot E[\beta] + E[\beta] \cdot E[\gamma] + E[\gamma] \cdot E[\delta]). \quad (14)$$

Noting the fact that the random variable δ becomes

$$\delta = P_A \cdot [(V+K+S) - \gamma] + (1 - P_A)[2(V+K+S) - \gamma] = (2 - P_A)(V+K+S) - \gamma, \quad (15)$$

the mean and second moment of δ are given by

$$E[\delta] = (2 - P_A)(V+K+S) - E[\gamma] \quad (16)$$

$$E[\delta^2] = (2 - P_A)^2 \cdot (V+K+S)^2 - 2 \cdot (2 - P_A) \cdot (V+K+S) \cdot E[\gamma] + E[\gamma^2]. \quad (17)$$

Substituting (16) and (17) into (13) and (14), we have

$$E[X_B{}^T] = E[\beta] + (2 - P_A)(V+K+S) \quad (18)$$

$$E[X_B{}^T)^2] = E[\beta^2] + 2(2 - P_A)(V+K+S) \cdot E[\beta] + (2 - P_A)^2 (V+K+S)^2 + 2 \cdot E[\gamma^2] - 2 \cdot E[\gamma]^2 \quad (19)$$

where $E[\beta]$ and $E[\beta^2]$ are given by (8) and (9), respectively, and $E[\gamma]$, $E[\gamma^2]$ by (10) and (11).

Finally, considering the fact that the probability of a terminal being in a transmission mode is ρ_B, the mean $E[X_B]$ of the packet service time X_B becomes as follows.

$$E[X_B] = (1 - \rho_B) \cdot E[X_B{}^I] + \rho_B \cdot E[X_B{}^T]. \quad (20)$$

Substituting (3) and (18) into the above equations, using the relation $\rho_B = \lambda_B \cdot E[X_B]$, and solving the equation with respect to S_B, we finally have

$$S_B = \frac{(2-P_A)(V+K+S)}{\left\{\begin{array}{l}\left[\left[\frac{1}{\lambda_B}+(P_A-\frac{3}{2})(V+K+S)+\left(\frac{K-1}{2}+R+1\right)\right]\cdot \rho_B\right. \\ \left. -\left[\left(\frac{K-1}{2}+R+1\right)+(P_A-\frac{3}{2})(V+K+S)\right]\right.\end{array}\right\}} \quad (21)$$

From (1) and (21), the following equation, with respect to ρ_B, must hold.

$$\left(1-\frac{\rho_B}{K}\right)^{N_B-1} = \text{the right-hand side of (21).} \quad (22)$$

In solving (22) to obtain the value of the utilization factor ρ_B, the steady-state condition for this system must be considered. The terminal in a transmission mode accesses to a slot in the ALOHA channel with probability $1/K$. Hence, the total access rate to a slot by all terminals G is

$$G = N_B \cdot \rho_B \cdot \frac{1}{K}. \quad (23)$$

Total access rate G must be less than one for this system to have the steady state. Thus, the following condition must be satisfied.

$$N_B \cdot \rho_B \cdot \frac{1}{K} < 1. \quad (24)$$

C. Mean Packet Transmission Delay

Each bursty terminal can be considered to be the following generalized $M/G/1$ queueing system. Packets arrive at a terminal according to a Poisson distribution with parameter λ_B. If a packet arrives when the terminal is in a transmission mode, its service time has mean $E[X_B^T]$ and second moment $E[(X_B^T)^2]$; while, if a packet arrives when the terminal has no packet to transmit, it has a service time with a different mean $E[X_B^I]$ and a different second moment $E[(X_B^I)^2]$. In [10], analysis was made of a queueing system where the customer who initiates a busy period has a service time distribution function different from that of customers who do not initiate a busy period. Using his results, the mean packet transmission delay D_B, that is, the mean time from a packet arrival instant to the end of its transmission, becomes as follows.

$$D_B = \frac{E[X_B^I]}{1-\lambda_B(E[X_B^T]-E[X_B^I])} + \frac{\lambda_B \cdot E[(X_B^T)^2]}{2\cdot(1-\lambda_B\cdot E[X_B^T])} + \frac{\lambda_B\cdot[E[(X_B^I)^2]-E[(X_B^T)^2]]}{2\cdot[1-\lambda_B\cdot(E[X_B^T]-E[X_B^I])]} \quad (25)$$

Through this analysis we can obtain the mean packet transmission delay D_B by the following procedure.

1) Assume that the values of λ_B, R, N_B, K, V, and S are given.
2) Solve (22) with respect to ρ_B and obtain the value of ρ_B which satisfies condition (24).
3) Calculate the value of S_B by (1).
4) Calculate the values of $E[X_B^I]$, $E[(X_B^I)^2]$, $E[X_B^T]$, and $E[(X_B^T)^2]$ by (3), (4), (18), and (19), respectively.
5) Calculate the value of D_B by (25).

V. ANALYSIS FOR HEAVILY LOADED TERMINALS—INFINITE BUFFER CAPACITY CASE

Heavily loaded terminals with infinite buffer capacity for arriving messages are analyzed and the mean message transmission delay at each heavily loaded terminal is considered. Mean message transmission delay D_H is defined as the time interval from when a message arrives at the terminal until it is completely received by the destination, that is, when the last packet in the message is received by the destination. This interval includes waiting time in the terminal buffer.

