Hierarchical Distribution of Video with Dynamic Port Allocation

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***Abstract*—A two-level distribution network for *broadcast* and *interactive* video is studied as an example of the hierarchical distribution method. This two-level design has the following advantages.**

1) **It can replace a large switch by a network of smaller switches, facilitating switch growth and enhancing switch reliability.**
2) **The second level switches (or the local switches) can be located at convenient places in their respective service districts, reducing the overall circuit mileage of the video distribution system.**
3) **Video requests can be processed independently by local switches, rendering a large call processor at the central switch unnecessary.**

A traffic model for this network is formulated and the optimum capacities of the central and local switches are determined for a given blocking requirement. By adding a small crosspoint switch between the two levels, the output ports of the central switch can be dynamically allocated to the local switches. We show that this sharing of output ports can significantly reduce the size of the central switch.

I. INTRODUCTION

PROPOSALS for residential video networks frequently distinguish two types of video services, broadcast, and interactive. In broadcast mode video signals are transmitted by the network and selected by customers as desired. Individual customers have no control over the content of broadcasts and no ability to dynamically change the network. With interactive video—video conferencing and video on demand [1], for example—network transmission is initiated by customer requests. Interactive video is obviously the preferred service since customers could have some freedom to choose when and what to see. Full-scale interactive video service will be possible with the future introduction of broad-band ISDN. In fact, the main goal of developing broad-band ISDN is to provide switched video service to the subscribers.

Tremendous amount of research has been conducted recently on the distribution of video, including how to accommodate both broadcast and interactive services onto a single system, what kinds of multiplexing and switching technologies could be used and their tradeoffs. Wagner and Menendez [2] reviewed the evolutionary architectures and techniques for video distribution on fibers, from the currently matured analog transmission techniques to fully switched digital systems for broad-band ISDN in the late 1990's and beyond. Cooperman, Paige, and Sieber [3] described the architecture, the operation and control of a state-of-the-art 64×16 broad-band video switch on a chip.

As video distribution technology becomes more and more mature, characterizing service demands and building traffic engineering tools for various design architectures are imminent. In this paper, we choose to do this on a two-level hierarchical distribution network that can accommodate both broadcast and interactive video. The hierarchical architecture has three advantages. First, the total number of switching cells can be reduced. Second, the second-level switch (or local switch) can be located at convenient places in their respective service districts. As a result, the overall circuit-mileage of the video distribution system can be significantly reduced. Third, most of the switching demands can be satisfied independently by the local switches. With this distributed processing feature, the speed and size of the system will no longer be limited by the speed of the central call processor.

Specifically, for this two-level distribution network we shall first formulate a traffic model and derive the blocking probabilities of both broadcast and interactive video services. We then formulate the optimum dimensioning of the central and local switches as a nonlinear integer program. By adding a small subsidiary switch the output ports of the central switch can be dynamically shared by the array of local switches. We shall show by numerical examples that such sharing can reduce the size of the central switch without increasing the blocking probability of video demands.

II. SYSTEM ARCHITECTURE

Fig. 1 shows the details of a two-level distribution system. It consists of a central switch and K local switches. The central switch is connected to a broad-band backbone network where the broadcast video programs are supplied and the circuits for interactive video are allocated. It has E input ports and M $(M \geq E)$ output ports and has embedded in it a copy network [4]. It is able to transmit a maximum of E video programs simultaneously to the M output ports, with some of them receiving the same programs. The M output ports supply the video programs to the K local switches, which in turn duplicate and distribute them to the subscribers in their respective regions. Let all local switches have J input ports and N output ports. Then the entire switching system can serve a maximum of $N_o = NK$ subscribers.

Paper approved by the Editor for Optical Switching of the IEEE Communications Society. Manuscript received January 3, 1990; revised October 5, 1990. This paper was presented at IEEE ICC'90, San Francisco, CA, April 1990.

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IEEE Log Number 9100812.

