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Fault-tolerant Design of Packet Switched Network with Unreliable Links

Chung G. Kang* *Regular Member*

불안정한 링크를 고려한 패킷 교환망 설계

正會員 강 충 구*

ABSTRACT

Network optimization and design procedures often separate quality of service (QOS) performance measures from reliability issues. This paper considers channel allocation and flow assignment (routing) in a network subject to link failures. Fault-tolerant channel allocation and flow assignments are determined which minimize network cost while maintaining QOS performance requirements. This approach is shown to yield significant network cost reductions compared to previous heuristic methods used in the design of packet switched network with unreliable links.

요 약

일반적으로 기존 통신망 최적화 및 설계에 있어서 통신망의 품질을 링크의 불안정성에 따른 신뢰도와 분리하여 다루어지고 있다. 본 논문은 패킷교환망에서 일반적으로 발생할 수 있는 링크의 손실을 고려하여 링크의 용량과 경로설정을 동시에 최적화하는 문제를 다룬다. 이와 같은 최적화 접근방법을 통해 최소의 망 구성비용으로, 확률적으로 발생 가능성이 높은 링크의 손실시에도 망 내에서의 버퍼 과밀로 인한 평균 패킷 손실확률 또는 종단간 평균 지연시간등과 같은 주어진 망 품질 목표를 만족시킬 수 있는 설계 방안을 제시한다. 링크의 손실을 고려한 기존의 설계 방식과 비교할 때, 본 논문에서 제안한 알고리즘은 망 구성비용의 최소화에 있어서 월등한 결과를 보인다.

I. Introduction

The joint capacity and flow assignment optimization problem plays a central role in the design of large scale packet switching networks[1-4]. This design methodology determines the capacity allocation and flow or routing assignment to optimize network cost subject to quality of service (QOS) performance constraints such as average delay, throughput or buffer overflow probability. In conventional capacity and flow assignment optimization problems, network reliability

*고려대학교 전기/전자/전파공학부
Schod of Electrical Korea University
論文番號:95385-1108
接受日字:1995년 11월 8일

issues are seldomly addressed. The common approach in network optimization procedures is to separate QOS requirement aspects from reliability issues, or vice versa. Network reliability clearly affects a quality of service or performance objective directly and thus, reliability issues should be integrated with other QOS measures in the course of network planning and design. In the tactical battlefield environment, for example, fault-tolerant network design methodologies are of particular importance. It is also important to develop fault-tolerant schemes for large-scale high-speed networks serving critical applications.

The concept of performance-related reliability measures was considered in [5] for analyzing a degradable computing system. A joint measure of performance and reliability has been formulated into a *performability* measure, which is defined to be the steady-state probability that the network is in a set of states, in which the performance measure is within a specified range[5]. Using the performability measure, [5] proposed a minimum-cost dimensioning approach for common channel signaling networks under both performance and reliability constraints. A network reliability measure based on a routing model was proposed for circuit switched networks in [7] where reliability is defined to be the difference between amount of the lost call traffic under no link failure and that in the presence of link failure. A fault-tolerant joint capacity and flow assignment design approach, called *proofing method*, has been proposed in [8]. This approach assigns redundant capacity, beyond that required to maintain a QOS level under normal network conditions, to each link in advance. This capacity augmentation prevents performance degradation in the presence of network state changes caused by link failures. Capacity augmentation approaches in the proofing method were based on heuristic considerations and were not claimed to be optimum in any sense. Moreover, the proofing method itself does not reflect the cost optimization issue.

In this paper, we generalize the proofing method by formulating an optimal capacity augmentation and flow assignment (OCA/FA) problem. The objective is to obtain fault-tolerant capacity and flow assignment schemes in which traffic demand and QOS network performance requirement are met at a minimum network cost regardless of the network topological state. This OCA/FA problem is generally a nonlinear convex optimization problem. A novel integer solution technique based on marginal analysis is devised to obtain a suboptimal capacity augmentation scheme while the optimal flow assignments in each state are determined using the optimal routing algorithm. Comparisons to previously proposed heuristic capacity augmentation procedures in [8] show that a significant reduction in network cost can be obtained by using this optimization approach.

This paper is organized as follows. The network design model with unreliable links and the QOS performance measures are introduced in Section 2. The fault-tolerant OCA/FA problem is formulated in Section 2. The proposed solution technique is given in Section 3 while numerical examples are given in Section 4.

II. Fault-Tolerant Optimal Channel Allocation and Flow Assignment Problem

2.1 Network Model

We consider a packet switched network in which the links between nodes are implemented using a multiple number of channels each of fixed capacity C. Let N denote the set of switching nodes and $L=\{1, 2, \cdots, L\}$ the set of L directed links. The network is assumed to be subject to link failures, with each link being either up or down. The network state is represented by the link failure configuration. Each state s can then be characterized by a set of L_s of L_s available links, where $L_s \subset L$. We assume a state space $S=\{0, 1, 2, \cdots, n-1\}$. In general, with L links, there are 2^N possible network states. In practice, only the most probable states need to be considered. Hence S would comprise of the n most probable states, which can be obtained by using the ORDER algorithm[9]. Moreover, n can be determined to obtain a desired level of system modeling granularity. To complete the network topology description, the number of channels must be specified for each link. Our objective is to implement a fault-tolerant channel allocation which is invariant with respect to the network state. Hence, let M_j be the maximum number of allowable channels for link j. The channel configuration C for the network is then specified by the vector $\underline{N}=(N_1, N_2, \cdots, N_L)$ where N_j is the number of channels implemented for link $j \in L$. Thus, the network topology under state s can be represented by the digraph (N, L_s, C).

We assume a set $W=\{1, 2, \cdots, R\}$ of R user sessions whose traffic demand requested by a user session $k \in W$ is denoted by γ_k. The set of traffic demands can then be represented by a vector $\underline{\Gamma}=(\gamma_1, \gamma_2, \cdots, \gamma_R)$. We assume routing or flow assignments can be implemented for each state $s \in S$. The flow assignment in state s is then specified by $f_s=\{f_{1s}, f_{2s}, \cdots, f_{Ls}\}$ where f_{js} is the traffic flow assignment for link $j \in L_s$.