The equilibrium equation for the system is derived in the next subsection to obtain the mean message transmission delay D_H.

A. Equilibrium Equation

The steady-state behavior of the system at the time epochs of the frame beginning is analyzed, and the equilibrium equation for the system is derived.

At first we define the following notations. Let

- S_H: probability that a reservation packet does not suffer collision at the up-link given that it has been transmitted.
- π_i: probability that there are i reserved (busy) slots in the message subchannel at the beginning of the frame.
- P_i: probability of i arrivals of noncollided reservation packets in a frame (i.e., in the reservation subchannel interval).
- $q_{k,j}$: probability of j busy slots in the message subchannel at the end of the message subchannel given that there were k present at the beginning of the message subchannel, that is, probability that $k-j$ end-of-use flags are found in the message subchannel.

Here we employ the following assumption.

Assumption 4: A terminal is assumed to transmit, with probability P, a reservation packet in a small slot in the reservation subchannel.

Then we have

$$S_H = (1-P)^{N_H-1}. \quad (26)$$

Noting the fact that there are L small slots in the reservation subchannel, and using Assumption 4, the probability P_i of

i noncollided reservation arrivals becomes

$$P_i \begin{cases} = {}_LC_i \cdot (1 - N_H \cdot P \cdot S_H)^{L-i} \cdot (N_H \cdot P \cdot S_H)^i & (\text{if } i \leq L) \\ = 0 & (\text{if } i \geq L + 1). \end{cases} \quad (27)$$

Furthermore, since message length is assumed to obey a geometric distribution with parameter q, the probability $q_{k,j}$ becomes

$$q_{k,j} \begin{cases} = {}_kC_j \cdot q^{k-j}(1-q)^j & (\text{if } j \leq k) \\ = 0 & (\text{if } j \geq k + 1). \end{cases} \quad (28)$$

Using the above probabilities, probability transition matrix $(P_{i,j})$ for the system becomes

$$P_{i,j} \begin{cases} = \sum_{k=\max(i,j)}^{A} [q_{k,j} \cdot P_{k-i}] + q_{S,j} \sum_{k=S-i}^{L} P_k & (\text{if } i \leq S-1, j \leq S) \\ = q_{S,j} & (\text{if } i = S, j \leq S) \\ = 0 & (\text{otherwise}) \end{cases} \quad (29)$$

where notation A is given by

$$A \begin{cases} = S - 1 & (\text{if } L \geq S) \\ = L + i & (\text{if } L \leq S - 1, i \leq S - L - 1) \\ = S - 1 & (\text{if } L \leq S - 1, i \geq S - L). \end{cases} \quad (30)$$

In (29) and the following, notation of summation Σ_a^b has meaning only if $a \leq b$. (If $a > b$, the term is assumed to be zero.) Finally, the equilibrium equation becomes

$$\pi_j = \sum_{i=0}^{S} \pi_i \cdot P_{i,j} \qquad (j = 0, 1, 2, \cdots, S) \quad (31)$$

where

$$\pi_j > 0 \qquad \text{for all } j$$

and

$$\sum_{j=0}^{S} \pi_j = 1. \quad (32)$$

Note that (31) has degenerate solution $\pi_j = 0$ for all j. To avoid this we drop one of the equations given in (31) and add a normalizing equation (32). This results in a set of $S + 1$ linear equations in $S + 1$ unknowns; standard computer packages can be used to solve these equations.

In solving the equilibrium equation, we have to consider the steady-state condition. The mean number of successfully transmitted messages per frame, that is, the mean number of messages leaving the system, M, is given by the following.

$$M \begin{cases} = \sum_{k=0}^{S-1} \left\{ \sum_{j=0}^{k} \left[(\pi_j \cdot P_{k-j}) \cdot \left(\sum_{i=0}^{k} i \cdot q_{k,k-i} \right) \right] \right\} \\ \quad + \sum_{j=0}^{S} \left[\left(\pi_j \sum_{i=S-j}^{L} P_i \right) \cdot \left(\sum_{i=0}^{S} i \cdot q_{S,S-i} \right) \right] & (\text{if } L \geq S) \\ = \sum_{k=0}^{L-1} \left\{ \sum_{j=0}^{k} \left[(\pi_j \cdot P_{k-j}) \cdot \left(\sum_{i=0}^{k} i \cdot q_{k,k-i} \right) \right] \right\} \\ \quad + \sum_{k=L}^{S-1} \left\{ \sum_{j=k-L}^{k} \left[(\pi_j \cdot P_{k-j}) \cdot \left(\sum_{i=0}^{k} i \cdot q_{k,k-i} \right) \right] \right\} \\ \quad + \sum_{j=0}^{S} \left[\left(\pi_j \sum_{i=S-j}^{L} P_i \right) \cdot \left(\sum_{i=0}^{S} i \cdot q_{S,S-i} \right) \right] & (\text{if } L \leq S - 1). \end{cases} \quad (33)$$

Since the mean number of arriving messages to all terminals per frame is $N_H \cdot \lambda_H \cdot (V + K + S)$, we have the following steady-state condition.

