Dynamic Channel Assignment in Integrated-Services Cable Networks

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Abstract — **Cable networks can offer a variety of video services such as video-on-demand, video conferencing, videotex, and real-time monitoring, besides broadcasting TV programs. These services can be extended when optical fibers, equipping tremendous bandwidth, are used to carry the traffic. Most of the newer cable systems are indeed using fibers as the distribution media. In this paper we propose a dynamic channel assignment strategy for an integrated-services cable system. The strategy allows the dynamic sharing of channels among the three types of video traffic: the *real-time* traffic, the *broadcast* traffic and the *delayable* traffic. Simulation results show that it can greatly increase the channel utilization without affecting service requirements.**

I. INTRODUCTION

Cable network plays an important role in supplying diverse video programs to different interest groups. Various types of traffic can be accommodated on a cable network [1,2]. At present, the predominant type is the *broadcast* video. Broadcast video includes basic programs from local TV stations, distant stations via microwave transmissions and satellite broadcasting as well as premium programs from the cable operators. Broadcast videos are prescheduled, so the number of channels they occupied on the cable is deterministic.

The second type of traffic is called real-time video. It is now on limited service but could have a tremendous market potential. It includes video-on-demand services [3] that provide instant access to a library of educational and entertainment programs, as well as interactive video for information retrieval and communications. Interactive video, in particular, will increase significantly as services such as video conferencing, telecommuting and real-time monitoring of activities at homes and at offices are available.

The third type of traffic is called *delayable* video. It requires the customer to specify the extent of delay that is tolerable at the time of request so that the system can transport the video to the customer any time before a customer's specified due-time. Thus a particular customer may make a request in the morning to watch a short documentation on robotics at 8:00 pm. The robotics video can be transported to the subscriber's VCR (Video Cassette Recorder) on any non-busy time segment before 8:00 pm. Delayable video is a very attractive traffic type to the network operators because it can often be transported through the network at non-busy hours. It will also be welcomed by the customers as they can enjoy off-peak rates for video transports and sharing of charge among a group of customers requesting the same video is possible.

Foreseeing the growth of all three types of traffic, it is foreseen that the most economical means of upgrading the cable system is to gradually switch over to the Fiber-To-The-Curb (FTTC) and then to Fiber-To-The-Home (FTTH) architectures [4-6]. Recent research has identified a variety of techniques for the distribution of videos on optical fibers including Time-Division Multiplexing (TDM), Subcarrier Multiplexing (SCM) [7], Wavelength-Division Multiplexing (WDM) [8], and some combinations of these schemes.

To make full use of the channel resources in cable networks, a flexible channel allocation strategy is clearly needed. In this paper, we propose a channel assignment strategy which allows the dynamic sharing of channels among the three types of traffic. The strategy is presented in section II, an illustrative example is given in section III, and a comparative study of various channel allocation strategies by simulation is given in section IV.

II. THE DYNAMIC CHANNEL ASSIGNMENT STRATEGY

Consider a cable system that can support a maximum of W video channels. Let $B(t)$ be the number of broadcast programs showing at time t, the remaining number of channels, $V(t) = W - B(t)$ can be used for real-time and delayable video. A typical plot of $B(t)$ is shown as Fig.1.

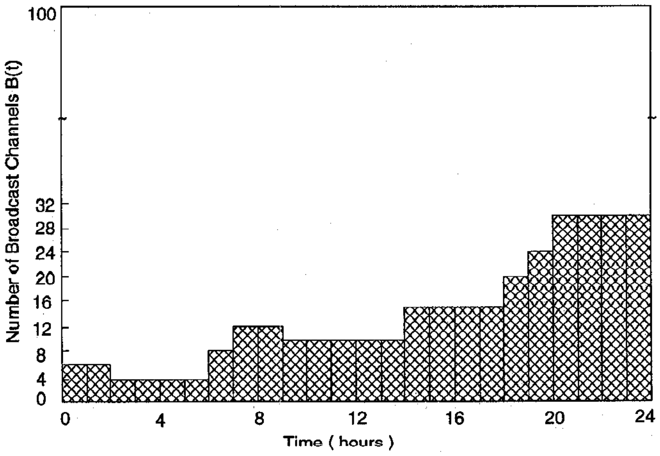

Fig. 1 Broadcast Channel Occupancy Profile.