The packets generated by all messages are assumed to arrive according to a Poisson distribution and the lengths of packets are assumed to be exponentially distributed with a mean $1/\mu$ (bits/packet). The packets destined to a node along a link j are equally distributed among the N_j channels. We assume that buffering for a link j is accomplished by N_j separate buffers, one for each channel. When the buffer space is full, the incoming packet is dropped and lost due to buffer overflow. We further assume that a packet is

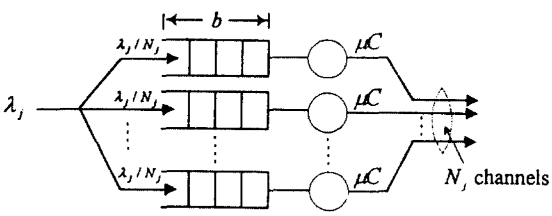

Fig. 1 $N_j-M/M/1/b$ Queueing Model

never lost in the switching component and therefore, a packet is lost only due to buffer overflow. Then each link j is modeled as an $N_j-M/M/1/b$ queue (see Figure 1) by parallelizing the N_j multiple channels in each link, where b is the common buffer size. Finally, we assume that a link j has a physical length L_j km. and a processing delay associated with its termination equal to v_j seconds/packet.

2.2 QOS Performance Measure

In high speed networks such as the ATM network for Broadband ISDN, packet loss due to buffer overflow is much more important than average packet delay. In these situations the end-to-end buffer overflow probability is a relevant QOS performance measure. For the $N_j-M/M/1/b$ queueing model, buffer overflow probability $B_{js}(\rho_{js}, b)$ for link j in state s is given by

$$B_{js}=\frac{(1-\rho_{js})\rho_{js}^b}{1-\rho_{js}^{b+1}} = \frac{\rho_{js}^b}{\sum_{k=0}^{b}\rho_{js}^k} \tag{1}$$

where ρ_{js} is the channel utilization factor given by $\rho_{js}=f_{js}/N_jC$. Assuming that the buffer overflow probability for each link is fairly small (e.g., 10^{-6} to 10^{-9}), the end-to-end average buffer overflow probability QOS performance measure in each state s can be approximated by

$$B_s(\underline{N}, \underline{f_s})=\frac{1}{\gamma}\sum_{j\in L_s}\mu f_{js}B_{js}(\rho_{js}, b) \tag{2}$$

where $\gamma=\sum_{k\in W}\gamma_k$ is the total external traffic rate (packets/sec).

In networks where buffer sizes are sufficiently large enough so that buffer overflow is not a significant issue, average packet delay is a more appropriate QOS performance measure. In considering average packet delay we assume an infinite buffer size ($b=\infty$) for analytical tractability. Hence, using the packet-length independence assumption of Kleinrock[10], the average end-to-end packet delay in state $s \in S$ is given by a weighted average of the average packet delay over each link j in state s $T_{js}(\cdot)$, as follows;

$$T_s(N, f_s) = \frac{1}{\gamma} \sum_{j \in L_s} \lambda_j T_{js}(N_j, f_{js})$$

$$= \frac{1}{\gamma} \sum_{j \in L_s} \left[\frac{N_j f_{js}}{N_j C - f_{js}} + \mu f_{js} \left(\frac{L_j}{c} + v_j \right) \right] \quad (3)$$

where c is the propagation constant(km/sec), e.g., a two-third of the speed of light. The first term of (3) represents the queueing and transmission delays incurred by a packet while the last two terms are the weighted average of the propagation and processing delays with respect to the link flows.

The optimization approach to be considered in this paper is strictly based on the network model and performance measures presented in the above. Since the accuracy of the proposed approach will depend on those assumption and approximation, the performance model needs to be validated. In [13] and [14], the approximation of the overall average network delay using the Kleinrock's independence assumption for a single channel network, modelled by a $M/M/1$ queue, has been validated by a simulation in the realistic network environment. Furthermore, it is shown in [2] that the delay performance of the parallel channel network in this paper, modelled by a $m-M/M/1$ queue, closely approximates the single channel network if the number of channels(m) is large enough as in most of applications. Based on these eariler results, the delay model adopted in this paper is considered to be valid towards our optimization approach. In fact, the delay model based on the $M/M/1$ queueing model has been commonly adopted and accepted towards the topological and routing optimization for the packet switching networks[1,2,3,8,15,16]. On the other hand, the average overflow probability approximation (equation (2)) is justifiable in a similar manner.

2.3 Network Cost

We assume that the network cost is the sum of the link costs and that the cost of each link j depends only on the number N_j of channels over that link. Let $D_j(N_j)$ be the cost function for link j. The total network cost function $D(N)$ is then given by

$$D(N) = \sum_{j \in L} D_j(N_j).$$

We shall further assume that each $D_j(N_j)$ is a monotonically increasing convex function of N_j. An example is the case of a high speed network where the cost of each link is linearly proportional to the number of channels as in conventional network design and the worst-case nodal hardware switching cost is proportional to the square of the number of channels to reflect the increase in complexity of switching components when additional channels are added[11]. This leads to the following cost function:

$$D(N) = \sum_{j \in L} D_j(N_j) = \sum_{j \in L} [\delta_j + \alpha_j N_j + \beta_j N_j^2], \quad (4)$$

where α_j, β_j, and δ_j are non-negative proportional factors varying with each link j. In practice, the cost of each channel is proportional to its physical length. So $\alpha_j = s_j L_j$, where s_j is the cost per channel per km for a simplex link j. On the other hand, the constants, δ_j and β_j, reflect the initial set up and switching costs respectively.