$$M = N_H \cdot \lambda_H \cdot (V + K + S). \quad (34)$$

The blocking probability PB at the satellite for noncollided reservations is now easily determined. The mean number ESR of successful reservation per frame is given by

$$\text{ESR} \begin{cases} = \sum_{j=0}^{S-2} \pi_j \left[\sum_{k=1}^{S-j-1} k \cdot P_k + (S-j)\left(1 - \sum_{k=0}^{S-j-1} P_k\right) \right] \\ \quad + \pi_{S-1} \cdot (1 - P_0) & (\text{if } L \geq S) \\ = \sum_{j=0}^{S-L-1} \pi_j \left[\sum_{k=1}^{L-1} k \cdot P_k + L \cdot \left(1 - \sum_{k=0}^{L-1} P_k\right) \right] \\ \quad + \sum_{j=S-L}^{S-2} \pi_j \left[\sum_{k=1}^{S-j-1} k \cdot P_k + (S-j)\left(1 - \sum_{k=0}^{S-j-1} P_k\right) \right] \\ \quad + \pi_{S-1} \cdot (1 - P_0) & (\text{if } L \leq S - 1). \end{cases} \quad (35)$$

The mean number of noncollided reservation arrivals per frame is $\Sigma_{i=0}^{L} i \cdot P_i$, and so PB is given by

$$\text{PB} = 1 - \text{ESR} / \left(\sum_{i=0}^{L} i \cdot P_i \right) = 1 - \text{ESR}/(N_H \cdot P \cdot S_H \cdot L). \quad (36)$$

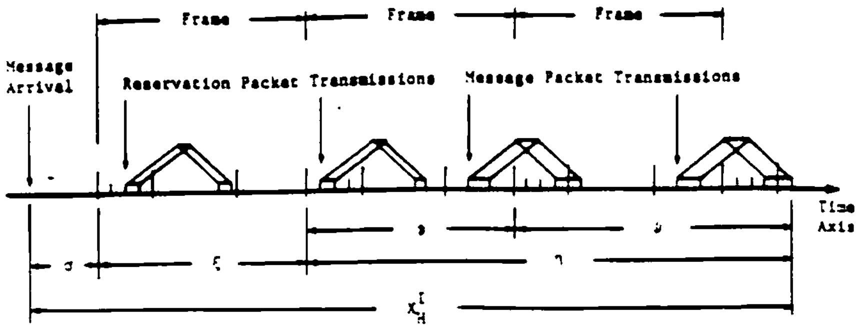

Fig. 3. Message service time $X_H{}^I$.

B. Mean Message Transmission Delay

Similar consideration to the bursty terminals leads us to consider each heavily loaded terminal as the generalized $M/G/1$ queueing system mentioned in Subsection IV-C.

The service time for a message arriving at the idle terminal $X_H{}^I$ is defined as the time interval from its arrival to the time instant when the last packet in the message is completely received by its destination (i.e., the end of its transmission). $X_H{}^I$ consists of the following three time intervals (see Fig. 3):

1) time interval from the message arrival to the beginning of the succeeding frame (σ),
2) time interval required for establishing reservation (ξ), and
3) time interval required for message transmission (η).

Since a Poisson arrival stream of new messages is assumed, random variable σ has the same mean and second moment that random variable α (defined in Section IV-B) has. Noting the fact that the probability $P_{Re}(i)$, which is defined as the probability of the reservation packet requiring exactly i retransmissions to establish reservation, is given by

$$P_{Re}(i) = \sum_{k=0}^{i} {}_iC_k(S_H \cdot \mathrm{PB})^k \cdot (1-S_H)^{i-k} \cdot S_H \cdot (1-\mathrm{PB})$$
$$= [1 - S_H \cdot (1-\mathrm{PB})]^i \cdot S_H \cdot (1-\mathrm{PB}), \tag{37}$$

mean $E[\xi]$ and second monent $E[\xi^2]$ of random variable ξ become

$$E[\xi] = \sum_{i=0}^{\infty} i \cdot (V+K+S) \cdot P_{Re}(i)$$
$$= (V+K+S) \cdot \frac{1 - S_H \cdot (1-\mathrm{PB})}{S_H \cdot (1-\mathrm{PB})} \tag{38}$$

$$E[\xi^2] = \sum_{i=0}^{\infty} [i \cdot (V+K+S)]^2 \cdot P_{Re}(i)$$
$$= (V+K+S)^2 \cdot \frac{[1 - S_H \cdot (1-\mathrm{PB})] \cdot [2 - S_H \cdot (1-\mathrm{PB})]}{[S_H \cdot (1-\mathrm{BP})]^2} \tag{39}$$

Random variable η consists of the following two time intervals (see Fig. 3):

1) time interval required for transmitting all packets except the last one in the message (ϕ) and
2) time interval required for transmitting the last packet in the message (ψ).

