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Bandwidth Allocation and QoS Routing for Heterogeneous Networks

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Abstract

We present a bandwidth allocation scheme offering optimal solutions to the network optimization problem. The bandwidth allocation policy in class-based networks can be defined with the proportionally fair rule expressed by piecewise linear objective functions. This scheme is formulated as a mixed-integer linear programming (MILP) model, preparing a database identifying suitable paths upon each connection request. We also study the blocking probability of an end-to-end transmission system with predetermined optimal solutions.

Mathematics Subject Classification: 90B10, 90B18, 90C11

Keywords: bandwidth allocation, QoS routing, blocking probability

1 Introduction

In recent years, network capabilities grow at a remarkable rate. A phenomenal growth in data traffic and a wide range of new requirements of emerging applications call for new mechanisms for the control and management of communication networks [2], [3], and [6]. Packet-switched networks have been proposed to offer the Quality of Service (QoS) guarantees in integrated-services networks [5].

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The rules for bandwidth allocation in networks carrying elastic traffic can be defined in several ways, meeting different overall network goals [9]. The available bandwidth can be divided between the users according to their needs. Therefore, a problem of network dimensioning with elastic traffic requires to allocate bandwidth to maximize flows fairly [11], [18]. Fair bandwidth allocation problems are concerned with the allocation of limited bandwidth among competing activities so as to achieve the best overall performances of the system but providing fair treatment of all the competitors (see [8], [10], and [11]). We introduce the methodology allowing the decision maker to explore a set of solutions that could satisfy users' preferences with respect to throughput and fairness. The formulation and analysis are carried out in a general utility-maximizing framework.

QoS routing concerns the selection of a path satisfying the QoS requirements of a connection [16]. The path selection process involves the knowledge of the connection's QoS requirements and information on the availability of bandwidth. QoS routing poses major challenges in terms of algorithmic design [13]. On one hand, the path selection process is a complex task, due to the need to concurrently deal with the connection's QoS requirements, as well as with the global utilization of network resources [2]; on the other hand, connection requests need to be handled promptly upon their arrival [19]. Depending on the specifics and the number of QoS metrics involved, computation in real time required for path selection can become prohibitively expensive as the network size grows.

An approach is presented for the fair resource allocation problem and QoS routing in networks offering multiple services to users. We focus on allocating resources with proportional fairness and finding a routing scheme on communication networks. The objective of the optimization problem is to determine the amount of required bandwidth for each class to maximize the sum of the users' satisfaction.

2 Network Management Schemes

2.1 Problem Definition

We deal with the problem of dimensioning bandwidth for elastic data applications in packet-switched communication networks of multiple classes, which can be considered as a mixed-integer linear programming (MILP) model. Each user is allowed to request more than one type of service, and users' satisfaction is summarized by means of their achievement functions.

Consider a directed network topology $\mathbb{G} = (\mathbb{N}, \mathbb{A})$, where $\mathbb{N}$ and $\mathbb{A}$ denote the set of nodes and the set of links in the network respectively. All connections are delivered between the same source $o \in \mathbb{N}$ and destination $d \in \mathbb{N}$ in this network. The maximal possible link capacity is U_e on each link $e \in \mathbb{A}$. Suppose, for each link e, we have a mean delay d_e related to the link's speed, propagation delay, and maximal transfer unit. We also have the link cost c_e for using one unit bandwidth. In general, link cost c_e is inversely proportional to mean delay d_e.

There are m different QoS classes of connections in the network. Let $\mathbb{I} = \{1, \ldots, m\}$ be an index set consists of m different QoS classes. In the same class $i \in \mathbb{I}$, every connection is allocated the same bandwidth x_i and has the same QoS requirement. The specific QoS requirements include minimal bandwidth requirement l_i and maximal end-to-end delay constraint D_i for each class $i \in \mathbb{I}$. We denote the total number of connections by K_i for each class $i \in \mathbb{I}$. Let $\mathbb{J}_i$ be an index set consists of K_i connections; that is, $\mathbb{J}_i = \{1, \ldots, K_i\}$.

Under a limited budget B, we plan to allocate the bandwidth in order to provide each class with maximal possible QoS and determine the optimal path from end to end under guaranteed service. A connection j in each class i should be routed through a path $p_{i,j}$ between o and d. Decision variables are listed as follows:

x_i	the bandwidth allocated to each connection in class i;
$y_{i,j}(e)$	the bandwidth allocated to link $e \in \mathbb{A}$ for connection j in class i;
$z_{i,j}(e)$	a binary variable which determines whether the link e is chosen for connection j in class i.