Let $N_o(t)$ be the minimum number of channels needed to satisfy the service liability of the delayable traffic at time t ($N_o(t)$ will be quantified later). Without affecting delayable video, the maximum number of channels available for real-time video

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therefore is $V(t)-N_o(t)$. In practice, we would allocate just enough channels to real-time videos such that its blocking requirement P_B^* could be satisfied as far as possible. Let the arrivals of real-time video be a Poisson process with rate λ and let the duration of these video programs be exponentially distributed with mean μ^{-1}. To satisfy P_B^*, the nominal number of channels R_o allocated to real-time traffic is

$$R_o = \min\left\{ c \,\middle|\, \frac{(\lambda/\mu)^c/c!}{\sum_{i=0}^{c}(\lambda/\mu)^i/i!} \le P_B^*,\ c \le V(t)-N_o(t) \right\} \tag{1}$$

To keep track of the change of traffic rate in the network, λ and hence R_o need to be updated periodically. If $R_o = V(t)-N_o(t)$, the real-time traffic is too heavy for the number of channels available and some kind of congestion control strategy might be needed to take care of the *more urgent* real-time traffic while blocking the less urgent ones.

Suppose at a particular time instance the actual number of real-time video connections n_o is only a fraction of R_o. Then some of the R_o channels could be used to transport delayable video. On the other hand, when $n_0 = R_0$, we could temporarily overflow new real-time videos onto the channels that have not been allocated (of quantity $W-B-R_o-N_o$). This is the essence of dynamic channel assignment and in the following, we shall derive the maximum number of channels that can be temporarily reassigned to carry the delayable traffic without affecting the blocking performance of the real-time video.

Let us say at time zero n_o channels are occupied by the real time video. Let the channel occupancy probabilities at time t be denoted as $\{P_o(t,n_o,R_o),\ P_1(t,n_0,R_o),\ \cdots,\ P_{R_o}(t,n_o,R_o)\}$. These probabilities are just the transient state probabilities of the $M/M/R_o/R_o$ queueing system [4] with initial conditions $P_{n_o}(0,n_o,R_o)=1$ and $P_n(0,n_o,R_o)=0$ for $n \ne n_o$. The solutions of these probabilities are very difficult and are not found in the literatures. But $P_n(t,n_o,R_o)$ can be approximated by the conditional transient state probabilities of the $M/M/\infty$ queue, $P_n(t,n_o,\infty)$, being conditioned on the event that at time t the process does not go beyond R_o, or

$$P_n(t,n_o,R_o) = \frac{P_n(t,n_o,\infty)}{\sum_{i=0}^{R_o} P_i(t,n_o,\infty)} \tag{2}$$

Following the method outlined in [9], $P_n(t,n_o,\infty)$ is derived as

$$P_n(t,n_o,\infty) = \begin{cases} \dfrac{1}{n!}\exp\left[(1-e^{\mu t})\dfrac{\lambda}{\mu}\right] e^{-\mu n t}(1-e^{-\mu t})^{n_o} \\ \quad \cdot \displaystyle\sum_{i=0}^{\infty} \frac{1}{i!}\left[(e^{\mu t}-1)\frac{\lambda}{\mu}\right]^i \frac{(n_o+i)!}{(n_o-n+i)!}(1-e^{-\mu t})^{i-n} \\ \qquad\qquad \text{for } n \le n_o \\ \dfrac{1}{n!}\exp\left[(1-e^{\mu t})\dfrac{\lambda}{\mu}\right] \\ \quad \cdot \displaystyle\sum_{i=0}^{\infty} \frac{1}{(n-n_o+i)!}\left[(e^{\mu t}-1)\frac{\lambda}{\mu}\right]^{n-n_o+i} \frac{(n+i)!}{i!} e^{-\mu n t}(1-e^{-\mu t})^i \\ \qquad\qquad \text{for } n > n_o \end{cases} \tag{3}$$

The validity of this approximation can be justified as follows. First, the relationship, or (2), is exact at steady state or at $t=\infty$. This follows from the well known fact that the queue length distribution of $M/M/c/c$ is just the truncated distribution of that of $M/M/\infty$. Second, they both have the same initial condition, or at $t=0$, the relationship is exact. Third, the dynamics of $M/M/R_o/R_o$ and $M/M/\infty$ queues are identical except for blocking at occupancy equal to R_o. Therefore, given that the current occupancy is n_o, the time to first reach occupancy R_o is the same for both $M/M/R_o/R_o$ and $M/M/\infty$ queues, independent of λ, μ, R_o and n_o. Fourth, we have done extensive simulation to verify that (2) is a good approximation.