Means and second moments of the above terms are given by the following.

$$E[\phi] = \sum_{i=1}^{\infty} [(i-1) \cdot (V+K+S)] \cdot (1-q)^{i-1} \cdot q$$
$$= (V+K+S) \cdot (1-q)/q \tag{40}$$

$$E[\phi^2] = \sum_{i=1}^{\infty} [(i-1) \cdot (V+K+S)]^2 \cdot (1-q)^{i-1} \cdot q$$
$$= (V+K+S)^2 \cdot \frac{(1-q) \cdot (2-q)}{q^2} \tag{41}$$

$$E[\psi] = \sum_{i=0}^{S-1} (V+K+i+1+R) \cdot \frac{1}{S}$$
$$= V + K + \frac{S-1}{2} + 1 + R \tag{42}$$

$$E[\psi^2] = \sum_{i=0}^{S-1} (V+K+i+1+R)^2 \cdot \frac{1}{S}$$
$$= (V+K+1+R)^2 + (V+K+1+R) \cdot (S-1) + \frac{(S-1) \cdot (2S-1)}{6}. \tag{43}$$

From (40)-(43), the mean and second moment of η are given by

$$E[\eta] = E[\phi] + E[\psi] \tag{44}$$

$$E[\eta^2] = E[\phi^2] + 2 \cdot E[\phi] \cdot E[\psi] + E[\psi^2]. \tag{45}$$

From the above discussion, the mean and second moment of $X_H{}^I$ become

$$E[X_H{}^I] = E[\sigma] + E[\xi] + E[\eta] \tag{46}$$

$$E[(X_H^I)^2] = E[\sigma^2] + E[\xi^2] + E[\eta^2] + 2\cdot(E[\sigma]\cdot E[\xi] + E[\xi]E[\eta] + E[\eta]\cdot E[\sigma]). \tag{47}$$

Next we consider the service time of a message arriving at the terminal in a transmission mode X_H^T, which is defined as the time interval from the end of transmission of the last message to the end of its own transmission. This service time X_H^T consists of the following three time intervals:

1) time interval from the end of transmission of the last message to the beginning of the succeeding frame (ζ),
2) time interval required for establishing reservation, which has been denoted by ξ, and
3) time interval required for message transmission, which has been denoted by η.

The mean and second moment of ζ are given by

$$E[\zeta] = \sum_{i=0}^{S-R-1} [(V+K+S)-(V+K+i+1+R)]\cdot\frac{1}{S} + \sum_{i=S-R}^{S}[2\cdot(V+K+S) - (V+K+i+1+R)]\frac{1}{S} = \frac{(S-R)\cdot(S-R-1)}{2S} + \frac{(R+1)}{S}\left(V+K+S-1-\frac{R}{2}\right) \tag{48}$$

$$E[\zeta^2] = \sum_{i=0}^{S-R-1}[(V+K+S) - (V+K+i+1+R)]^2\cdot\frac{1}{S} + \sum_{i=S-R}^{S}[2\cdot(V+K+S) - (V+K+i+1+R)]^2\cdot\frac{1}{S} = \frac{1}{6S}\cdot(S-R-1)\cdot(S-R)\cdot(2S-2R-1) + \frac{R+1}{S}\cdot\left[(V+K+S-1)^2 - (V+K+S-1)R + \frac{R\cdot(2R+1)}{6}\right]. \tag{49}$$

Therefore, the mean and second moment of X_H^T are given by

$$E[X_H^T] = E[\zeta] + E[\xi] + E[\eta] \tag{50}$$

$$E[(X_H^T)^2] = E[\zeta^2] + E[\xi^2] + E[\eta^2] + 2\cdot(E[\zeta]\cdot E[\xi] + E[\xi]\cdot E[\eta] + E[\eta]\cdot E[\zeta]). \tag{51}$$

Finally, the mean message transmission delay is given by (25). (Of course, the right lower subscript H has to be substituted for the subscript B.)

Through this analysis we can obtain the mean message transmission delay D_H by the following procedure.

1) Assume that the values of λ_H, q, R, N_H, K, V, S, and L are given.
2) Set the initial value of the access probability P.
3) Calculate the value of S_H by (26).
4) Calculate the values of P_i and $q_{k,j}$ by (27) and (28), respectively.
5) Calculate the values of transition probabilities $P_{i,j}$ by (29).
6) Solve the equilibrium equation (31) with respect to π_js.
7) Calculate the value of M by (33), and check whether the steady-state condition (34) is satisfied or not. If the condition is satisfied, go to step (8). Otherwise, change the value of P and return to step 3).
8) Calculate the value of the blocking probability PB by (36).
9) Calculate the values of $E[X_H^I]$, $E[(X_H^I)^2]$, $E[X_H^T]$, and $E[(X_H^T)^2]$ by (46), (47), (50), and (51), respectively.
10) Calculate the value of the mean message transmission delay D_H by the formula in the generalized $M/G/1$ queueing theory mentioned in Subsection IV-C.

VI. ANALYSIS FOR HEAVILY LOADED TERMINALS–BLOCKED CALLS CLEARED CASE

Analysis is made of the heavily loaded terminals with buffer capacity for only one message, and the call blocking probability and the mean line setup delay are considered in this section.

We first consider the blocking probability for arriving messages P_{BC}. Newly arriving messages are assumed to be generated according to a Poisson distribution with parameter λ_H, but only those finding the terminal empty will be allowed entry into the system. Hence, actual arrival rate to the terminal is $\lambda_H(1 - P_{BC})$. Furthermore, the message service time in this case is equal to X_H^I, which is defined in Section IV-B. Thus, we have

$$\lambda_H\cdot(1-P_{BC})\cdot E[X_H^I] = P_{BC}. \tag{52}$$

Solving the above equation with respect to P_{BC}, we have

$$P_{BC} = \frac{\lambda_H\cdot E[X_H^I]}{1+\lambda_H\cdot E[X_H^I]} \tag{53}$$

where $E[X_H^I]$ is given by (46).

