Call Blocking Probabilities of Dynamic Routing Algorithms in B-ISDN Networks

Sae-woong Bahk and Joon-hwan Kim

Abstract

In this paper we apply routing algorithms in circuit switched networks to B-ISDN networks and investigate the performance. B-ISDN supports a wide range of services with heterogeneous bandwidth requirements. We assume that the network supports D classes of traffic. It is modeled as a finite D dimensional Markov chain. A call is blocked on arrival if the required bandwidth is not available on the route. The shortest path routing, alternate routing and trunk reservation are considered for performance comparison. We also consider trunk reservation with restricted access control where the network reserves certain amount of bandwidths for one class of traffic that assumes a higher transmission priority. Through the method of successive iterations, we obtain the steady state equilibrium probabilities and call blocking probabilities for dynamic routing. The results can be used to design a B-ISDN network that improves network connection availability and efficiency while simultaneously reducing the network costs.

I. Introduction

Dynamic routing of calls in circuit switched networks can improve throughput and robustness. Throughput is improved by establishing calls on alternate routes when the primary route is blocked. Robustness measured in terms of the network's ability to respond to unexpected network conditions, is improved by transferring calls to backup routes [1-8]. Alternate routing and trunk reservation are the two of well-known dynamic routing schemes used to alleviate network congestion in circuit switched networks. There is a large literature investigating the performance of these schemes. The methodology of successive iterations was developed for performance bounds and approximations since dynamic routing destroys the product-form result.

A lot of investigations have been done for single service loss networks for which a call occupies exactly one circuit (or channel) in each link along its route [5]. However, the performance of dynamic routing for B-ISDN has not been considered in detail, yet. Given the great gains in performance achieved by dynamic routing in circuit switched networks, we are motivated to apply the same routing schemes to B-ISDN networks. This is mainly because B-ISDN networks based on like ATM use the virtual circuit switching technology. The statistical multiplexing and the heterogeneity of traffic complicate the design of the routing scheme in B-ISDN networks. Even though various QoS parameters can be given by a call, in this paper, we assume that only the bandwidth requirement of the call, such as an effective bandwidth or peak rate, is used for admission control. Namely, each call's QoS class is represented in the form of required bandwidth. The concept of the effective bandwidth has arisen from numerous studies on integrated networks [10][11]. It is an accurate assessment of the capacity required by an incoming call in order to guarantee constrains on cell loss or delay. Effective bandwidth admission is an admission policy that is easy to implement in ATM networks.

In this paper we apply dynamic routing in circuit switched networks to B-ISDN networks and analyze the performance through the methodology of successive iterations to solve a D dimensional Markov chain problem. We consider both networks of mesh and regular topology. Each call has an heterogeneous bandwidth requirement. An incoming call is accepted if the required bandwidth is available on the route to the destination. Otherwise the network blocks the call.

This paper is organized as follows. We investigate the performance of dynamic routing in a network of mesh in Section II, and then we consider a fully connected network in Section III. Some numerical examples are given in Section

Manuscript received March 29, 1997; accepted January 5, 1998.
The authors are with the School of Electrical Engineering, Seoul National University.

IV, followed by the conclusion in Section V.

II. Performance Analysis for a Network of Mesh

In this section, we briefly study the product form solution for the shortest path routing first
and consider the performance of dynamic routing in B-ISDN networks. The network supports D classes of traffic; for each class-d call at node i destined for node j, arrivals are assumed to form a Poisson process with rate λ^d_{ij}, and the holding time is exponentially distributed with mean $1/\mu_d$. For convenience, we assume that each call requests a discrete value of bandwidth and that each link has equal capacity. Therefore, the capacity requirements have a greatest common divisor equal to 1. Throughout the paper, we define the following notations:

$N \equiv$ the number of nodes,

$L \equiv$ a set of links (unidirectional),

$B^d_{ij} \equiv$ the blocking probability of class-d calls at node i destined for node j,

$B^{(k,l)}_d \equiv$ the link blocking probability of class-d calls at link (k, l),

$B^{(k,l)}_{d,s} \equiv$ the link blocking probability of the shortest path routed class-d calls at link (k, l),

$B^{(k,l)}_{d,a} \equiv$ the link blocking probability of alternate routed class-d calls at link (k, l),

$L^{d,1}_{ij} \equiv$ the set of tandem links on the shortest path for class-d calls at node i destined for node j ; $L^{d,1}_{ij} \subset L$,