2.2 Achievement Function

The decision maker specifies requirements in aspiration and reservation levels by introducing desired and required values for bandwidth [11]. We transform the different QoS measurements onto a normalized scale by using the concept of achievement functions [15]. Depending on the specified aspiration level, a_i, and reservation level, r_i, we construct the achievement function $f_i(x_i)$ of bandwidth x_i as a piecewise linear function for each class $i \in \mathbb{I}$. We assume the relationship between the utility and the bandwidth is linear in a proper (sufficiently small) region. Between r_i and a_i, we have break points $r_i = k_{i,0} < k_{i,1} < \ldots < k_{i,n} = a_i$. We assume $k_{i,l} - k_{i,l-1}$ are the same for all $l = 1, \ldots, n$. Moreover, we denote the point l_i to represent the minimal bandwidth requirement for each class i.

Lemma 2.1 *Let κ be the cheapest cost per unit bandwidth given in an end-to-end path. Suppose the total budget is $B < \infty$. There exists a finite number $M_i \leq B/\kappa K_i$ such that $x_i \leq M_i$, $\forall\, i \in \mathbb{I}$.*

Formally, we define $f_i(\cdot)$ over the range $[0, M_i]$. Depending on the specified reference levels, this achievement function can be interpreted as a measure of the decision maker's satisfaction with the value of the i-th criteria [15], [18]. It is a strictly increasing function of x_i, having value 1 if $x_i = a_i$, and value 0 if $x_i = r_i$. The achievement function is formulated as follows:

$$f_i(x_i) = \begin{cases} -M_i & \text{for } 0 \le x_i < l_i \\ \rho_0 \cdot (x_i - r_i) & \text{for } l_i \le x_i < r_i \\ \rho_1 \cdot (x_i - k_{i,1}) + g_i(k_{i,1}) & \text{for } r_i \le x_i < k_{i,1} \\ \vdots & \\ \rho_n \cdot (x_i - a_i) + 1 & \text{for } k_{i,n-1} \le x_i < a_i \\ \rho_M \cdot (x_i - M_i) + g_i(M_i) & \text{for } a_i \le x_i \le M_i. \end{cases} \tag{1}$$

Denote $\alpha_i = \frac{a_i}{r_i}$, we have parameters $g_i(M_i) = \log_{\alpha_i} M_i/r_i$ and $g_i(k_{i,l}) = \log_{\alpha_i} k_{i,l}/r_i$ for $l = 1, \ldots, n-1$. Moreover, the parameters $\rho_0 = M_i/(r_i - l_i)$, $\rho_M = (g_i(M_i) - 1)/(M_i - a_i)$ and

$$\rho_l = \frac{n \log_{\alpha_i}(k_{i,l}/k_{i,l-1})}{a_i - r_i}, \text{ for } l = 1, \ldots, n,$$

represent the slope on l-th line segment for $l = 0, 1, \ldots, n+1$.

Next, we present an appealing property of the achievement function (1), which holds in the bandwidth allocation problem we are studying.

Proposition 2.2 *The achievement function (1) is continuous, increasing, and concave.*

These results are entirely consistent with those assumptions on the utility functions for end-to-end flow control in [9], where the objective is to maximize the aggregate source utility over their transmission rates.

The achievement function can map the different criteria values onto a normalized scale of the decision maker's satisfaction [15]. Moreover, the achievement function will be intimately associated with the concept of proportional fairness (see [8], [16] , and [18]). By the achievement function (1) interpreted as a measure of QoS on networks, we can formulate the mathematical model of the fair bandwidth allocation.

2.3 Mixed-Integer Linear Programming Model

Let $\mathbb{A}_o \subseteq \mathbb{A}$ and $\mathbb{A}_d \subseteq \mathbb{A}$ be subsets of links connected with the source o and destination d respectively. We denote $\mathbb{A}_\nu^{in} \subseteq \mathbb{A}$ a subset of incoming links to the node $\nu \in \mathbb{N}$, and we also denote $\mathbb{A}_\nu^{out} \subseteq \mathbb{A}$ a subset of outgoing links from the node $\nu \in \mathbb{N}$. By using the achievement function (1), the utility function for each class i is expressed. Our goal is to maximize the total utility of all competing classes. The MILP model is formulated as follows:

$$\text{Max} \quad \sum_{i\in\mathbb{I}} w_i \cdot f_i(x_i) \tag{2}$$

$$\text{s. t.} \quad \sum_{e\in\mathbb{A}} \sum_{i\in\mathbb{I}} \sum_{j\in\mathbb{J}_i} c_e \cdot y_{i,j}(e) \le B \tag{3}$$

$$\sum_{i\in\mathbb{I}} \sum_{j\in\mathbb{J}_i} y_{i,j}(e) \le U_e, \ \forall\, e \in \mathbb{A} \tag{4}$$

$$\sum_{e\in\mathbb{A}} z_{i,j}(e) \cdot \theta_i + \sum_{e\in\mathbb{A}} d_e \cdot y_{i,j}(e) \le D_i \cdot x_i, \ \forall\, j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{5}$$