Suppose one channel is to be temporarily used for transporting a delayable video. Then, without violating the blocking requirement of the real-time video, the maximum transmission time X_1 allowed for the delayable video is given by the solution of

$$P_{R_o-1}(X_1,n_o,R_0-1) = P_B^* \tag{4}$$

and can be found by standard numerical methods. If two channels are lent, the maximum transmission time X_2 allowed for the second delayable video is given by the solution of

$$P_{R_o-2}(X_2,n_o,R_0-2) = P_B^*. \tag{5}$$

Similarly, we can compute $X_3, X_4, \ldots, X_{R_o-n_o-1}$. It is easy to verify that $X_1 > X_2 > \ldots > X_{R_o-n_o} = 0$.

Let $\Phi(Y_i)$ denote the delayable video with size Y_i that is currently queuing in the system for transmission. Let the program index be ordered such that $Y_1 \le Y_2 \le Y_3 \le \cdots$. The problem then is how to fit as many $\Phi(Y_i)$'s into the set of transmission intervals X_j's as possible. This can be done simply by finding the longest videos that can be fit into $X_1, X_2, \cdots$ etc.. An algorithm for matching the Y_i's to the X_i's is given in [10].

Customers ordering delayable services, usually want a guarantee of their services' delivery within the indicated time frame when their requests are accepted. So at any particular time t, the system will require a minimum number of channels $N_o(t)$ to cover the service liability of the accepted delayable traffic. A new delayable video request is accepted only when the delayable video backlog, *with the present request included,* can be accommodated in the delayable channel space $V(t)-R_o$. An algorithm for finding it can be found in [10].

Since the real-time traffic has random arrival time and random service duration, precise planning of channel resources to be used in the future is not possible. What can be done is to periodically estimate the traffic rate λ, based on past history and set aside R_o channels as specified by (1). The remaining channel resources can then be used by the delayable traffic. To find out whether a new delayable video can be accommodated when there is a large backlog requires the solving of a constrained "multiple-bin-packing" problem. In Job-Shop Scheduling terminology [11], this problem is called Job Scheduling in Variable Capacity Multi-Machine System with Due-Time and there is no efficient algorithm for its solution. A greedy algorithm (i.e. without backtracking) described in [10] can be used to give very quick solutions without affecting appreciably the throughput. Backtracking is not essential in the present case because delayable traffic has a lot of flexibility in scheduling transmission start times and can easily be packed into the unused channels.

Once a delayable video request is accepted, it is put on a multiserver Head-Of-the-Line (HOL) queue. The number of channels available for delayable traffic $D(t)$ varies with time and is equal to $V(t)-R_o+E(t)$, where $V(t)-R_o$ is the number of channels nominally allocated to delayable traffic and $E(t)$ is the number of channels that can be borrowed. Let $T(t)$ be the number of delayable transmissions at time t. A delayable video of length Y minutes is put onto transmission if $D(t) \geq T(t)+1$ during the next Y minutes. Occasionally, when the real-time traffic gets very heavy and all R_o channels are used up, overflow of real-time videos onto idle channels is allowed if these idle channels have no commitment to serve a broadcast program later on. This restriction is necessary because a real-time connection, once established, should not be interrupted. Idle channels with no future commitment can be seized for carrying real-time videos without affecting the service liability of the delayable traffic.

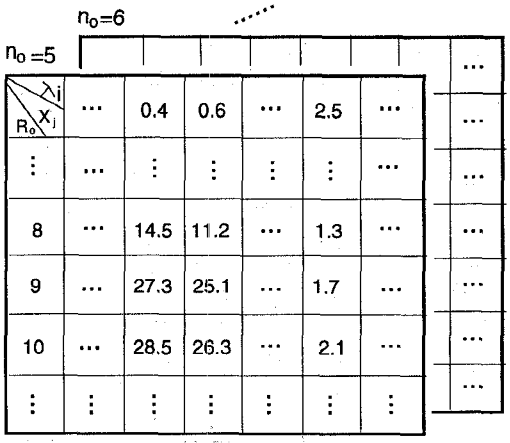
III. AN ILLUSTRATIVE EXAMPLE

Instead of computing R_o's and X_i's every time there is a state change, tables can be built for later retrievals. Fig. 2a shows a typical configuration of a table giving the R_o values for different λ according to (1) while Fig. 2b shows the X_1 values for various λ, n_o and R_o according to (4). The values for $X_2, X_3, \cdots$ are obtained from the same table but with R_o replaced by R_o-1, $R_o-2, \cdots$. This can be easily verified by comparing (4) and (5).