2.4 Fault-Tolerant OCA/FA Problem

Suppose the traffic demand requirement Γ is given, along with a QOS requirement specified in terms of a maximum allowable performance threshold P_{max} imposed on a performance measure in each state, i.e., $P_s \le P_{max}$, $\forall s \in S$. This performance measure P_s is taken to be either the average packet delay T_s given by (3) or the average buffer overflow probability B_s given by (2). Subsequently, depending on a type of the performance measure taken, P_{max} is denoted by T_{max} or B_{max}, correponding to the maximum allowable allowable average packet delay or the average buffer overflow probability, respectively. We are interested in simultaneously determining the design variables $\underline{N}$ (channel configuration) and $\underline{f_s}$ (flow configuration) in each state s to minimize the total network cost (4) with respect to the performance constraint, $P_s \le P_{max}$. We refer to this problem as the fault-tolerant OCA/FA problem, which can be formally stated as follows:

- Given: Network topologies(N, L_s, C) associated with a state space S and traffic demand $\underline{\Gamma}$,
- Minimize:

$$D(\underline{N}) = \sum_{j \in L} D_j(N_j), \tag{5}$$

- Over channel configuration $\underline{N} = (N_1, N_2, \ldots, N_L)$ and flow assignments $\underline{f_s}$, $s \in S$
- Subject to the constraints:

$$P_s(\underline{N}, \underline{f_s}) \le P_{max} \qquad \forall s \in S, \tag{6}$$

$$N_j \le M_j \qquad \forall j \in L, \tag{7}$$

$$\text{and} \quad f_{js} \le N_j C \qquad \forall j \in L_s, \forall s \in S \tag{8}$$

and the multicommodity flow satisfying the traffic demands.

The first constraint in (6) imposes the performance requirement on each state and thus the network performance is ensured not to exceed the given design threshold P_{max} regardless of the network state in S. The constraints in (7) give the maximum limit on the number of channels for each link while the constraints in (8) guarantee the feasibility of the flow assignment with respect to the link capacity. Note that both QOS performance measures $T_s(\underline{N}, \underline{f_s})$ and $B_s(\underline{N}, \underline{f_s})$ are convex separable functions of $(\underline{N}, \underline{f_s})$. Since $D(\underline{N})$ is assumed to be a convex separable function of $\underline{N}$, this fault-tolerant OCA/FA problem has a global optimal solution.

The complexity of performing a joint optimization over $\underline{N}$ and $(\underline{f_0}, \underline{f_1}, \cdots, \underline{f_{n-1}})$ involving multiple nonlinear constraints can be circumvented by separating the above problem into two subproblems. The first subproblem determines the optimum channel allocation for given flow assignments in every state. The second subproblem involves $|S| = n$ optimization problems each of which determines the optimum QOS flow assignments in each state. These two subproblems can be solved sequentially until there is no further improvement in reducing the network cost. We restate the above fault-tolerant OCA/FA problem in terms of these two subproblems as follows:

<u>Subproblem 1</u>

- Given: Network topologies (N, L_s, C) associated with a state space S, traffic demands $\underline{\Gamma}$ and flow configurations $\underline{f_s}$, $s \in S$,
- Minimize:

$$D(\underline{N}) = \sum_{j \in L} D_j(N_j), \tag{9}$$

- Over the augmented channel configuration $\underline{N} = (N_1, N_2, \ldots, N_L)$
- Subject to the constraints:

$$P_s(\underline{N}, \underline{f_s}) \le P_{max} \qquad \forall s \in S,$$

$$N_j \le M_j \qquad \forall j \in L,$$

$$\text{and} \quad f_{js} \le N_j C \qquad \forall j \in L_s, \forall s \in S$$

<u>Subproblem 2</u>

For each state $s \in S$:

- Given: Network topology (N, L_s, C) associated with a state $s \in S$, traffic demands $\underline{\Gamma}$ and channel configuration $\underline{N}$,
- Minimize: $P_s(\underline{N}, \underline{f_s})$
- Over the flow assignment $\underline{f_s}$,
- Subject to the multicommodity flow constraints.

Ⅲ. Solution Approach

Each of the $|S|$ optimizations in Subproblem 2 above can be efficiently handled using the flow deviation method[1] or other optimal routing algorithms. The set of $|S|$ nonlinearinequality constraints in Subproblem 1 imposed by the QOS performance requirements presents some difficulties for large state spaces. For example, 20 states in a small size network is not unusual. Since efficient primal nonlinear integer programming techniques are not available for a large number of nonlinear inequality constraints, an efficient solution method for Subproblem 1 has to be devised. We applied the concept of marginal analysis [12] to obtain an efficient incremental allocation solution of the subproblem 1. The following assumptions, which must be satisfied to apply the marginal analysis, are valid here:

1. The cost objective function $D(\underline{N})$ and the performance objective function $P_s(\underline{N}, f_s)$ are convex separable functions.
2. For $P_s(\underline{N}, f_s)=\sum_{j\in L_s} P_{js}(N_j, f_{js})$, each $P_{js}(N_j, f_{js})$ is monotonically decreasing in N_j for fixed f_{js}.
3. $D_j(N_j)$ is monotonically increasing in N_j.

The basis for this approach is the following intuitive consideration. Consider the two conflicting objectives of minimizing network cost and maintaining the QOS performance constraints. If an additional channel is available, it should be assigned to return the maximum possible economic benefit in the sense that the link cost should increase rather slowly while decreasing the performance measure in each state rapidly. The marginal benefit is measured by the allocation margin, which is defined as the ratio of performance degradation due to cost decrease with respect to each channel allocation. Therefore, every additional channel must be assigned to a link with the largest allocation margin. This is the basis of Fox's marginal analysis[12]. The channel allocation method which we previously devised in [11] is a link-by-link incremental allocation (LICA) algorithm based on this marginal analysis approach.