Next, we consider the line setup delay, which is defined as the time interval from the message arrival to the time instant when the first packet in the message has begun to be transmitted. The line setup delay consists of the following thr time intervals:

1) time interval from the message arrival to the beginning of the succeeding frame, which has been denoted by σ in Section IV-B,
2) time interval required for establishing reservation, which has been denoted by ξ, and

3) time interval from when the terminal established reservation until the terminal begins transmission of the first packet in the message (θ).

Mean of the random variable θ becomes

$$E[\theta] = \sum_{i=0}^{S-1} (V + K + i) \cdot \frac{1}{S} = V + K + \frac{S-1}{2}. \tag{54}$$

Therefore, the mean line setup delay D_S is given by

$$D_S = E[\sigma] + E[\xi] + E[\theta] \tag{55}$$

where $E[\theta]$ is given by (54), and $E[\sigma]$ and $E[\xi]$ have already been obtained in Section IV-B.

The terms in (53) and (55) being the functions of S_H and PB, we have to know the values of S_H and PB to obtain D_S and P_{BC}. These values, S_H and PB, can be obtained by solving equilibrium equation (31), which is valid for this blocked calls cleared system. In solving the equilibrium equation, the steady-state condition must be considered. As mentioned above, the actual arrival rate to a terminal is $\lambda_H(1 - P_{BC})$. Therefore, the steady-state condition becomes

$$M = N_H \cdot \lambda_H \cdot (1 - P_{BC}) \cdot (V + K + S) \tag{56}$$

where M is given by (33).

D_S and P_{BC} are obtained by the following procedures.

1) Assume that the values of λ_H, q, R, N_H, K, V, S, and L are given.
2) Set the initial value of P.
3) Calculate the value of S_H by (26).
4) Solve the equilibrium equation (31) with respect to π_js.
5) Calculate the value of M by (33).
6) Calculate the values of $E[X_H{}^l]$ and P_{BC} by (46) and (53), respectively.
7) Check whether the steady-state condition (56) is satisfied or not. If satisfied, go to step 8). Otherwise, change the value of P and return to step 3).
8) Calculate the values of S_H and PB by (26) and (36), respectively.
9) Calculate the values of P_{BC} and D_S by (53) and (55), respectively.

VII. NUMERICAL RESULTS

In all of the following numerical examples, the parameters R, N_B, N_H, and q are set to be 12 (large slots), 120 (terminals), 50 (terminals), and 0.1 (hence, the mean message length is 10 packets/message), respectively. Furthermore, one large slot in the reservation subchannel is divided into 5 small slots.

A. Infinite Buffer Capacity Case

Here, we consider the case of heavily loaded terminals with infinite buffer capacities, and show that there exists an optimal frame length, that is, optimal values of S, V, and K, which minimize the mean transmission delay for one kind of traffic, ... mean transmission delay for the other kind under ... The proposed scheme is compared ...

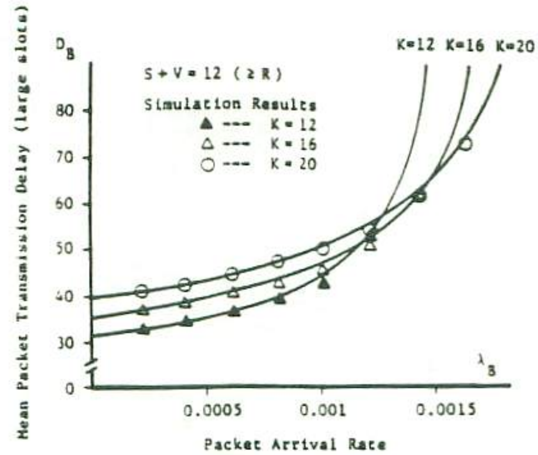

Fig. 4. Mean packet transmission delay ($S + V \geq R$).

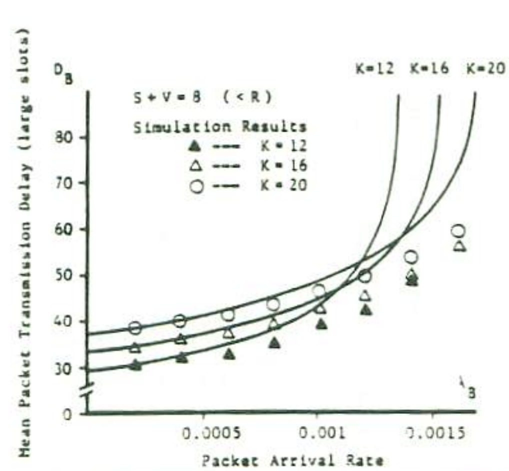

Fig. 5. Mean packet transmission delay ($S + V < R$).