As an example to illustrate the dynamic sharing of channels, consider the following case. Let the total number of available channels be $W=100$, the average service time of both real-time and delayable video be $1/\mu = 15$ minutes. At time t_o, let $\lambda = 2.5$/minute, $B(t_o)=40$ and $n_o=30$. The minimum number of channels needed by the delayable traffic is $N_o(t_o)=5$ and $V(t_o) = W-B(t_o) = 60$. From Fig. 2a, the unconstrained number of nominal channels for real-time traffic is $R_o' = 57$. Since $R_o' > V(t_o)-N_o(t_o) = 55$, the actual number of nominal channels is $R_o = 55$.

λ	···	0.4	0.6	0.8	···	2.5	···
R_0	···	15	20	24	···	57	···

(a) R_0 as a function of



R_o \ X_j \ λ_i	···	0.4	0.6	···	2.5	···
⋮	···	⋮	⋮	⋮	⋮	···
8	···	14.5	11.2	···	1.3	···
9	···	27.3	25.1	···	1.7	···
10	···	28.5	26.3	···	2.1	···
⋮	⋮	⋮	⋮	⋮	⋮	⋮

(b) X_0 as a function of R_0 , , and n_0

Fig. 2 A typical tabular configuration for storing R_0.

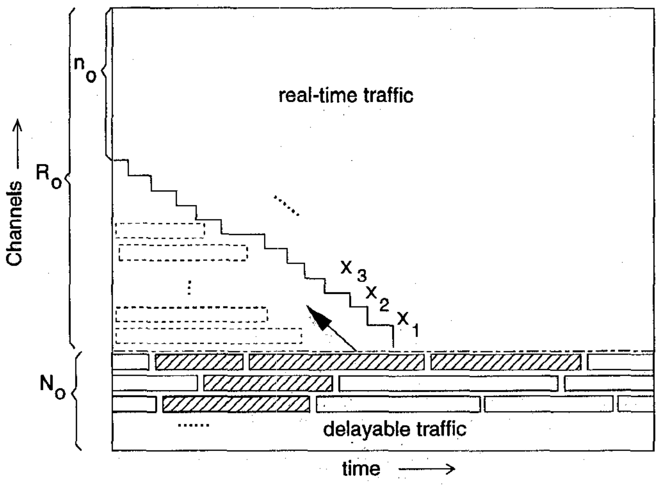
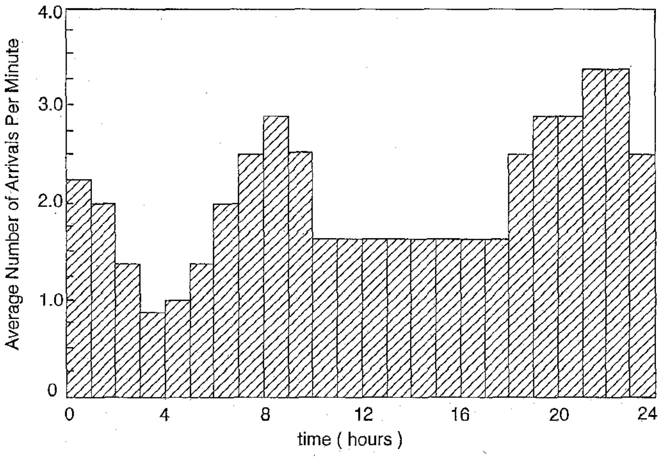


Fig. 3 Assignment of delayable videos to channels nominally allocated to real-time traffic.