$L^{d,q}_{ij} \equiv$ the set of tandem links on the qth shortest path for class-d calls at node i destined for node j; $L^{d,q}_{ij} \subset L$,

$\rho^d_{ij} \equiv \lambda^d_{ij}/\mu_d$; the offered external traffic intensity of class-d calls at node i destined for node j,

$\rho^{(m,n)}_{d,s} \equiv$ the shortest path routed offered class-d loads over link (m, n),

$\rho^{(m,n)}_{d,a} \equiv$ the alternate routed offered class-d loads over link (m, n),

$\rho^{(m,n)}_d \equiv \rho^{(m,n)}_{d,s} + \rho^{(m,n)}_{d,a}$,

$M^d_{ij} \equiv$ the number of candidate paths for class-d calls at node i destined for j,

$K^{d,q}_{ij} \equiv$ the blocking probability of class-d calls on the q th shortest path at node i destined for node j, $q = 1, \cdots, M^d_{ij}$,

$CH \equiv$ the link rate [bps],

$BW_d \equiv$ the required bandwidth[bps] of a class-d call that guarantees its required QoS,

$BW_G \equiv$ the greatest common divisor of $\{BW_1, \cdots, BW_D\}$ which corresponds to the bandwidth of one channel,

$\boldsymbol{A} \equiv (A_1, A_2, \cdots, A_D)$ where $A_d = \frac{BW_d}{BW_G}$ is the number of channels required by a class-d,

$C \equiv \lfloor \frac{CH}{BW_G} \rfloor$; the total number of channels that a link can support where $\lfloor x \rfloor$ represents the largest integer less than or equal to x,

$\boldsymbol{x} \equiv (x_1, x_2, \cdots, x_D)^T$; the state vector of a link where x_d represents the number of class-d calls on the link,

$P(\boldsymbol{x}) \equiv$ the steady state probability that a link is in state $\boldsymbol{x}$,

$\boldsymbol{R} \equiv \{R_1, R_2, \cdots, R_D\}$; where R_d is the trunk reservation parameter for class-d\$d\$ calls.

Then, the set of all possible states of a link is given by

$$\Omega(C,D) := \{\boldsymbol{x}: \boldsymbol{A}\boldsymbol{x} \le C\} = \{\boldsymbol{x}: \sum_{i=1}^{D} A_i x_i \le C\}. \quad (1)$$

Therefore, we can write the probability of the link being in unreachable states

$$P(\boldsymbol{x}) = 0 \quad \text{for} \quad \boldsymbol{x} \notin \Omega(C,D). \quad (2)$$

Consider the one link problem first where the directly offered loads of class-d calls are ρ_d.

In this case, it is well known that the unique equilibrium probabilities associated with this model have a product form solution [4]-[6]. Then, $P(\boldsymbol{x})$ is given by

$$P(\boldsymbol{x}) = G^{-1}(C,D)\,\hat{P}(\boldsymbol{x}), \quad (3)$$

where

$$\hat{P}(\boldsymbol{x}) = \prod_{d=1}^{D} \frac{\rho_d^{x_d}}{x_d!}, \quad (4)$$

and

$$G(C,D) = \sum_{\boldsymbol{x} \in \Omega(C,D)} \prod_{d=1}^{D} \frac{\rho_d^{x_d}}{x_d!}. \quad (5)$$

The quantity $G(C,D)$ is termed the normalization constant. The link (or call) blocking probabilities of class-d calls are given by

$$B_d = 1 - \frac{G(C-A_d, D)}{G(C,D)}, \quad d = 1, \cdots, D. \quad (6)$$

Let's apply this to a network of mesh with N nodes that uses the shortest path routing scheme. In this scheme, a call tries the shortest path only. If busy, the call is blocked. Since there are no alternate routed calls, the offered loads at link (m, n) are given by

$$\rho^{(m,n)}_{d,s} = \sum_{i,j \in N} \rho^d_{ij} \prod_{(k,l) \in L^{d,1}_{ij} - \{(m,n)\}} (1 - B^{(k,l)}_d), \quad (7)$$

$$\rho_{d,a}^{(m,n)} = 0. \tag{8}$$

Then

$$\rho_d^{(m,n)} = \rho_{d,s}^{(m,n)}. \tag{9}$$

Therefore, the call blocking probabilities B_{ij}^d are given by

$$B_{ij}^d = K_{ij}^{d,1} = 1 - \prod_{(k,l)\in L_{ij}^{d,1}} (1 - B_d^{(k,l)}), \quad d = 1, \cdots, D. \tag{10}$$

Given the call arrival rates to link (m, n), we can obtain $B_d^{(m,n)}$ with the assumption that each link blocks the calls independently.