0090-6778/91/0800-1268$01.00 © 1991 IEEE

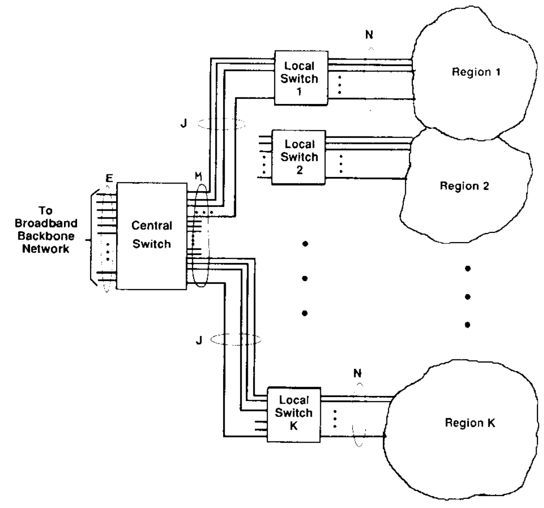


Fig. 1. Two-level video distribution system.

Let us first consider the distribution of broadcast video. After a customer turns on his TV set, he will select a particular TV program from his remote control unit. His selection will be transmitted to the local switch through an embedded signaling channel. If the local switch is currently transmitting that program, it just sends a copy to that customer. On the other hand, if that customer is the first one in that region to request that program (after a period of idling), the local switch sends a signal to the central switch to ask for a copy and passes it on to the customer. Subsequent requests for the same program can be satisfied by the local switch through electronic copying. If on the other hand, a customer wants to start an interactive video session, his/her request will be relayed through the local switch to the backbone network and a dedicated circuit is allocated to the two communication parties.

III. TRAFFIC MODEL AND BLOCKING PROBABILITIES

Let there be a total of C broadcast programs available in the entire region of service and let c_i $(i = 1, 2, \cdots, C)$, be the probability that program i is being watched. For simplicity of computation, let us reorder the program numbers such that $c_1 \geq c_2 \geq c_3 \cdots \geq c_C$. A typical distribution is shown in Fig. 2.

At the busiest hour of a day let p_1 be the probability that a subscriber chooses to watch a broadcast program and p_2 be the probability that a subscriber requests an interactive session. Then in a region with N subscribers, the probability that there are n_1 broadcast requests and n_2 interactive requests is

$$\begin{aligned} A(n_1,n_2) &= \binom{N}{n_1, n_2} p_1^{n_1} p_2^{n_2} (1-p_1-p_2)^{N-n_1-n_2} \\ &= \frac{N!}{n_1!n_2!(N-n_1-n_2)!} p_1^{n_1} p_2^{n_2} \\ &\quad \cdot (1-p_1-p_2)^{N-n_1-n_2} \\ &\quad 0 \leq n_1 + n_2 \leq N. \end{aligned} \tag{1}$$

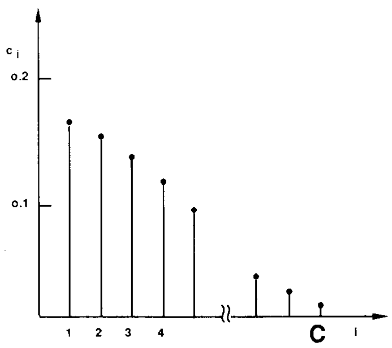


Fig. 2. Channel patronage distribution.

The respective marginal probabilities are denoted as $A(n_1, \bullet)$ and $A(\bullet, n_2)$.

The n_2 interactive video sessions require precisely n_2 channels. But many of the n_1 subscribers on broadcast programs will be sharing channel if they are watching the same program. Thus, given n_1, the probability that r broadcast channels are required $b_r(n_1)$ is

$$b_r(n_1) = \sum_{\Omega_1} \left[\sum_{\Omega_2} \binom{n_1}{m_1, m_2, \cdots, m_r} c_{k_1}^{m_1} c_{k_2}^{m_2} \cdots c_{k_r}^{m_r} \right]$$
$$r = 1, 2, \cdots, \min(n_1, C)$$

where $c_{k_i}^{m_i}$ is the probability that m_i customers are watching program k_i $(i = 1, 2, \cdots, r)$,

$$\Omega_1 = \{(k_1, k_2, \cdots, k_r) | 1 \leq k_1 < k_2 < \cdots < k_r \leq C\}$$

is the set of all the combinations of r programs selected from the set of C programs, and

$$\Omega_2 = \{(m_1, m_2, \cdots, m_r) | m_1 + m_2 + \cdots + m_r = n_1\}$$

is the set of all the combinations of the n_1 customers watching the r programs specified by the elements of Ω_1.