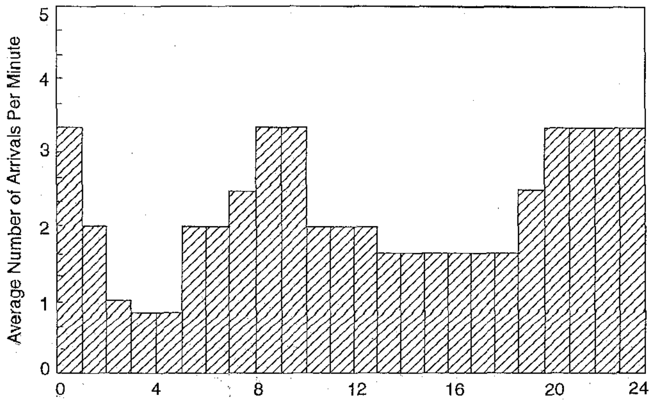
Let the size of the set of delayable videos $(Y_1, Y_2, Y_3, \cdots)$ be $(4.8, 6.0, 8.5, 10.2, 10.5, 11.5, 13.9, \cdots)$. From (2) and (3), $(X_1, X_2, \cdots, X_{R_o-n_o-1})$ are obtained as (10.9, 10.8, 10.8, 10.7, 10.6, 10.1,..., 0.3, 0.1). Working through the matching of Y_i's to X_i's, we find that $\Phi(Y_1)$ to $\Phi(Y_6)$ can be loaded onto the channels nominally assigned for real-time traffic without violating the blocking requirement. This situation is illustrated in Fig.3, where the shaded boxes represent the delayable videos in queue that can be put into the channels nominally assigned for real-time traffic. With the use of dynamic channel assignment these delayable videos can be moved to the dotted boxes as indicated.

IV. A SIMULATION COMPARISON

In this section, we compare the performance of the Dynamic Channel Assignment strategy to that of Fixed Channel Assignment strategy and the Semi-Dynamic Assignment strategy. With the use of the Fixed Channel Assignment strategy, delayable traffic is treated as if it were real-time traffic with the arrival time of videos set at their respective due-time. A fixed number of channels equal to $W - B_{\max}$ are assigned to the combined real-time and delayable traffic. The Semi-Dynamic Assignment strategy is the same as the Dynamic Channel Assignment strategy but without channel borrowing (or temporarily channel reassignment). The number of channels allocated is based on the hourly average traffic rate: R_o channels (computed from (1)) are allocated to real-time traffic, and $W - B(t) - R_o$ channels are assigned to delayable traffic. Both the Dynamic and Semi-Dynamic Assignment strategies use the same acceptance criterion for the delayable traffic.



(a) Real-Time Traffic



(b) Delayable traffic

Fig. 4 Arrival rate profiles for real-time and delayable traffic.

Let W=100, and let $B(t)$ has a period of 24 hours as shown in Fig.1. Let the arrivals of real-time and delayable requests be Poisson processes with rates shown in Fig.4. We let the service time of both real-time and delayable traffic be exponentially distributed with a mean of 15 minutes. The due-time of delayable videos is also assumed to be exponentially distributed with a mean of 7 hours. In determining R_o, we set P_B^*=0.01.

TABLE 1 : SIMULATION RESULTS

	Fixed Assignment	Simidynamic Assignment	Dynamic Assignment
Blocking Prob. of Real-Time Traffic (in %)	8.6±0.2	1.5±0.3	1.1±0.3
Blocking Prob. of Delayable traffic (in %)	——	8.2±0.2	1.8±0.2
Overall Blocking Prob. (in %)	8.6±0.2	4.8±0.2	1.4±0.2
System Throughput *	0.637± 0.005	0.681± 0.005	0.722±0.005

* : Excluding broadcast traffic

Many sets of simulation are performed, each over a period of 22 days. The statistics of the first and the last days are discarded to eliminate the transient and boundary effects. Table 1 summarizes the blocking and throughput performance with 95 percent confidence intervals. It is readily seen that the Dynamic strategy offers significantly smaller blocking probabilities for both the real-time and delayable traffic in comparison to the Semi-Dynamic strategy. Specifically, the blocking of real-time and delayable traffic are reduced from 1.5% to 1.1% and from 8.2% to 1.8% respectively. As a result, the throughput is increased by 6% (from 0.681 to 0.722). This therefore shows that channel borrowing is a powerful feature in channel management. Comparing the Dynamic strategy with the Fixed