1. Alternate Routing Scheme

In this scheme a class- d call at node i destined for node j tries the shortest path first. If busy, it will try up to $(M_{ij}^d - 1)$ alternate routes in order of preference. If the shortest path and all alternate paths are busy, the call is blocked.

Consider a network with five nodes in figure 1. λ_{25}^3 and B^3_{25} represent the arrival rate and blocking probability of class-3 calls at node 2 destined for node 5, respectively. Table 1 shows the list of candidate paths and link set for each path for $M_{25}^3 = 4$. If all the candidate paths are not available for an incoming class-3 call, the call is blocked.

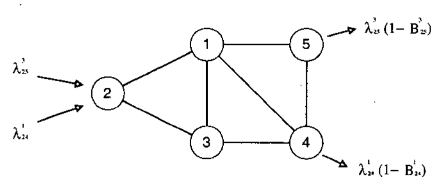


Fig. 1. An example of a network with five nodes.

Table 2. An example of the list of candidate paths.

Candidate paths	Set of links
1	$L_{25}^{3,1} = \{(2,1), (1,5)\}$
2	$L_{25}^{3,2} = \{(2,3), (3,1), (1,5)\}$
3	$L_{25}^{3,3} = \{(2,3), (3,4), (4,5)\}$
4	$L_{25}^{3,4} = \{(2,3), (3,1), (1,4), (4,5)\}$

Generally the offered loads of class- d calls over link (m, n) are given by

$$\rho_{d,s}^{(m,n)} = \sum_{i,j\in N} \rho_{ij}^d \prod_{(k,l)\in L_{ij}^{d,1} - \{(m,n)\}} (1 - B_d^{(k,l)}), \tag{11}$$

$$\begin{aligned} \rho_{d,a}^{(m,n)} = & \sum_{i,j\in N} \rho_{ij}^d K_{ij}^{d,1} \prod_{(k,l)\in L_{ij}^{d,2} - \{(m,n)\}} (1 - B_d^{(k,l)}) + \\ & \sum_{i,j\in N} \rho_{ij}^d K_{ij}^{d,1} K_{ij}^{d,2} \prod_{(k,l)\in L_{ij}^{d,3} - \{(m,n)\}} (1 - B_d^{(k,l)}) + \cdots \\ & + \sum_{i,j\in N} \rho_{ij}^d \prod_{q=1}^{M_{ij}^d - 1} K_{ij}^{d,q} \prod_{(k,l)\in L_{ij}^{d,M_{ij}^d} - \{(m,n)\}} (1 - B_d^{(k,l)}), \end{aligned} \tag{12}$$

where

$$K_{ij}^{d,q} = 1 - \prod_{(k,l)\in L_{ij}^{d,q}} (1 - B_d^{(k,l)}), \quad q = 1, 2, \cdots, M_{ij}^d, \; d = 1, 2, \cdots, D. \tag{13}$$

The total offered loads $\rho_d^{(m,n)}$ are given by

$$\rho_d^{(m,n)} = \rho_{d,s}^{(m,n)} + \rho_{d,a}^{(m,n)}. \tag{14}$$

These equations are obtained by assuming that the class- d call stream offered to the q-th shortest path is thinned by the factor $(1 - B^{(k,l)_d})$ at each link $(k,l) \in L_{ij}^{d,q} - \{(m,n)\}$ before being offered to link (m, n). The quantity $K_{ij}^{d,q}$ is the proportion of class- d calls at node i destined for node j offered to the q-th shortest route which are lost. Consequently, the offered rate becomes $\lambda_{ij}^d \prod_{l=1}^{q-1} K_{ij}^{d,l}$. Equations (3)-(4) and (11)-(14) can be solved iteratively to obtain the link blocking probabilities $B_d^{(m,n)}$, given the convergence range, the external offered loads ρ_{ij}^d, and the initial arbitrary values of the total offered loads $\rho_d^{(m,n)}$. This means that the product form solution is valid for alternate routing. Then, we obtain

$$B_{ij}^d = \prod_{q=1}^{M_{ij}^d} K_{ij}^{d,q}, \quad d = 1, 2, \cdots, D. \tag{15}$$