Figs. 4 and 5 show the mean packet transmission delay D_B as a function of λ_B for fixed values of K. The value of $S + V$ is 12 ($\geq R$) in Fig. 4, and 8 ($< R$) in Fig. 5, respectively. Fig. 6 shows the mean message tranmission delay D_H as a function of λ_H for fixed values of S. In Fig. 6 the values of K and V are 12 and 2, respectively. The theoretical results are well verified by the simulation points shown in these figures. From Fig. 4 it can be seen that, in a low traffic case, the mean packet transmission delay D_B becomes smaller as the value of K decreases. However, the system with the smaller K becomes saturated more easily as the traffic increases. This is because collisions of packets easily lead to instability in the system with the smaller K. A similar tendency can be seen in Fig. 6. Fig. 5 shows that approximate analysis in the case where $S + V < R$ gives the upper bound of the mean packet transmission delay.

In what follows, we show that there exists optimal values of S, V, and K which minimize D_H, keeping D_B under a given constant, say $D_B{}'$.

Fig. 7 shows D_B as a function of K for fixed values of λ_B. The frame length in this figure is 26 (slots). This figure shows the values of K which satisfy the condition $D_B \leq D_B{}'$. For example, the value of K must be greater than or equal to 18 in order to satisfy the condition $D_B \leq 74$, when the frame length is equal to 26 and λ_B is 0.0016.

Fig. 8 shows D_H as a function of V for fixed values of λ_H. In this figure, the frame length and the value of K, hence the value of $S + V$, are taken as constants, and are equal to 26, 18,

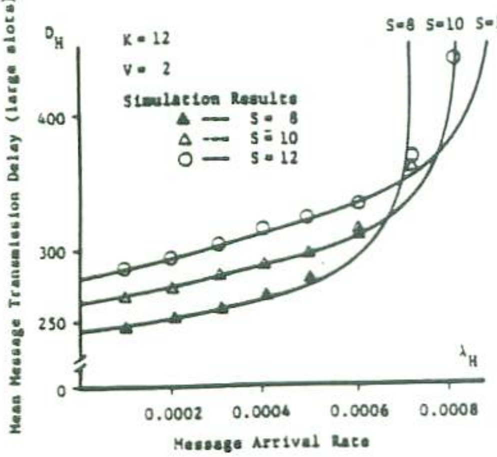

Fig. 6. Mean message transmission delay.

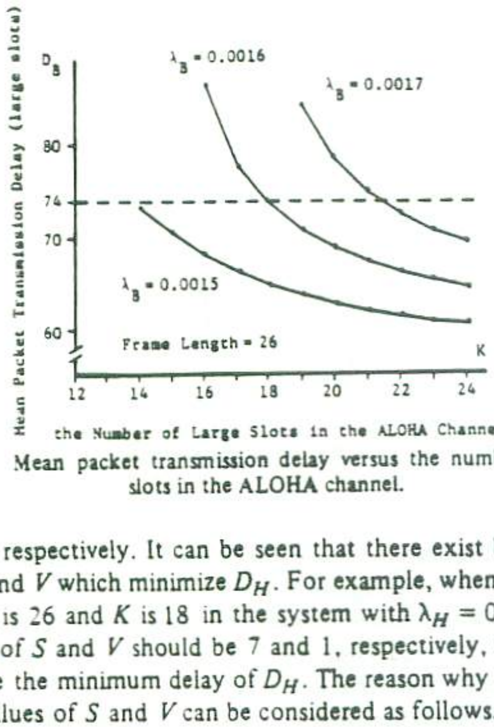

Fig. 7. Mean packet transmission delay versus the number of large slots in the ALOHA channel.

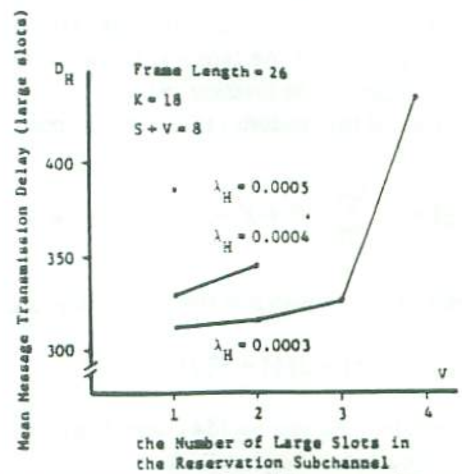

Fig. 8. Mean message transmission delay versus the number of large slots in the reservation subchannel.

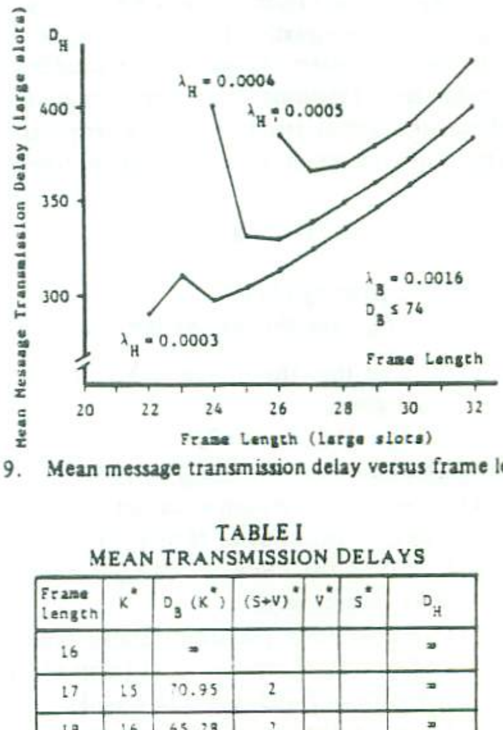

Fig. 9. Mean message transmission delay versus frame length.

and 8, respectively. It can be seen that there exist best values of S and V which minimize D_H. For example, when the frame length is 26 and K is 18 in the system with $\lambda_H = 0.0004$, the values of S and V should be 7 and 1, respectively, in order to achieve the minimum delay of D_H. The reason why there exist best values of S and V can be considered as follows. The number of collisions of a reservation packet, with resultant retransmissions, will increase as the value of $S(V)$ increases (decreases); the blocking probability of a reservation packet at the satellite, however, will decrease.