Thus, given n_1 and n_2, the probability that a total of j channels are required, denoted as $d_j(n_1, n_2)$, is just the probability that $j - n_2$ channels are required by the broadcast video. Therefore,

$$d_j(n_1, n_2) = \begin{cases} 0 & 0 \leq j \leq n_2 - 1 \\ b_{j-n_2}(n_1) & n_2 \leq j \leq n_2 + \min(n_1, C) \end{cases}$$
$$n_1 + n_2 > 1 \tag{2}$$

with $d_0(0,0) = d_1(1,0) = d_1(0,1) = 1$. Removing conditioning on n_1 and n_2, we have

$$\begin{aligned} d_j &= \text{Prob}[j \text{ channels are required at the local switch}] \\ &= \sum_{n_1=0}^{N} \sum_{n_2=0}^{N-n_1} d_j(n_1, n_2) A(n_1, n_2) \end{aligned}$$
$$j = 0, 1, 2, \cdots, N. \tag{3}$$

A. Blocking of the Interactive Video

Let there be J input ports at all local switches. Then given n_1 and n_2 the probability that a requested channel is blocked at a local switch, denoted as $B_L(J|n_1, n_2)$, is

$$B_L(J|n_1,n_2) = \sum_{j=J+1}^{n_2+\min(n_1,C)} \frac{j-J}{j} d_j(n_1,n_2).$$

Removing conditioning on n_1 and n_2, we have

$$B_L(J) = \sum_{n_2=0}^{N} \sum_{n_1=0}^{N-n_2} B_L(J|n_1,n_2)A(n_1,n_2).$$

Next, let W_i be the number of requests for interactive video channels from local switch i to the central switch. Then, for $i = 1, 2, \cdots, K$ and $w = 0, 1, 2, \cdots, J$, we have

$$\begin{aligned} P[W_i = w] &= P[W_i = w, j \le J\,] + P[W_i = w, j > J\,] \\ &= \sum_{j=w}^{J} \sum_{n_1=0}^{N-w} d_j(n_1,w)A(n_1,w) \\ &\quad + \sum_{j=J+1}^{N} \sum_{n_2=w}^{j} \sum_{n_1=0}^{N-n_2} \frac{\binom{n_2}{w}\binom{j-n_2}{J-w}}{\binom{j}{J}} \\ &\quad \cdot\ d_j(n_1,n_2)A(n_1,n_2). \end{aligned}$$

Let $W_S = W_1 + W_2 + \cdots + W_K$ be the total number of interactive video requests from all K regions. Since all W_i's are i.i.d. random variables, the distribution of W_S is just the K-fold convolution of the distribution of W_1 with itself. Assuming all C broadcast programs are available at the central switch, the blocking probability $B_C(E, J, K)$ for the interactive video at the central switch is

$$B_C(E,J,K) = \sum_{k=E-C+1}^{KJ} \frac{k-(E-C)}{k} P[W_S = k].$$

The overall blocking probability of interactive video $B_O(E, J, K)$ given that there are E input ports at the central switch and J input ports at each of the K local switches is

$$B_O(E,J,K) = B_L(J) + B_C(E,J,K).$$

B. Blocking of the Broadcast Video

Blocking of broadcast video occurs when the selected program is not currently being broadcast to the local switch *and* all J input ports of the local switch are occupied. The blocking probability therefore depends on the particular program being selected. Consider the selection of program z. Given n_1 (as defined before), the probability that program z is not in a set of j broadcast video programs, denoted as $f_i(z, n_1)$, is

$$f_i(z,n_1) = \sum_{S_j} \left[\sum_{Y_j} \binom{n_1}{m_1, m_2, \cdots, m_j} c_{k_1}^{m_1} c_{k_2}^{m_2} \cdots c_{k_j}^{m_j} \right] \qquad j = 1, 2, \cdots C-1.$$

where

$$S_j = \{(k_1, k_2, \cdots k_j) | 1 \le k_1 < k_2 < \cdots < k_j \le C; \text{ all } k_i \ne z\}$$

is the set of all the combinations of j programs selected from the set of $C - 1$ programs (excluding program z) and

$$Y_j = \{(m_1, m_2, \cdots, m_j) | m_1 + m_2 + \cdots m_j = n_1\}$$

is the set of all the combinations of the n_1 customers watching the specified j programs. The probability that program z is blocked, denoted as $B_B(z)$, is obtained by removing the conditionings of j and n_1 on $f_j(z, n_1)$:

$$B_B(z) = \sum_{n_1=1}^{N} \sum_{j=1}^{\min(n_1,C)} f_j(z,n_1)A(n_1, J-j). \qquad (4)$$