However, the link-by-link incremental allocation algorithm in [11] cannot be directly applied to Subproblem 1 because of the multiple performance constraints here. We shall modify the LICA algorithm in the following manner. Assuming that there exists an optimal channel allocation within the given resource level, i.e., $P(\underline{M}, f_s)\le P_{max}$, $\forall s\in S$, the procedure is to start with the initial allocation,

$$N_j^{(0)}=\max_{s\in S}\ f_{js}/C, \qquad \forall j\in L,$$

so that every additional channel allocation always satisfies the capacity constraint (8). As far as the incremental channel allocation is concerned in Subproblem 1, there will be two directions to be optimized, one for a state and the other for a link, in each allocation cycle. We conjecture that in one direction, the state with the worst QOS performance measure must be optimized and subsequently in the other direction, a link must be selected to improve the QOS performance of the corresponding state. In other words, a state with the worst QOS performance measure in each allocation cycle and in turn, a link returning the most economic benefit in the corresponding state are considered to be the steepest descent direction with respect to link-by-link incremental channel allocation. Once a state with the largest QOS performance measure, denoted by $s^*\in S$, is identified under the current channel allocation and flow assignment, the economic benefit achieved by the incremental allocation for each link is measured in terms of the following allocation margin Δ_{js^*}:

$$\Delta_{js^*}=\begin{cases}\dfrac{\Delta P_{js^*}}{\Delta D_j}, & j\in L_s\\ 0, & j\in L-L_{s^*},\end{cases} \tag{10}$$

where

$$\Delta P_{js^*} = P_{js^*}(N_j, f_{js^*}) - P_{js^*}(N_j + 1, f_{js^*})$$

is the decrease in the QOS performance measure for link j in state s^*, and

$$\Delta D_j = D_j(N_j + 1) - D_j(N_j)$$

is the increase in the link cost when an additional channel is allocated to link j. The maximum economic benefit for each channel allocation is then achieved by assigning it to a link with the largest allocation margin. Let $\max_{i\in I}^{-1} f_i$ denote the index $i^* \in I$ such that $f_{i^*} = \max_{i \in I} f_i$ for a set of indices I. The algorithm then allocates one channel at a time to the link j^* with the largest allocation margin, i.e.,

$$j^* = \max_{j\in L}{}^{-1} \Delta_{js^*}$$

Consequently the steepest descent is bi-directional given by (s^*, j^*) in each channel allocation cycle. When the additional channel allocation violates the channel constraint, i.e., $N_{j^*} > M_{j^*}$, the corresponding link is excluded from further consideration by setting $\Delta_{j^*l^*}$ to $-\infty$. This algorithm is completed by repeating the above link-by-link incremental channel allocation with the (s^*, j^*)-descent direction until $P_s(\underline{N}, \underline{f_s}) \leq P_{max}$, $\forall s \in S$. The link-by-link capacity augmentation procedure to solve the Subproblem 1 is summarized below. The superscript of each variable denotes the iteration number starting from 0 in the following presentation.

Step 1 Initialize the parameters:

$$\Delta_j \leftarrow 0, \qquad \forall j \in L,$$

$$N_j^{(0)} \leftarrow \max_{s\in S} \frac{f_{js}}{C}, \qquad \forall j \in L,$$

$$n \leftarrow 1.$$

Step 2 Identify the state with the worst performance measure:

$$s^* = \max_{s\in L}{}^{-1} P_s(\underline{N}^{(n-1)}, \underline{f_s}).$$

Step 3 Compute allocation margins $\{\Delta_{js^*}\}$ given by

$$\Delta_{js^*} = \frac{P_{js^*}(N_j^{(n-1)}, f_{js^*}) - P_{js^*}(N_j^{(n-1)} + 1, f_{js^*})}{D_j(N_j^{(n-1)} + 1) - D_j(N_j^{(n-1)})}$$

Step 4 Find a j^*-th unit vector $\underline{e}_{j^*}$ such that

$$j^* = \max_{j\in L}{}^{-1} \Delta_{js^*}$$

Step 5 Determine $\underline{N}^{(n)} = (N_1^{(n)}, N_2^{(n)}, \ldots, N_L^{(n)})$ by $\underline{N}^{(n)} = \underline{N}^{(n-1)} + \underline{e}_{j^*}$.

Step 6 If $N_{j^*}^{(n)} = M_j$, set $\Delta_{j^*} \leftarrow -\infty$.

Step 7 If $P_s(\underline{N}^{(n)}, \underline{f_s}) > P_{max}$, $\forall s \in S$, set $n \leftarrow n+1$ and go to Step 2.
Otherwise, $\underline{N}^{(n)}$ is the augmented channel solution.

Convexity of both $D(\underline{N})$ and $P_l(\underline{N}, \underline{f_l})$ in $\underline{N}$ guarantee convergence to an suboptimal integer solution. We note that the above bi-directional allocation strategy requires an $|S|$ element ranking to find a state of the worst performance measure and an $|L|$ element ranking to find the maximum margin among the links in the corresponding state for each allocation cycle. The computational requirements for the above procedure are relatively small because the procedure terminates within $L \times \max_{j\in L} M_j$ iterations.

Subproblems 1 and 2 are iterated sequentially until no further significant reduction in network cost is obtained. This iterative procedure can be started in Subproblem 2 with each N_j set to the maximum number M_j of channels. The iteration is stopped when $|D(\underline{N}^{(k)}) - D(\underline{N}^{(k-1)})| \leq \varepsilon$ for tolerance level ε.

Ⅳ. Numerical Examples

We have evaluated the proposed fault-tolerant

OCA/FA problem approach on a 12 node example network shown in Figure 2, with the network cost function given by (4). We assume 20 user sessions with uniform traffic demands as listed in Table 1. Each channel is assumed to have 24 channels of 10 kbps capacity and other necessary design parameters are included in Table 3.