2. Trunk Reservation Scheme

The purpose of trunk reservation is to limit excessive alternate routing during periods of general overload, and yet not to exclude alternate routing altogether. This is because the alternate route consumes much of the bandwidth resource. In this scheme, alternate routed class- d calls are blocked if a minimum number of idle trunks, say R_a, are not available. The shortest path is tried first. If busy, then alternate paths will be tried in order of preference. Therefore, we obtain

$$\rho_{d,s}^{(m,n)} = \sum_{i,j\in N} \rho_{ij}^d \prod_{(k,l)\in L_{ij}^{d,1} - \{(m,n)\}} (1 - B_{d,s}^{(k,l)}), \tag{16}$$

$$\begin{aligned} \rho_{d,a}^{(m,n)} = & \sum_{i,j\in N} \rho_{ij}^d K_{ij}^{d,1} \prod_{(k,l)\in L_{ij}^{d,2} - \{(m,n)\}} (1 - B_{d,a}^{(k,l)}) + \\ & \sum_{i,j\in N} \rho_{ij}^d K_{ij}^{d,1} K_{ij}^{d,2} \prod_{(k,l)\in L_{ij}^{d,3} - \{(m,n)\}} (1 - B_{d,a}^{(k,l)}) + \cdots \\ & + \sum_{i,j\in N} \rho_{ij}^d \prod_{q=1}^{M_{ij}^d - 1} K_{ij}^{d,q} \prod_{(k,l)\in L_{ij}^{d,M_{ij}^d} - \{(m,n)\}} (1 - B_{d,a}^{(k,l)}), \end{aligned} \tag{17}$$

where

$$K_{ij}^{d,1} = 1 - \prod_{(k,l)\in L_{ij}^{d,1}} (1 - B_{d,s}^{(k,l)}), \tag{18}$$

$$K_{ij}^{d,q} = 1 - \prod_{(k,l)\in L_{ij}^{d,q}} (1 - B_{d,a}^{(k,l)}), \quad q = 2, \cdots, M_{ij}^d, \; d = 1, 2, \cdots, D \tag{19}$$

We also obtain the same form of $\rho_d^{(m,n)}$ as in (14). These equations are obtained by assuming that class- d call streams offered to the shortest path and alternate paths are thinned by the factor $(1-B^{(k,l)}{}_{d,s})$ and $(1-B^{(k,l)}{}_{d,a})$, respectively, at each link $(k,l)\in L_{ij}^{d,q}-\{(m,n)\}$ before being offered to link (m,n).

Figures 2 illustrates the Markov chain for the case of $K=2$ with the numbers of channel requirement of 1 and 2, respectively. Figure 3 shows the general state transition diagram at state $\boldsymbol{x}$ for the case of D. The steady state equilibrium probability $P(\boldsymbol{x})$ satisfies the normalization condition $\sum_{\boldsymbol{x}\in\Omega}P(\boldsymbol{x})=1$, and can be solved by an iterative method. If we omit the superscripts (m,n) for $\rho_d^{(m,n)}$, $\rho_{d,s}^{(m,n)}$, $\rho_{d,a}^{(m,n)}$, we can write the state equation for link (m,n) as

$$\sum_{d=1}^{D}(x_d\mu_d+\eta_d(\boldsymbol{x})\mu_d)P(\boldsymbol{x})=\sum_{d=1}^{D}((x_d+1)\mu_d P(\boldsymbol{x}_d^{+1}) + \eta_d(\boldsymbol{x}_d^{-1})\mu_d P(\boldsymbol{x}_d^{-1})) \quad \text{for } \boldsymbol{x}\in\Omega \tag{20}$$

where

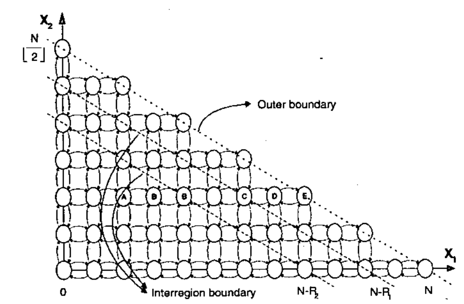


Fig. 2. Markov chain for trunk reservation ($K=2, A_1=1, A_2=2$).