From the above numerical examples we have shown that, when the frame length is given, there exist best values of S, V, and K which minimize D_H, satisfying the condition $D_B \leqslant D_B'$. In the following, we designate these best values of S, V, and K as S^*, V^*, and K^*, respectively.

Fig. 9 shows D_H as a function of the frame length for fixed values of λ_H. Fig. 9 and Table I are for the system with $\lambda_B = 0.0016$ and with the condition $D_B \leqslant 74$. In this figure, the values of S, V, and K are taken as best values mentioned above for each value of the frame length. Table I shows these best values of S^*, V^*, and K^*, and furthermore, corresponding values of D_H and D_B for each value of the frame length. In this table, the value of λ_H is 0.0004. It is shown that there exists an optimal frame length which minimizes D_H. For example, when the system with $\lambda_H = 0.0004$ and $\lambda_B = 0.0016$ is

TABLE I
MEAN TRANSMISSION DELAYS

Frame Length	K^*	$D_B(K^*)$	$(S+V)^*$	V^*	S^*	D_H
16		∞				∞
17	15	70.95	2			∞
18	16	65.28	2			∞
19	16	69.31	3			∞
20	17	66.28	3			∞
21	17	69.37	4			∞
22	17	72.22	5			∞
23	18	69.32	5			∞
24	18	71.17	6	1	5	400.06
25	18	72.60	7	1	6	329.36
26	18	73.54	8	1	7	329.27
27	18	73.96	9	1	8	337.44
28	18	73.86	10	1	9	348.01
29	18	73.30	11	1	10	359.73
30	18	72.34	12	2	10	371.24
31	19	71.47	12	2	10	[illegible]
32	20	71.17	12	2	10	385.63

λ_B = 0.0016

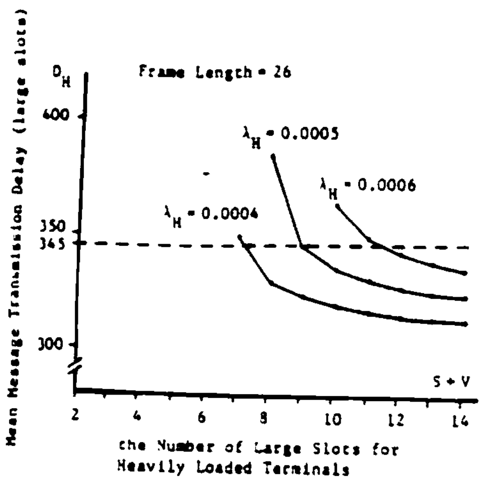

Fig. 10. Mean message transmission delay versus the number of large slots for heavily loaded terminals.

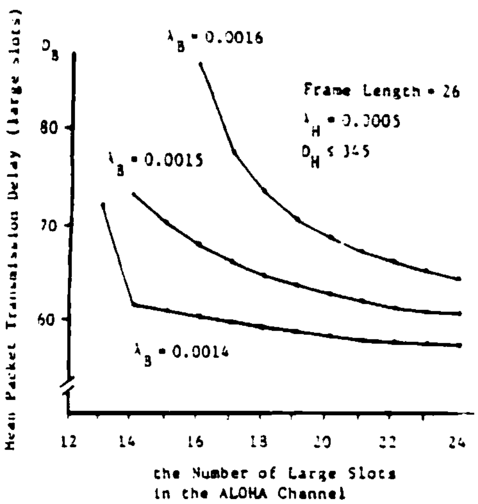

Fig. 11. Mean packet transmission delay versus the number of large slots in the ALOHA channel.

given with the condition $D_B \leqslant 74$, the optimal frame length is 26, and optimal values of S^*, V^*, and K^* are 7, 1, and 18, respectively, and the minimum value of D_H is 329.27

We, secondly, show that there exist optimal values of S, V, and K which minimize D_B, keeping D_H under the given constant.

Fig. 10 shows D_H as a function of $S + V$ for fixed values of λ_H. In this figure the frame length is 26, and furthermore, the values of S and V are selected optimally for each value of $S + V$, that is, S and V are taken so as to minimize D_H. It can be seen that, for instance, $S + V$ must be more than or equal to 9, in order to satisfy the condition $D_H \leqslant 345$, when the frame length and λ_H are equal to 26 and 0.0005, respectively.

Fig. 11 shows D_B as a function of K for fixed values of λ_B. Here, the frame length is 26. It is shown that, for instance, when the frame length, λ_B, and λ_H are equal to 26, 0.0015, and 0.0005, respectively, and if the condition $D_H \leqslant 345$ (this condition implies that K must be less than or equal to 17, as shown in Fig. 10) is given, the best value of K which minimizes D_B is 17 and the minimum value of D_B is 66.22.