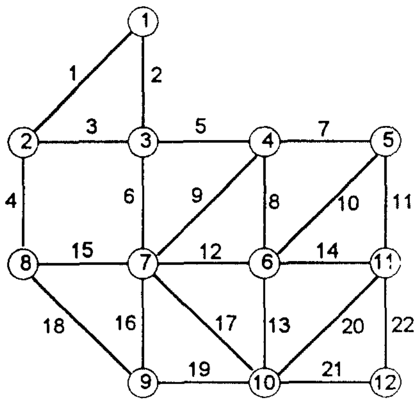

Fig. 2 Example Network

Table 1. Traffic Demand Requirement

session	1	2	3	4	5	6	7	8	9	10
Source	1	2	3	3	3	4	5	6	7	7
Dest.		8	6	6	9	12	12	8	2	11
Demand	12	12	12	12	12	12	12	12	12	12
Session	11	12	13	14	15	16	17	18	19	20
Source	8	8	9	9	10	10	11	11	12	12
Dest.	1	9	5	11	2	5	3	9	3	8
Demand	12	12	12	12	12	12	12	12	12	12

We have considered 5 different link failure configurations as specified in Table 2 where a set of failed links is listed for each state. Among all 2^{24} possible states of link failures, for example, 24 most *probable* link failure network states have been generated and the failed links are identified in each state for the link failure configuration I. In this case, the fault-tolerant design is applied to guarantee the performance objectives in these 24 states only, since it is simply assumed that the rest of states rarely occur probabilistically. The similar scenario is applied to the configuration II, III, IV and V.

Table 2. Link Failure Configurations

Link Failure Configuration	I	II	III	IV	V
No. of States	24	23	20	30	40
State 0					
State 1	12	1	1, 2	2	2
State 2	4	2	4, 7	14	14
State 3	8	3	4, 5	8	9
State 4	3	4	3, 14	5	12
State 5	13	5	8, 11	11	10
State 6	19	6	6, 9	10	6
State 7	9	7	9, 13	9	8
State 8	7	8	11, 12	6	0
State 9	20	9	15, 18	21	20
State 10	5	10	14, 17	7	1
State 11	7	11	12, 13	3	4
State 12	14	12	9, 10	13	13
State 13	10	13	13, 19	19	11
State 14	17	14	16, 18	17	17
State 15	6	15	13, 21	15	5
State 16	2	16	15, 17	20	3
State 17	12, 14	17	12, 20	16	15
State 18	12, 8	18	12, 16	2, 14	21
State 19	4, 8	19	10, 21	2, 8	19
State 20	12, 3	20		2, 5	6
State 21	8, 3	21		2, 10	18
State 22	4, 13	22		14, 8	7
State 23	4, 19			8, 5	2, 14
State 24				14, 11	2, 9
State 25				2, 9	2, 12
State 26				14, 21	14, 9
State 27				2, 14, 8	14, 12
State 28				14, 11, 20	9, 12
State 29				14, 8, 13	2, 10
State 30					2, 6
State 31					9, 10
State 32					14, 10
State 33					14, 6
State 34					9, 6
State 35					14, 8
State 36					12, 10
State 37					2, 14, 9
State 38					2, 9, 12
State 39					2, 14, 10

The average packet delay and average buffer overflow probability QOS performance measures are both considered. In each case, the traffic demand $\underline{\Gamma}$ has been carefully adjusted so that the network can fully accommodate the total traffic demand γ in any operational mode with the maximum number of channels M_j available for each link j under the QOS requirement of $P_s(\underline{N}, \underline{f_s}) \leq P_{max}$, $\forall s \in S$(here, $P_{max} = T_{max}$ or B_{max}, i.e., the maximally tolerable performance threshold, either for the average network delay or buffer overflow probability). Our results were compared with the heuristic Max and Max-average methods considered in [8]. Note that the so-called pathological incoming or outgoing nodes in [8] are not observed in our example.

We illustrate the channel allocation results for the Max method, the Max average method and the fault-tolerant method in Table 3 under two different performance requirements: $T_s(\underline{N}, \underline{f_s}) \leq T_{max} = 0.4$, $\forall s \in S$, for the average packet delay and $B_s(\underline{N}, \underline{f_s}) \leq B_{max} = 1.0 \times 10^{-6}$, $\forall s \in S$, for the average buffer overflow probability. All the necessary parameters to evaluate the network cost, such as the link cost(α_j) and switching cost(β_j), are listed in Table(3). Without a loss of generality, all the initial set-up costs are set to zero, i.e., $\delta_j = 0$, $\forall j$, in these examples. Table 3 also includes the results in the normal operational mode with no link failures (i.e., without capacity augmentation.) These examples show that the OCA/FA method reduces network cost by 70% to 140% with respect to the Max average method and by 15% to 16% with respect to the Max method. These significant network cost reductions are also accompanied by dramatic savings in the number of channels over some of the links. For example, consider link 12 and 22 for $T_{max} = 0.4$ and, link 1, 7 and 16 for $B_{max} = 1 \times 10^{-6}$. The weakness of both the Max and Max-average methods is apparent. The similar cost reduction results are summarized for various link failure configurations and performance constraints in Table 4.