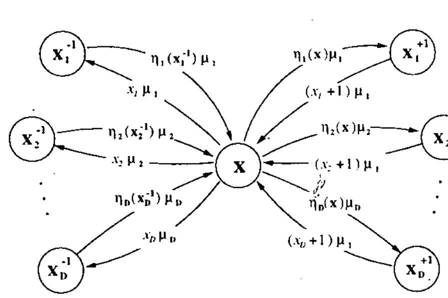


Fig. 3. State transition ($K=D$)

$$\eta_i(\boldsymbol{x})\equiv\begin{cases}\rho_d & \text{if } \mathbf{Ax}_d^{+1}\le \mathrm{C}-\mathrm{R}_d\\ \rho_{d,s} & \text{otherwise,}\end{cases}$$

and

$$\boldsymbol{x}_d^{\pm1}\equiv(x_1,\cdots,x_{d-1},x_d\pm1,x_{d+1},\cdots,x_D).$$

$\eta_i(\boldsymbol{x})$ represents the change of offered class- d traffic loads between the interregion boundaries. The link blocking probabilities, $B_{d,s}^{(m,n)}$ and $B_{d,a}^{(m,n)}$ are given by

$$\begin{aligned}B_{d,s}^{(m,n)} &= \sum_{\boldsymbol{x}\in\Omega_{d,s}}P(\boldsymbol{x}),\\ B_{d,a}^{(m,n)} &= \sum_{\boldsymbol{x}\in\Omega_{d,a}}P(\boldsymbol{x}), \quad d=1,\cdots,D,\end{aligned} \tag{21}$$

where

$$\Omega_{d,s}:=\{\boldsymbol{x}: C-R_d < \boldsymbol{Ax}\le C\},$$

$$\Omega_{d,a}:=\{\boldsymbol{x}: C-R_d-A_d < \boldsymbol{Ax}\le C\}.$$

Then, the call blocking probabilities B_{ij}^d are given by

$$B_{ij}^d=\prod_{q=1}^{M_{ij}^d}K_{ij}^{d,q}, \quad d=1,2,\cdots,D. \tag{22}$$

3. Trunk Reservation Scheme with Restricted Access Control

We evaluate an trunk reservation scheme reserving certain amount of trunks for one class of traffic. Specifically, we assume that n_1 channels are reserved for class-1 traffic. This means that if less than n_1 channels are idle, only class-1 traffic is admitted into the network.

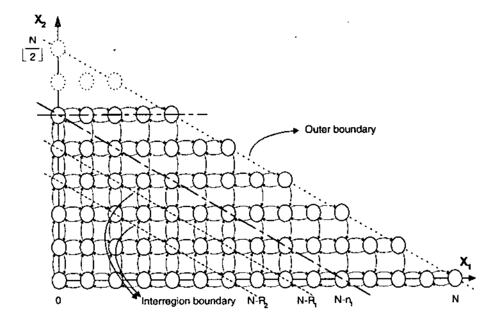


Fig. 4. Markov chain for trunk reservation with restricted access control ($K=2, A_1=1, A_2=2$).

For example, figure 4 shows the Markov chain with some unreachable states for the case of $K=2$. For convenience,

$$\delta_d(\boldsymbol{x})\equiv\begin{cases}0 & \text{if } \boldsymbol{x}\in\Omega_d\\ 1 & \text{otherwise,}\end{cases}$$

where

$$\Omega_1:=\{\boldsymbol{x}: C-A_1 < \boldsymbol{Ax}\le C\},$$

$$\Omega_d:=\{\boldsymbol{x}: C-n_1-A_d < \boldsymbol{Ax}\le C \text{ and } x_i\le \lfloor \frac{C-n_1}{A_i} \rfloor, i=2,\cdots,D\} \text{ for } d=2,\cdots,D.$$

We can write

$$P(\boldsymbol{x})=0 \quad \text{for} \quad \boldsymbol{x}\notin\Omega_{feas}(C,D), \tag{23}$$

where the feasible region is

$$\Omega_{feas}(C,D):=\{\boldsymbol{x}: \boldsymbol{Ax}\le C \text{ and } x_d\le \lfloor \frac{C-n_1}{A_d} \rfloor, d=2,\cdots,D\}. \tag{24}$$

The state equation for link (m, n) is

$$\sum_{i=1}^{D}(x_i\mu_i + \eta_i(x)\mu_i\delta_i(x))P(x) = \sum_{i=1}^{D}((x_i+1)\mu_i P(x_i^{+1}) + \eta_i(x_i^{-1})\mu_i\delta_i(x_i^{-1})P(x_i^{-1})), \quad (25)$$

for $x \in \Omega_{feas}(C, D)$.