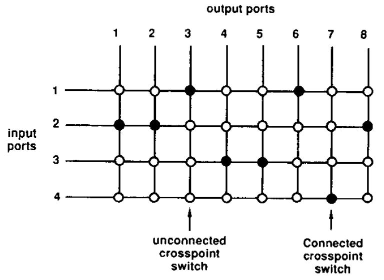


Fig. 3. A crosspoint network performing multicast function.

It is easy to imagine that the blocking probability is practically zero for popular programs and is always smaller than the blocking probability of the interactive video for infrequently accessed programs. Blocking requirement therefore needs only be set on the interactive video for switch capacity optimization.

IV. CAPACITY OPTIMIZATION

Aside from the advantages of distributed processing, the main reason for adopting the two-level architecture is that the switch complexity can be reduced. In this section, we derive the minimum complexity configurations for the crosspoint and the broadcast banyan switches.

A. Crosspoint Switch [5]

The crosspoint switch can perform the multicast function by making multiple output connections. Fig. 3 shows the switch connections whereby program 1 is being received by output ports 3 and 6, program 2 is being received by output ports 1, 2, and 8, etc. The complexity of a crosspoint switch is usually measured by the total number of crosspoints L in the switch. For the switching system shown in Fig. 1, L is given as

$$L = EKJ + KJN. \qquad (5)$$

The minimum complexity configuration of the switching system can be determined by minimizing L with respect to E, J, and K simultaneously subject to $B_o(E, J, K) \le B^*$ where B^* is a given blocking requirement. A popular method of solving this type of nonlinear integer program is by Branch and Bound [10].

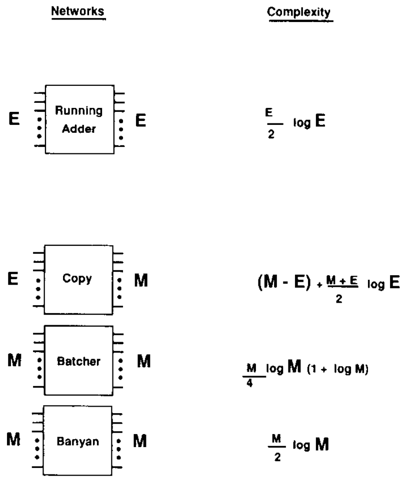


Fig. 4. Switching parts and their complexities.

In comparison, if a single crosspoint switch is used and the same blocking requirement B^* is to be satisfied, a minimum of E_o input ports are needed where E_o is given by

$$E_o = \min\left[E \,\middle|\, \sum_{n_2=E-C}^{N_o} \frac{n_2 - (E-C)}{n_2} A(\bullet, n_2) \leq B^*\right]. \quad (6)$$

The total number of crosspoints L_o in this case is just $L_o = E_o N_o$.

B. Broadcast Banyan Switch [4], [6]–[9]

The same optimization problem can be formulated with the use of a broadcast banyan switch. Here, the complexity is measured in terms of the total number of switching units. The central switch can be partitioned into four parts, namely, the running adder, the copy network, the Batcher network, and the banyan network. Their complexities are shown in Fig. 4. For such a switch with E inputs and M outputs, we define the switch complexity function $\phi(E, M)$ as

$$\phi(E, M) = \frac{M}{4}(\log M)^2 + \frac{M}{2}\log M + \frac{M+E}{2}\log E. \quad (7)$$

Since the K local switches are similar to the central switch except that the number of input and output ports are J and N_o/K, the complexity L of the switching system is

$$L = \phi(E, JK) + K\phi(J, N_o/K). \quad (8)$$

As before, the optimum E, J, and K values can be determined by minimizing L subject to $B_o(E, J, K) \leq B^*$. The single stage switch has a complexity L_o given by $L_o = \phi(E_o, N_o)$ where E_o is given by (6).