Table 3. Channel Allocation Results: Link Failure Configuration I

	Parameters			$T_{max} = 0.4$				$B_{max} = 1 \times 10^{-6}$			
Link	α_j	β_j	M_j	No Aug.	Max	Max avg	OCA/FA	No Aug.	Max	Max avg	OCA/FA
1	1.0	0.5	24	8	9	14.9	9	10	12	23.5	8
2	1.0	0.5	24	0	9	9.0	9	4	11	9.9	11
3	0.5	1.0	24	6	10	11.8	9	8	10	19.5	9
4	2.5	1.0	24	9	13	16.7	11	13	19	30.6	18
5	3.0	1.0	24	8	14	15.3	12	12	19	29.0	18
6	5.5	1.0	24	9	16	17.8	15	13	20	32.2	19
7	0.5	1.0	24	7	9	13.1	8	10	14	24.0	10
8	5.0	0.5	24	9	14	17.2	13	12	16	28.8	16
9	6.5	1.0	24	6	8	11.1	8	10	14	23.2	11
10	1.0	1.0	24	6	10	11.7	9	6	12	14.9	11
11	4.0	1.0	24	5	8	9.7	7	5	11	13.1	11
12	3.0	0.5	24	9	20	17.7	17	12	21	29.3	22
13	1.0	1.0	24	5	9	9.3	9	6	12	14.7	11
14	2.0	0.5	24	7	13	13.4	13	9	13	21.4	12
15	1.0	1.0	24	7	10	13.8	10	11	14	26.7	12
16	1.5	1.0	24	6	8	11.6	8	9	11	21.6	7
17	1.0	1.0	24	9	12	17.3	10	12	17	29.0	16
18	2.0	1.0	24	7	9	12.8	8	7	13	16.9	12
19	2.5	1.0	24	8	11	15.5	10	9	17	22.6	27
20	7.0	0.5	24	8	12	15.5	10	7	15	22.3	13
21	2.0	1.0	24	9	10	16.7	10	11	13	26.3	12
22	7.0	1,0	24	3	11	6.1	7	5	15	12.4	13
Total Cost				1392.0	3087.0	4416.2	2556.0	2315.0	5088.5	11596.1	4338.5

Table 4. Cost Reductions for Different Failure Configurations

Link Failure Configuration	I	II	III	IV	V
Total No. of States	24	23	20	30	40
T_{max}	0.4	0.4	0.4	0.4	0.4
Max Method	3037.0	2878.5	5187.5	3493.0	3148.5
OCA/FA Method	2556.0	2315.5	4038.0	2818.5	2442.0
% Cost Reduction	15.8%	19.6%	22.2%	19.3%	22.4%
B_{max}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}
Buffer Size(b)	12	12	20	12	12
Max Method	5088.5	4745.0	3367.5	5051.0	5065.0
OCA/FA Method	4338.5	3915.5	3032.5	4219.0	4095.0
% Cost Reduction	14.7%	18.3%	17.5%	16.5%	19.2%

Figure 3 and 4 illustrate the network cost for the different QOS requirements under link failure configuration I as the number of iterations between the two subproblems increases. The vertical lines are corresponding to the total costs obtained by the Max method. It can be seen that only a small number of iterations are required.

Figure 5-10 shows the respective average packet delays and buffer overflow probabilities in every state, which have resulted from both heuristic and optimization approaches. From these figures, a trade-off between the network cost and QOS performance is obvious for the optimization approach. That is, the network cost reduction obtained by OCA/FA procedure (as illustrated in Table 3 and 4) relative to the Max and Max-average methods is achieved with the performance constraints in some of the states becoming active. For example, cost reduction of 15.8% by the OCA/FA approach, for the configuration I with T_{max} =0.4, is achieved by the increased delay as shown in Figure 5. That is, this numerical result shows that the lower network cost is traded with the worse QOS per-

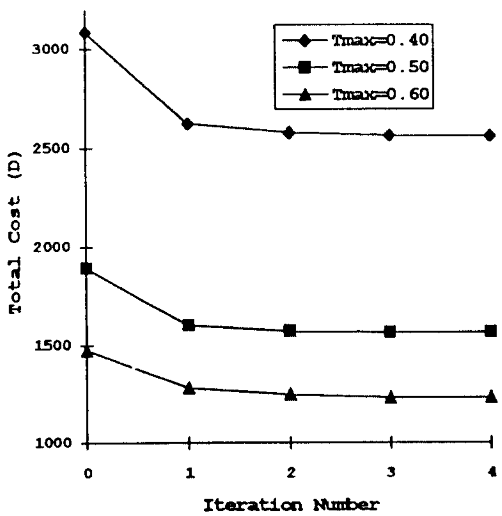

Fig. 3 Network Cost vs. Iterations: Average Packet Delay QOS Measure

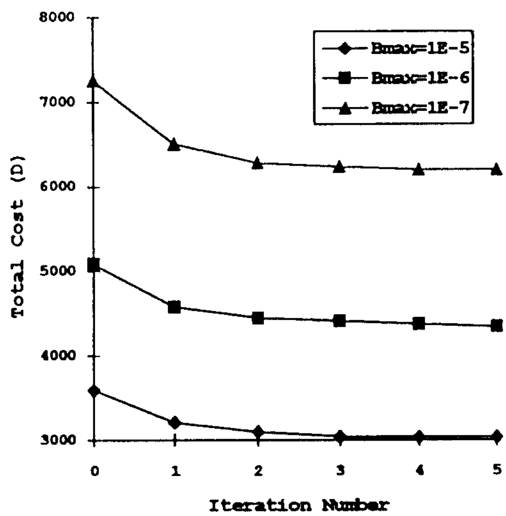

Fig. 4 Network Cost vs. Iterations: Average Buffer Overflow Probability QOS Measure

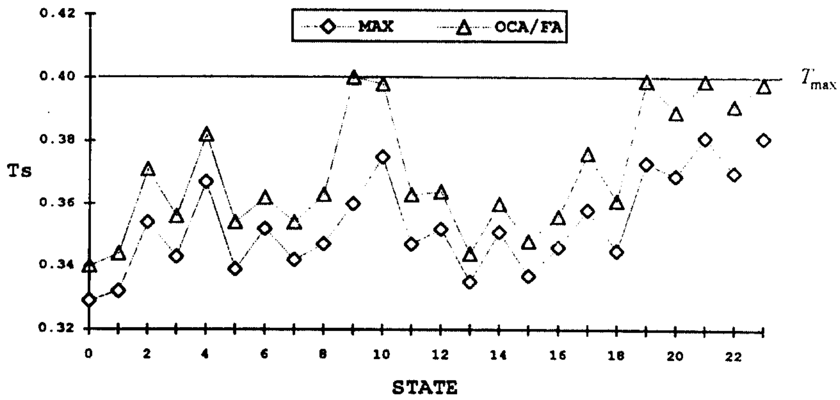

Fig. 5 Average Packet Delay vs. State($T_{max}=0.4$ sec)