The link blocking probabilities $B_d^{(m,n)}$ are given by

$$B_d^{(m,n)} = \sum_{x\in\Omega_d} P(x), \quad d=1,\cdots,D. \quad (26)$$

Then we obtain

$$B_{ij}^d = \prod_{q=1}^{M_{ij}^d} K_{ij}^{d,q}, \quad (27)$$

where

$$K_{ij}^{d,q} = 1 - \prod_{(k,l)\in L_{ij}^{d,q}}(1 - B_d^{(k,l)}), \quad q = 1,\cdots,M_{ij}^d, \quad d=1,\cdots,D. \quad (28)$$

III. Performance Analysis for a Fully Connected Network

In this section, we consider a network with N nodes that is symmetric and fully connected. In ATM networks, a fully connected network can be configured by the engineering of trunks through virtual path routing. For this topology, we can keep the notations much simple. We assume that the direct (shortest) path consists of one hop only, while alternate routes consist of M disjoint two-link paths ($M \le N-2$).

1. Alternate Routing Scheme

In this scheme, a call tries the direct path first. If busy, it will try up to M more alternate routes, in order of preference. If the direct path and all M paths are busy, the call is blocked. Let $\rho_{d,s}$ represent the intensity of direct routed class-d traffic that comes from the directly linked node. Let $\rho_{d,a}$ represent the intensity of alternate routed class-d traffic. Each link is offered an equal amount of the class-d alternate routed traffic that overflows to the rest of the network. Under the assumption that traffic conditions of the successive links are independent and that all node-pair traffic loads are equal, we can describe the traffic statistics for one source-destination node pair on a link. The total offered loads of a link, ρ_d, are the sum of direct routed traffic and alternate routed traffic.

$$\begin{aligned} \rho_{d,a} &= 2\rho_{d,s}B_dH_d + 2\rho_{d,s}B_d(1-H_d^2)H_d + \cdots + 2\rho_{d,s}B_d(1-H_d^2)^{M-1}H_d \\ &= 2\rho_{d,s}B_d(1-(1-H_d)^M)/H_d, \\ \rho_d &= \rho_{d,s} + \rho_{d,a}, \\ H_d &= 1 - B_d, \quad d=1,2,\cdots,D, \end{aligned} \quad (29)$$

where H_d is the link availability for class-d overflow traffic. As before, the above equations can be solved iteratively to obtain the link blocking probabilities B_d(5), given the convergence range, the external offered loads $\rho_{d,s}$, and the initial arbitrary values of the total offered loads ρ_d. Then, the call blocking probabilities CB_d experienced by class-d calls are given by

$$CB_d = B_d(1-H_d^2)^M, \quad d=1,2,\cdots,D. \quad (30)$$

2. Trunk Reservation Scheme

In this scheme the direct path is tried first. If busy, then alternate paths will be tried in order of preference. If alternate routed calls find less than R_d channels on all the alternate routes, they are blocked. Let $B_{d,s}$ and $B_{d,a}$(21) represent the link blocking probabilities of direct routed and alternate routed class-d calls, respectively. Then, we obtain

$$\begin{aligned} \rho_{d,a} &= 2\rho_{d,s}B_{d,a}H_{d,a} + 2\rho_{d,s}B_{d,s}(1-H_{d,a}^2)H_{d,a} + \cdots + 2\rho_{d,s}B_{d,s}(1-H_{d,a}^2)^{M-1}H_{d,a} \\ &= 2\rho_{d,s}B_{d,s}(1-(1-H_{d,a})^M)/H_{d,a}, \\ \rho_d &= \rho_{d,s} + \rho_{d,a}, \\ H_{d,a} &= 1 - B_{d,a}, \quad d=1,2,\cdots,D. \end{aligned} \quad (31)$$

The state equations for the fully connected network have the same form as in a network of mesh. Then, we obtain

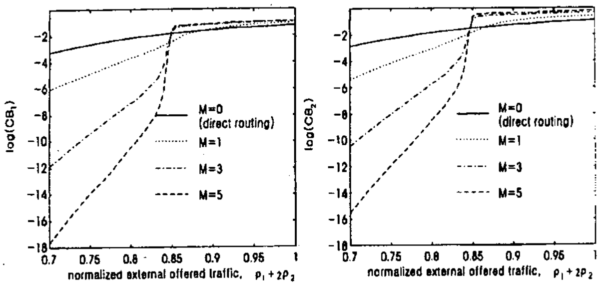
$$CB_d = B_{d,s}(1-H_{d,a}^2)^M, \quad d=1,\cdots,D. \quad (32)$$

IV. Numerical Analysis

In this section, we investigate the performance of the routing algorithms through numerical analysis. As the required CPU time for a network of mesh is too large, we consider the fully connected network with each link capacity of 100 channels. We assume the following:

- The network supports two classes of traffic ($A_1 = 1, A_2 = 2, R = R_1 = R_2$).
- The intensity of class-1 traffic is one and a half times higher than that of class-2 traffic.