V. DYNAMIC PORT ALLOCATION

The previous design requires KJ output ports in the central switch. But since it is highly unlikely that *all* K local switches will have *all* their input ports loaded simultaneously, using KJ output ports at the central switch is overengineering. But if a smaller number of output ports is to be used, how are they going to be shared? In the following, we propose the use of a simple intermediate crosspoint switch, called the port allocation (PA) switch, to perform the dynamic sharing function.

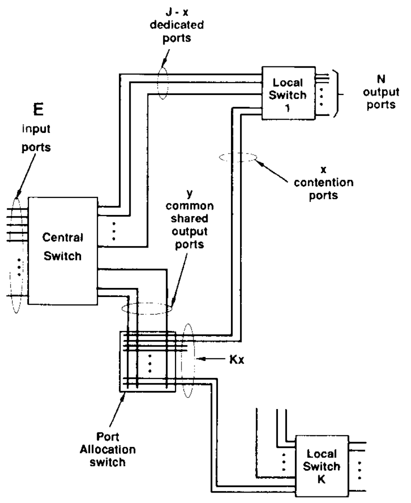


Fig. 5. The port allocation switch.

Fig. 5 shows a PA switch with its connections to the central and local switches. Among the J input ports of the local switch, let us assign x of them to be the contention ports. These x ports are connected to the PA switch to share, together with the contention ports of the other local switches, the y common-shared output ports of the central switch. The other $J-x$ ports of the local switch are called the dedicated ports and are connected directly to the central switch. Thus, the central switch has a total of $(J-x)K + y$ output ports and the PA switch has y input ports and Kx output ports.

Video calls from a local switch are normally assigned to the dedicated ports. Only when all dedicated ports are occupied will the traffic be overflowed to the contention ports. Under a fairly rare occassion that

1) the y common-shared output ports are all occupied,
2) there are one or more free dedicated ports in a local switch, and
3) there are one or more occupied contention ports in the same switch,

a video session on a contention port will be reassigned to one of the dedicated port. In doing so, one of the common-shared output ports of the central switch can be freed to serve new calls from the contention ports of the local switches.

For the calculation of the blocking probability, we shall assume in the following that N is sufficiently large such that all C broadcast programs are being distributed in all local switches. Thus, the number of input ports that can be used for interactive video at each local switch is $J-C$. The number of interactive video connections in local switch i, denoted as W_i, has distribution

$$P[W_i = k] = \binom{N}{k} p_2^k (1-p_2)^{N-k}.$$

Given $W_1 = k_1$, $W_2 = k_2, \cdots, W_K = k_K$, the blocking probability $B(x,y,J,K,E)$ of the interactive video programs consists of three terms, B_1, B_2, and B_3 denoting the blocking contributions from the local switches, the PA switch and the central switch, respectively. Let a_i be the number of interactive video requests that gets blocked at local switch i or

$$a_i = \max[k_i - (J-C), 0]$$

and b be the number of requests that overflow onto the PA switch, or

$$b = \sum_{i=1}^{K} \min[\max[k_i - (J-C-x), 0], x].$$

Furthermore, let

$$a_s = \sum_{i=1}^{K} a_i$$
$$k_s = \sum_{i=1}^{K} k_i$$

Then

$$\begin{aligned} B_1 &= \frac{a_s}{k_s} \\ B_2 &= \frac{\max[b-y,0]}{b} \\ B_3 &= \frac{\max[\{k_s - a_s - \max[b-y,0]\} - (E-C), 0]}{k_s - a_s - \max[b-y,0]}. \end{aligned}$$

Removing conditioning on the set of k's, we have

$$B(x,y,J,K,E) = \sum_{k_1=0}^{N} \cdots \sum_{k_K=0}^{N} \cdot \left[(B_1 + B_2 + B_3) \prod_{i=1}^{K} P[W_i = k_i] \right]. \quad (9)$$

Let the cost of a switching unit in the broadcast banyan switch be one and that of a crosspoint in the PA switch be α ($\alpha < 1$). The search of the optimal switch configuration can be formulated as a nonlinear integer program as follows. (The formulation for the crosspoint switch is similar:)

$$\min_{x,y,K,J,E} L = \phi(E, (J-x)K + y) + K\phi(J, N_o/K) + \alpha K x y \quad (10)$$

subject to

1) $B(x,y,J,K,E) \leq B^*$
2) x, y, J, K, E positive integers.