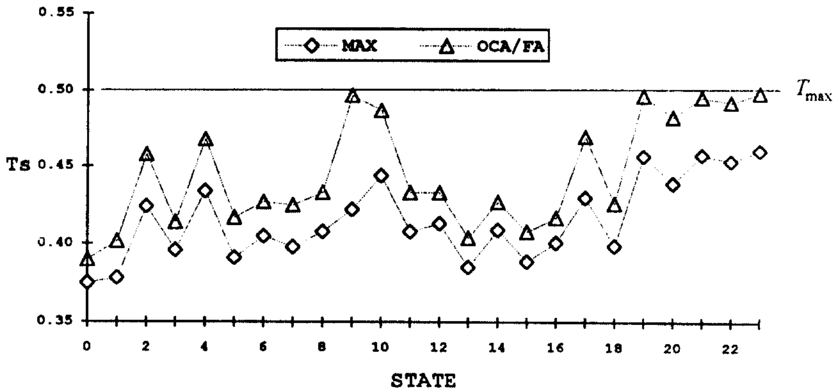

Fig. 6 Average Packet Delay vs. State($T_{max}=0.5$ sec)

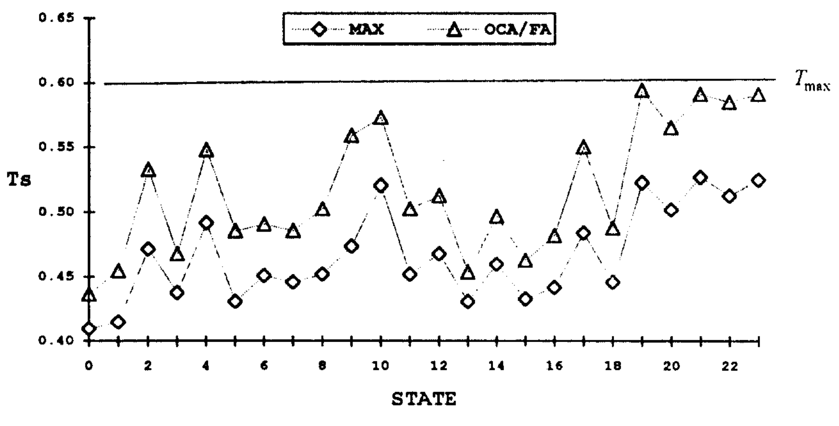

Fig. 7 Average Packet Delay vs. State($T_{max}=0.6$ sec)

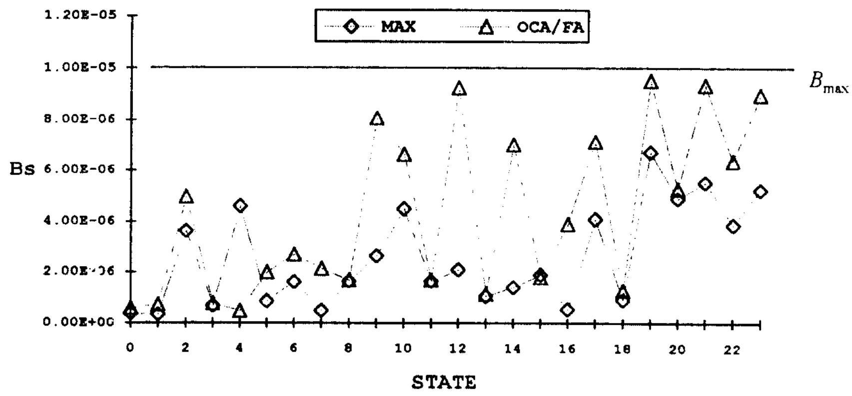

Fig. 8 Average Buffer Overflow Probability vs. State($B_{max} = 1.0 \times 10^{-5}$)

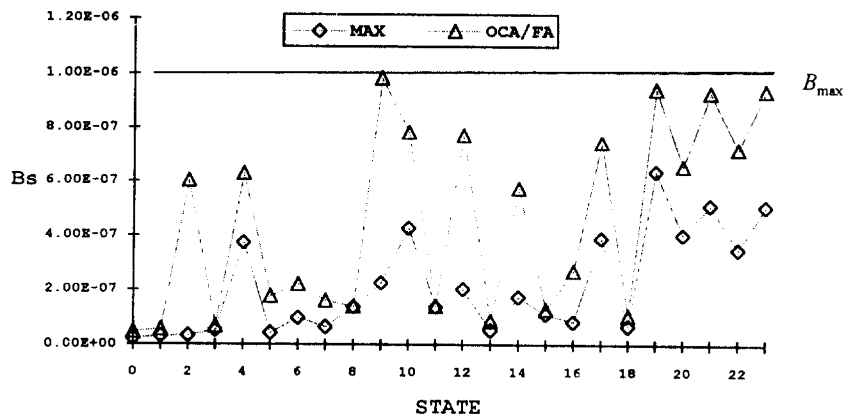

Fig. 9 Average Buffer Overflow Probability vs. State($B_{max} = 1.0 \times 10^{-6}$)

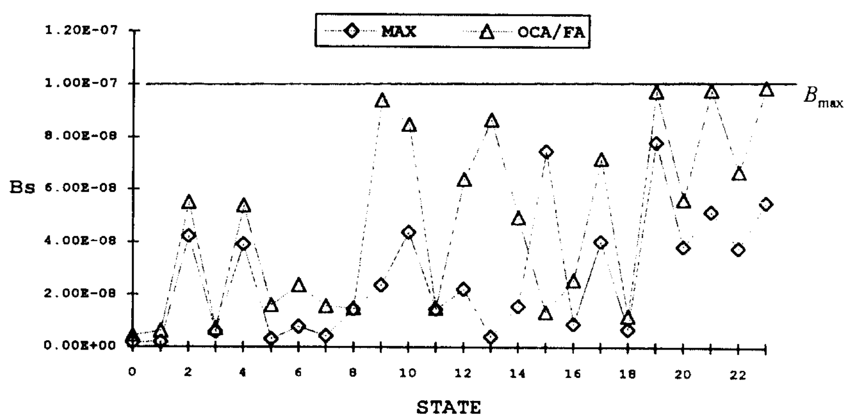

Fig. 10 Average Buffer Overflow Probability vs. State($B_{max} = 1.0 \times 10^{-7}$)

formance. On the top of such a trade-off, it should be noted that the QOS requirement($T \leq 0.4$ in this example) set for the design is always satisfied for all 24 states considered in the configurationI. Meanwhile, 4 states (state 9, 19, 21 and 23) are close to saturation for the OCA/FA method while none of the state is saturated for the Max method, which illustrates that the network cost is further minimized by the optimization approach until some of the states reach the maximum allowable delay. Similar observations are found in Figures 6-10.