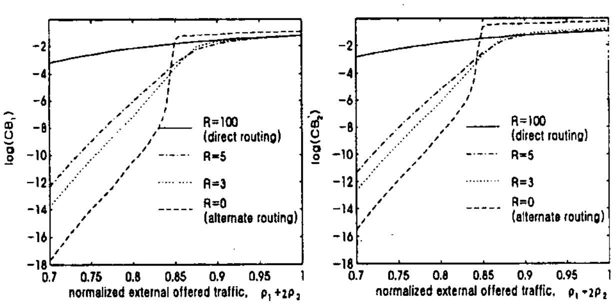
For the trunk reservation scheme e model the system as a two dimensional Markov chain which has 2601 states. Through the method of iterations we can obtain the steady state equilibrium probabilities. The iterations are stopped when the maximum change in blocking probability is less than 10^{-8}. Calculations were done by using OCTAVE (compatible with MATLAB). It was executed on a Pentium Pro 200MHz CPU machine. It took about 10 minutes to calculate one point in the graph.



(a) (b)

Fig. 5. Call blocking probabilities of direct routing and dynamic alternate routing. (a) Class-1 traffic. (b) Class-2 traffic.

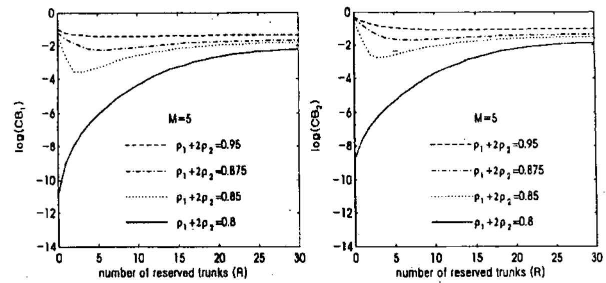
The offered load of a link changes from 0.7 to 1.0 which is the interval of heavy loading showing interesting results. Figure 5 plots the call blocking performance of direct (the shortest path) routing and dynamic alternate routing for various values of M. The case of $M=0$ corresponds to direct routing. Dynamic alternate routing improves the blocking performance at light and moderate loading as M increases. This result also shows that when heavy traffic is offered, alternate routing becomes much more sensitive than direct routing due to routing oscillations.



(a) (b)

Fig. 6. Call blocking probabilities of trunk reservation scheme (M=5) (a) Class-1 traffic. (b) Class-2 traffic.

Figure 6 plots the performance of trunk reservation for various values of R. This result shows that trunk reservation behaves very similarly to alternate routing for small R. The case for $R=0$ corresponds to dynamic alternate routing. In most cases, trunk reservation performs better than direct routing. In heavy traffic, the performance of trunk reservation is about the same as that of direct routing. This means that since reserved trunks for direct routed traffic are in effect, too much use of alternate routes (routing oscillations) can be avoided.



(a) (b)

Fig. 7. Call blocking probabilities vs. number of reserved trunks (M=5). (a) Class-1 traffic. (b) Class-2 traffic.

Figure 7 shows the call blocking probabilities of the trunk reservation scheme with respect to the number of reserved trunks when five alternate paths are available for each source-destination node pair. Four patterns of the external offered loads are considered. This figure shows that at the loading of 0.8, dynamic alternate routing works better than trunk reservation. However, as the traffic load increases, the trunk reservation scheme with optimum R shows the best performance. Routing oscillations and instability are observed at low number of reserved trunks when heavy loads are offered. Too high a number of reserved trunks for direct path users also deteriorates the performance. This is because the network limits too much use of alternate paths. In the case of the external offered load of 0.85, this figure also shows that the optimal number of reserved trunks is 3.

Figure 8 shows the performance of the trunk reservation scheme for which the number of alternate paths are 5 and 10, respectively. The shape of the curves in figure 8 can be divided into three parts: a steep segment for small R, a shallow segment around optimum R, and a concave segment with an asymptote for large R. The curve of $\rho_1+2\rho_2=0.85$ in figure 7 has a similar shape. As Mitra observed in [4], it is undesirable to operate in the region where R is too small with respect to the optimum R and otherwise performance is relatively insensitive.