Fig. 12 shows D_B as a function of the frame length for fixed values of λ_B. Here, the values of S, V, and K are selected optimally for each value of the frame length so as to minimize D_B, satisfying the condition $D_H \leqslant 345$. It is shown that there exists an optimal frame length which minimizes D_B, satisfying the condition $D_H \leqslant 345$.

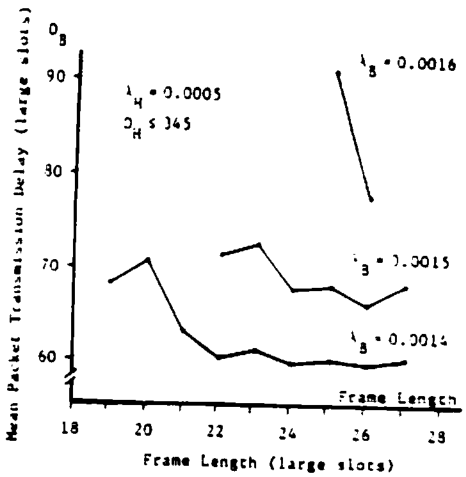

Fig. 12. Mean packet transmission delay versus frame length.

TABLE II
MEAN TRANSMISSION DELAYS IN VARIOUS SCHEMES

	Mean Packet Transmission Delay D_B	Mean Message Transmission Delay D_H
TDMA Scheme	281.67	453.54
Slotted ALOHA	87.15	593.34
Proposed Scheme	73.54	329.27

λ_B = 0.0016 λ_H = 0.0004

Finally we show comparison of the proposed scheme to the TDMA and the slotted ALOHA schemes. Here, in the slotted ALOHA scheme, messages arriving at a heavily loaded terminal are divided into packets and each packet is transmitted according to the slotted ALOHA scheme after the previous packet has been successfully received by its destination. Table II shows mean transmission delays in each of the above three schemes. The values of λ_B and λ_H are 0.0016 (packets/slot) and 0.0004 (messages/slot), respectively. Mean transmission delays in the TDMA scheme are obtained through the exact analysis [11]. Because of the difficulty in the analysis, mean transmission delays in the slotted ALOHA scheme are obtained through simulations. In the simulation, the random time delay in the retransmission is taken optimally so as to minimize the mean transmission delay. The values in the proposed scheme show mean transmission delays in the system with K, V, and S being equal to 18, 1, and 7, respectively (see Table I). It can be seen that the proposed scheme has better delay characteristics for certain traffic parameters in comparison to the TDMA and the slotted ALOHA schemes.

B. Blocked Calls Cleared Case

We show numerical examples for the blocked calls cleared system. The blocking probability P_{BC} for arriving messages and the mean line setup delay D_S are shown as a function of λ_H for various values of V, in Figs. 13 and 14, respectively. The values of K and $S + V$ are equal to 17 and 18, respec-

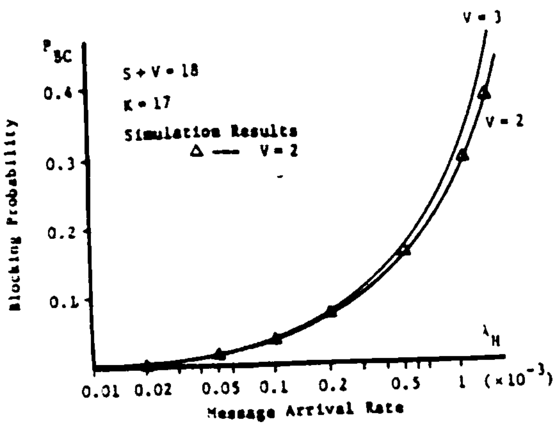

Fig. 13. Blocking probability.

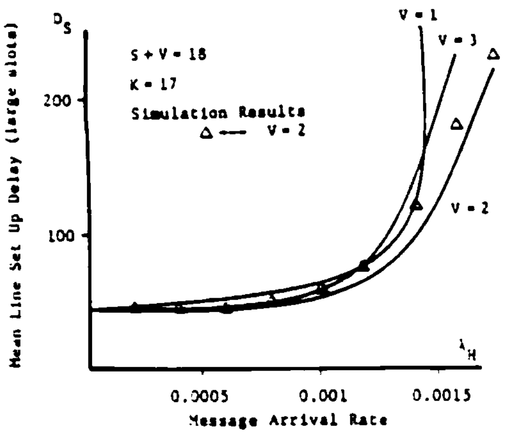

Fig. 14. Mean line setup delay.

tively. Simulation results shown coincide with the analytic results.

VIII. CONCLUSION

A new integrated access scheme in a satellite communication system where there are both bursty terminals and heavily loaded terminals has been proposed and analyzed in this paper. We have obtained mean transmission delays at both kinds of terminals, and have shown that there exists an optimal frame length which minimizes the mean transmission delay at one kind of terminals while keeping the mean transmission delay at the other kind under some permissible value.

In the analysis we assumed infinite buffer capacity, but this assumption is not representative of a real application. Hence, the analysis for the system with finite buffer capacity may be necessary to know system capacity requirements. But it is quite difficult, and is beyond the scope of this paper.

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