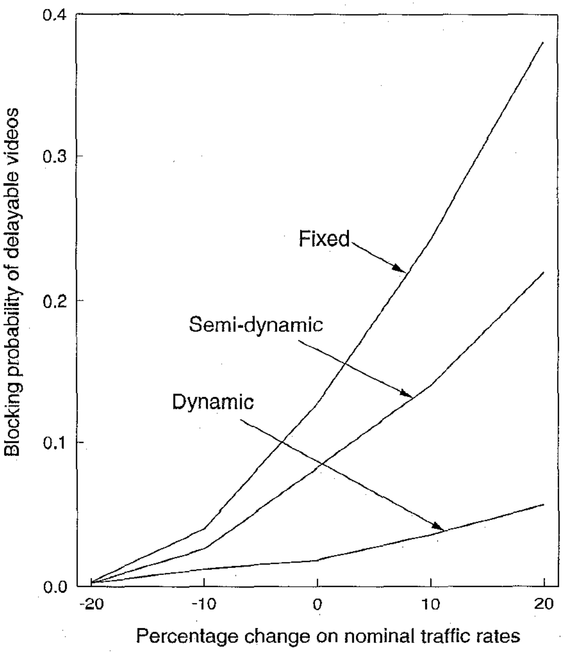


Fig. 5 Comparison of the three strategies under time varying traffic rate conditions.

strategy, we find that in addition to the dramatic reduction of blocking probability, an increase of 13.3% throughput is also observed. To study the performance of the strategies under different traffic load condition, we vary the rates shown in Fig.4 uniformly by ±20% and allocate enough channels to the real-time traffic such that its blocking probability is about 1%. Fig.5 shows the blocking probabilities of the delayable traffic as a result of this traffic rate change. Fig.6 shows the results for delayable traffic rate equal to real-time traffic rate equal to λ for all time with $W-B(t)=70$, a constant. These results show that the Dynamic strategy is effective in the fair allocation of channel resources to competing traffic types. Comparing Figs.5 and 6, it is seen that the advantage of the Dynamic strategy is more prominent in the more realistic time-varying traffic rate conditions.

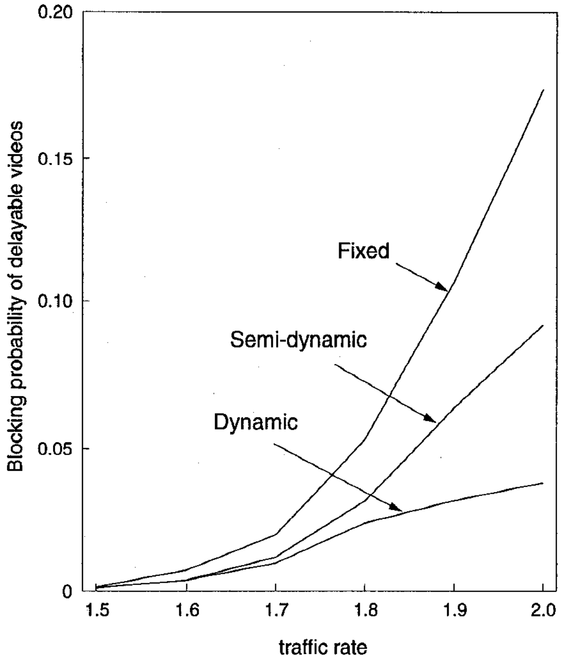


Fig. 6 Comparison of the three strategies under constant traffic rate conditions.

V. CONCLUSIONS

We have designed a dynamic channel assignment strategy for the broadcast, real-time and delayable traffic, the three types of traffic that is expected to be common in integrated services cable systems. The strategy has the following desirable features:

1. Broadcast video programs are preplanned. So they always get channels when they are ready to broadcast.
2. Real-time traffic is allocated with a nominal number of channels R_o that guarantees the real-time traffic to have a blocking probability no larger than some specified requirement P_B^*. When all R_o channels are used, overflow onto the channels allocated for delayable traffic is allowed provided that the delayable traffic is not heavy.
3. Delayable requests, once accepted, have a guaranteed delivery. They are delivered through as many channels as possible so that when the real-time traffic is momentarily at a low delayable traffic is overflowed onto the real-time channels. The amount of overflow, however, is just not large enough as to cause blocking of the real-time traffic beyond that stipulated by the requirement.

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