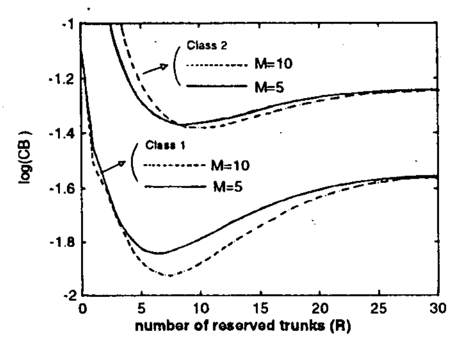


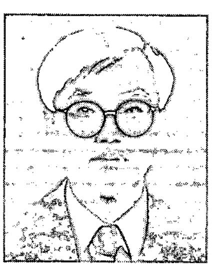
Fig. 8. Call blocking probabilities of two classes traffic vs. number of reserved trunks ($\rho_1+2\rho_2=0.9$).

V. Conclusion

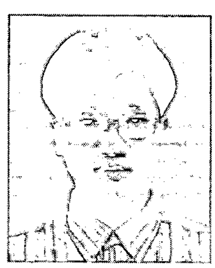
In this paper, we applied routing algorithms in circuit switched networks to B-ISDN networks and analyzed the performance. The considered network supports D classes of calls with heterogeneous bandwidth requirements. Networks of mesh and regular topology are both considered. They were modeled as a finite D dimensional Markov chain. Alternate routing and trunk reservation were considered for the study of performance comparison. The performance of alternate routing with restricted access control was also considered. Some numerical results were also provided. Through the method of successive iterations, we could obtain the steady state equilibrium probabilities and the blocking probabilities experienced by each call. The results can be used to design a B-ISDN network that improves network connection availability while simultaneously the reducing network costs. Performance analysis of dynamic routing with several routing parameters is left for further studies.

References

[1] S. Bahk, "Routing for interconnected networks and high speed wide area networks", Ph. D. Thesis, University of Pennsylvania, Philadelphia, 1991.
[2] R. Cooper, "Introduction to Queueing Theory", 2nd Ed., New York: Macmillan Co., 1981.
[3] D. Mitra and J. Seery, "Comparative evaluations of randomized and dynamic routing strategies for circuit switched networks", IEEE Trans. on Communications, Vol. 39, No. 1, Jan. 1991.
[4] D. Mitra, R. Gibbens, and B. Huang, "State-dependent routing on symmetric loss networks with trunk reservations-I", IEEE Trans. on Communications, Vol. 41, No. 2, Feb. 1993.
[5] K. Ross, "Multiservice loss models for broadband telecommunication networks", Springer-Verlag, London, 1995.
[6] D. Tsang and K. "Ross Algorithms for determining exact blocking probabilities in tree networks", IEEE Trans. on Communications, Vol. 38, pp. 1266-1271, 1990.
[7] E. van Doorn and F. Panken, "Blocking probabilities in a loss system with arrivals in geometrically distributed batches and heterogeneous service requirements", IEEE/ACM Trans. on Networking, Vol. 1, No. 6, Dec. 1993.
[8] W. Wang and T. Saadawi, "Trunk congestion control in heterogeneous circuit switched networks", IEEE Trans. on Communications, Vol. 40, No. 7, Jul. 1992.
[9] T. Yum and M. Schwartz, "Comparison of routing procedures for circuit switched traffic in nonhierarchical networks", IEEE Trans. on Communications, Vol. 35, No. 5, May 1987.
[10] R. Gibbens and P. Hunt, "Effective Bandwidths for the Multitype UAS Channel", Queueing Systems, Vol. pp. 17-28, 1991.
[11] J. Hui, "Resource Allocation for Broadband Networks", IEEE JSAC, Vol. 6, pp. 1598-1608, 1988.



Sae-woong Bahk received the B.S. and M.S. degrees in electrical engineering from Seoul National University in 1984 and 1986 respectively, and the Ph.D. Degree from the University of Pennsylvania in 1991. He majored Telecommunication Networks for his study. From 1991 through 1994 he was with the Department of Network Operations Systems at AT&T Bell Laboratories as an Member of Technical Staff where he worked on the projects for the development of network operation systems for AT&T networks. In 1994 he joined the faculty of the School of Electrical Engineering at Seoul National University, where he is currently an assistant professor. His areas of interests include performance analysis and design of communication networks, interworking of ATM and non-ATM networks, wireless ATM networks, bandwidth allocation and traffic control at high speed networks, and high speed network protocols.



Joon-Hwan Kim received B.S. and M.E. degrees in electronics engineering from Seoul National University, Seoul, Korea, in 1993 and 1995. He is now working toward the Ph.D. degree in school of electrical engineering at the same university. His current research interests include high speed network design and network planning for future data service.