Finally we note that the OCA/FA method incurs substantially higher network costs, e.g., in some cases almost twice as much as the design cost compared to the normal network cost without capacity augmentation. This may not be practical in some applications. In these cases, the performance constraints may be relaxed in some states to arrive at a more reasonable network cost. The OCA/FA problem then needs to be modified to take into account non-uniform(over the states) QOS performance requirements.

V. Conclusion

This paper has considered networks subject to link failures. We have formulated a *fault-tolerant* optimal capacity allocation and flow assignment (OCA/FA) problem to minimize the network cost. The approach developed here produces fault-tolerant capacity and flow configurations with significant network cost reduction in comparison with previous heuristic methods. Since the solution technique given in Section 3 obtains only a suboptimal solution, more work has to be performed to determine how close this solution is to the optimal solution. Moreover, the approach taken here can be applied to circuit switched networks.

References

1. **Gerla. M and Kleinrock. L,** "On topological design of distributed computer networks," *IEEE Transactions on Communications*, vol. 25, no. 1, pp. 1253-1262, Jan. 1977.
2. **Ng, T.M.G and Hoang, D.B,** "Joint optimization of capacity and flow assignment in a packet switched communications network," *IEEE Transactions on Communications*, vol. 35, no. 2, pp. 202-209, Feb. 1987.
3. **Chan, H.W. and Yan, T.Y,** "Combined capacity allocation, routing, and flow control algorithm for packet-switched networks," Internal Report, Jet Propulsion Lab, June 1988.
4. **LeBlanc, L,** "Design and Operation of Packet-Switched Networks with Uncertain Message Requirement," *IEEE Transactions on Communications*, vol. 38, no. 8, pp. 1223-1230, Aug. 1990.
5. **Beaudry, M D,** "Performance related reliability measures for computing system," *IEEE Transactions on Communications*, vol. 27, no. 6, June 1978.
6. **Lim, Y,** "Minimum-Cost Dimensioning Model for Common Channel Signalling Networks under Joint Performance and Reliability Constraints," *IEEE Transactions on Communications*, vol. 8, no. 10, pp. 1658-1666, Dem. 1990.
7. **Sanso, B, Soumis, F, and Gendreau, M,** "On the Evaluation of Telecommunications Network Reliability Using Routing Model," *IEEE Transactions on Communications*, vol. 39, no. 10, pp. 1494-1501, Oct. 1991.
8. **Nishida, T and Miyahara, H,** "Fault Tolerant Packet Switched Network Design Using Capacity Augmentation," *Proceedings of IEEE INFOCOM '88*, pp. 934-940, 1988.
9. **Li, V O and Silvester, J A,** "Performance Analysis of Networks with Unreliable Components," *IEEE Transactions on Communications*, vol. 32, no. 10, pp. 1105-1110, Oct. 1984.
10. **Kleinrock, L,** *Communication Nets-Stochastic Message Flow and Delay*, Dover New York U.S.A. 1972.
11. **Kang, C and Tan, H.H,** "Combined Channel Allocation and Routing Algorithms," *Proceedings of*

GLOBECOM '91, Phoenix U.S.A. 1991.

12. **Fox, B,** "Discrete Optimization via Marginal Analysis," *Management Science*, vol. 13, no. 2, pp. 210-216, Nov. 1966.
13. **Kleinrock, L,** *Queueing Systems, Volume II: Computer Applications*, A Wiley-Interscience Publication, New York. 1976.
14. **Kleinrock, L,** *Communication Nets: Stochastic Message Flow and Delay*, McGraw-Hill, New York, 1964.
15. **Bauer, G. and Bolch, G,** "Analytical approach to discrete optimization of queueing networks," *Computer Communications*, vol. 13, no. 8, pp. 494-502, Oct. 1990.
16. **Gavish, B. and Neuman, I,** "A System for Routing and Capacity Assignment in Computer Communication Networks," *IEEE Transactions on Communications*, vol. 37, no. 4, pp. 360-366, Apr. 1989.
17. **Cheng, K.-T. and Lin, F. Y.-S,** "Minimax End-to-end Delay Routing and Capacity Assignment for Virtual Circuit Networks," *Proceedings of GLOBECOM '95*, Singapore, 1995.

강 충 구(Chung G. Kang)정회원

1962년 12월 12일생

1987년 6월 : 미국 University of California, San Diego 전기공학과 학사(BS)

1989년 9월 : 미국 University of California, Irvine 전기 및 컴퓨터 공학과 석사(MS)

1993년 3월 : 미국 University of California, Irvine 전기 및 컴퓨터 공학과 박사(Ph.D)

1991년 7월~1992년 5월 : 미국 Aerospace Corp. 연구원

1993년 4월~1994년 2월 : 미국 Rockwell International, Advanced Systems Department 연구원

1994년 3월~현재 : 고려대학교 전기·전자·전파 공학부 근무(조교수)

※주관심분야 : 통신망 최적 설계 알고리즘, ATM 망에서의 트래픽 모델링 및 성능분석, CDMA 시스템 공학, 무선 멀티미디어 통신망