$B(x,y,J,K,E)$ given by (9) is very difficult to compute as it involves summation over a K-dimensional space. On the other hand, simultaneous minimization with respect to five variables is also very difficult. We propose in the following a two-stage optimization process that can be used to obtain a suboptimal solution with considerable saving of computation and search efforts. First, determine the optimum E, K, and J assuming the absence of the PA switch and denote them as E_1, K_1, and J_1. Add in the PA switch and find the optimum x and y by solving the following simplified integer program:

$$\min_{x,y} L = \phi(E_1, (J_1 - x)K_1 + y) + K\phi(J_1, N_o/K_1) + \alpha K_1 x y$$

subject to

1) $B_{\mathrm{PA}}(x,y) \leq \beta B^*$
2) x and y positive integers.

Here $B_{\mathrm{PA}}(x,y)$ is the blocking probability at the PA switch. By setting $\beta \ll 1$ the blocking contributed by the PA switch will be insignificant so that the total blocking probability would still be around B^*. To find $B_{\mathrm{PA}}(x,y)$, define U_i as the number of overflowed calls to the PA switch from local switch i, or $U_i = \min[\max[0, W_i - (J-C-x)], x]$. Then U_i has distribution given by

$$P[U_i = u] = \begin{cases} P[W_i \leq J - C - x] & u = 0 \\ P[W_i = u + J - C - x] & 1 \leq u \leq x - 1 \\ P[W_i \geq J - C] & u = x \end{cases}.$$

The total number of overflowed calls R to the PA switch is

$$R = U_1 + U_2 + U_3 + \cdots + U_K.$$

As all U_i's are i.i.d. random variables the distribution of R is just the K-fold convolution of the distribution of any U_i with itself. The blocking probability at the PA switch is then

$$B_{\mathrm{PA}}(x,y) = \sum_{r=y+1}^{Kx} \frac{r-y}{r} P[R=r].$$

The central switch complexity reduction ratio γ is

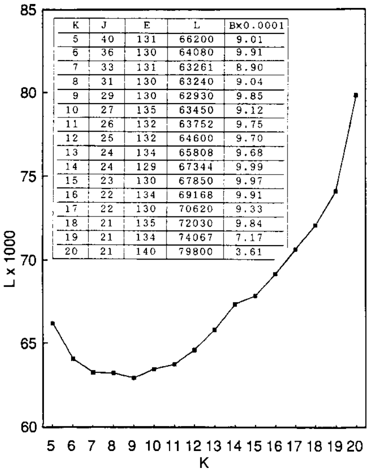
$$\gamma = \frac{\phi(E_1, J_1K_1) - \phi(E_1, (J_1-x)K_1 + y) - \alpha K_1 x y}{\phi(E_1, J_1 K_1)}.$$

VI. Examples and Discussions

As an example of optimal design, consider a network serving a population of $N_o = 1000$ users. Let $C = 10$, $B^* = 10^{-3}$, $p_1 = 0.5$, and $p_2 = 0.1$. With the use of crosspoint switches in hierarchical distribution the optimal values of K, J, E, and L are $K^* = 9$, $J^* = 29$, $E^* = 130$, and $L^* = 62\,930$. If a single switch is used, $L_o = 128\,000$ under the same blocking requirement with $E = 128$. Thus, using hierarchical distribution, the switch complexity is reduced to 49% of the original. This percentage gets smaller and smaller as N_o increases. Thus, for $N_o = 2000$, the complexity is reduced further to 38% with $K^* = 15$, $J^* = 32$, $E^* = 237$, and $L^* = 177\,760$. To investigate the sensitivity of the optimal design to K, we plot, in Fig. 6, L versus K. Here for each K

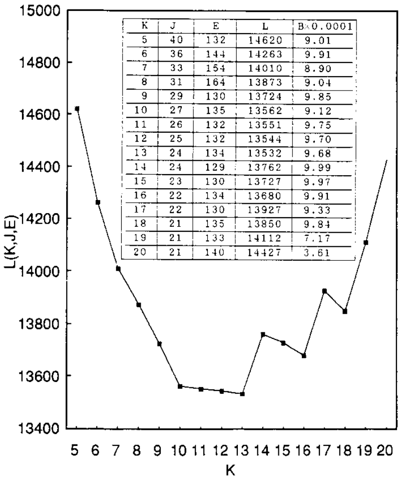
TABLE I
COMPARISON OF OPTIMAL RESULTS

		crosspoint switch		banyan switch	
		$N_o = 1000$	$N_o = 2000$	$N_o = 1000$	$N_o = 2000$
with PA	X^*	6	7	4	3
	Y^*	20	32	15	15
	L^*	59 590	163 819	13 148	27 764
no PA	E^*	130	237	134	246
	J^*	29	32	24	26
	K^*	9	15	13	21
	L^*	62 930	177 760	13 532	28 407
Single Stage	E^*	128	234	128	234
	L_o^*	128 000	468 000	18 120	42 581



K	J	E	L	B×0.0001
5	40	131	66200	9.01
6	36	130	64080	9.91
7	33	131	63261	8.90
8	31	130	63240	9.04
9	29	130	62930	9.85
10	27	135	63450	9.12
11	26	132	63752	9.75
12	25	132	64600	9.70
13	24	134	65808	9.68
14	24	129	67344	9.99
15	23	130	67850	9.97
16	22	134	69168	9.91
17	22	130	70620	9.33
18	21	135	72030	9.84
19	21	134	74067	7.17
20	21	140	79800	3.61

Fig. 6. Sensitivity of the optimal design to K, crosspoint switch.



K	J	E	L	B×0.0001
5	40	132	14620	9.01
6	36	144	14263	9.91
7	33	154	14010	8.90
8	31	164	13873	9.04
9	29	130	13724	9.85
10	27	135	13562	9.12
11	26	132	13551	9.75
12	25	132	13544	9.70
13	24	134	13532	9.68
14	24	129	13762	9.99
15	23	130	13727	9.97
16	22	134	13680	9.91
17	22	130	13927	9.33
18	21	135	13850	9.84
19	21	133	14112	7.17
20	21	140	14427	3.61

Fig. 7. Sensitivity of the optimal design to K, broadcast banyan switch.

chosen, L is optimized with respect to J and E. The optimal J and E values for specific K's are also shown.

Using the broadcast banyan switch, $K^* = 13$, $J^* = 24$, $E^* = 134$, and $L^* = 13\,532$. In comparison, $L_o = 18\,036$ under the same blocking probability. Thus, the complexity is reduced to 75% for this case. When N_o is increased from 1000 to 2000, the complexity reduction percentage is reduced from 75 to 66.6% with $K^* = 21$, $J^* = 26$, $E^* = 246$, and $L^* = 28\,407$. The optimal single stage configuration has $L_o = 42\,581$ and $E = 234$. Fig. 7 shows the complexity of the optimal configuration as a function of K.

The optimal design with the addition of the PA switch is shown in Table I. To summarize, using the crosspoint switch $\gamma = 9.8\%$ and $\gamma = 12.3\%$ for $N_o = 1000$ and $N_o = 2000$, respectively. For the broadcast banyan switch γ depends on α, which is difficult to determine. Using a hypothetical value of $\alpha = 0.3$, $\gamma = 8.4$, and $\gamma = 7\%$ are obtained for $N_o = 1000$ and $N_o = 2000$, respectively. Note that γ is positive even for $\alpha = 1$.

VII. CONCLUSION

Video will constitute the bulk of the traffic in broad-band ISDN. It is therefore essential to understand the switching requirements for this traffic. A video traffic model and an optimal two-level hierarchical video distribution network are studied in this paper. Reduction of switch size via dynamic port allocation is suggested. Numerical results show that the hierarchical configuration can offer substantial reduction of switch complexity and that the addition of a port allocation switch can further reduce the complexity of the central switch by 10%. Extensions of the present work include the optimal design of switch configuration for multirate channels and the dynamic management of channel resources.

ACKNOWLEDGMENT

This research was carried out while the author held a visiting fellowship at Bellcore, U.S.A. during the summer of 1989. It is a pleasure to acknowledge the invitation offered by E. Nussbaum and the helpful conversations the author had with T. T. Lee. Sincere thanks are also due to E. W. M. Wong who pointed out an error in my blocking probability derivation, to M. Chen and Y.-W. Leung who developed the optimization programs, and to S. H. Kan who typed the manuscript. During the revision of this paper, the reviewers had suggested many changes that lead to a smoother presentation.

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Tak-Shing P. Yum (S'76–M'78–SM'86) for a photograph and biography, see p. 1140 of the July 1991 issue of this TRANSACTIONS.