$$y_{i,j}(e) \le M \cdot z_{i,j}(e), \ \forall\, e \in \mathbb{A}, \ j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{6}$$

$$x_i - y_{i,j}(e) \le M(1 - z_{i,j}(e)), \ \forall\, e \in \mathbb{A}, \ j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{7}$$

$$y_{i,j}(e) - x_i \le M(1 - z_{i,j}(e)), \ \forall\, e \in \mathbb{A}, \ j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{8}$$

$$x_i \ge l_i, \ \forall\, i \in \mathbb{I} \tag{9}$$

$$\sum_{e\in\mathbb{A}_o} y_{i,j}(e) = x_i, \ \forall\, j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{10}$$

$$\sum_{e\in\mathbb{A}_\nu^{in}} y_{i,j}(e) = \sum_{e\in\mathbb{A}_\nu^{out}} y_{i,j}(e), \ \forall\, \nu \in \mathbb{N} \setminus \{o, d\}, \ j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{11}$$

$$\sum_{e\in\mathbb{A}_d} y_{i,j}(e) = x_i, \ \forall\, j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{12}$$

$$y_{i,j}(e) \ge 0, \ \forall\, e \in \mathbb{A}, \ j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{13}$$

$$x_i \ge 0, \ \forall\, i \in \mathbb{I} \tag{14}$$

$$z_{i,j}(e) = 0 \text{ or } 1, \ \forall\, e \in \mathbb{A}, \ j \in \mathbb{J}_i, \ i \in \mathbb{I} \tag{15}$$

where $w_i \in (0, 1)$ is the weight assigned to each class i, $\sum_{i\in\mathbb{I}} w_i = 1$, and $M = \sum_{i\in\mathbb{I}} w_i M_i$ is a constant. Continuous decision variables and binary variables are nonnegative in constraints (13)-(15).

The budget constraint (3) is due to the limited budget on network planning. The constraint (4) means that the aggregate bandwidth of all connections at any link does not exceed the capacity. We have the end-to-end delay constraint (5) since every connection has the maximal end-to-end delay constraint. When a connection j in class i is routed along a path $p_{i,j} = \{e \in \mathbb{A} | \ z_{i,j}(e) = 1\}$, the end-to-end delay $D(p_{i,j})$ is computed from the following formula [2], [7]:

$$D(p_{i,j}) = \frac{n(p_{i,j}) \cdot \theta_i}{x_i} + \sum_{e\in p_{i,j}} d_e, \tag{16}$$

where $n(p_{i,j})$ is the number of links along path $p_{i,j}$ and θ_i is the mean packet size for each class i, $i \in \mathbb{I}$. A path $p_{i,j}$ between o and d is feasible, for a connection j of class i, if $D(p_{i,j}) \leq D_i$. That is,

$$\frac{\sum_{e\in\mathbb{A}} z_{i,j}(e)\cdot\theta_i}{x_i} + \sum_{e\in\mathbb{A}} d_e \cdot z_{i,j}(e) \leq D_i. \tag{17}$$

If both sides of constraint (17) are multiplied by $x_i \geq 0$, then (17) becomes (5) with the help of $x_i \cdot z_{i,j} = y_{i,j}(e)$.

The inclusion of constraints (6)-(8) is equivalent to at least one of $y_{i,j}(e) = 0$ and $y_{i,j}(e) = x_i$ being satisfied by either $z_{i,j}(e) = 0$ or $z_{i,j}(e) = 1$. Constraint (9) shows that every connection in the same class has the same bandwidth requirement. Constraints (10), (11), and (12) express the node conservation relations indicating that flow in equals flow out for every connection j in class i. Constraints (10)-(12) are standard flow conservation constraints.

Theorem 2.3 *The maximization model is bounded.*

Proof. Since each achievement function (1) has a upper bound M_i by Lemma 2.1. Hence, the objective function in (2) is bounded. □

3 Performance Evaluation

3.1 Optimal Solutions

We determine the optimal choices of links, $z^*_{i,j}(e)$, the optimal bandwidth allocation for each link e and for each connection of class i, $y^*_{i,j}(e)$ and x^*_i. The optimal solution x^*_i is unique, and it can provide the proportional fairness to every connection in all classes. That is, this allocation can provide the fair satisfaction to each user in all classes. We also find the total bandwidth allocated to each class i, $K_i x^*_i$.

Definition 3.1 *The ratio* $\sum_{j=1}^{K_i}\sum_{e\in\mathbb{A}} c_e y^*_{i,j}(e)/B$ *is called a* ***budget ratio*** *allocated to class* i.

Each class is given a percentage, budget ratio, of the total budget B.

Proposition 3.2 *If* $p_{i,j} = \{e \in \mathbb{A} |\ z^*_{i,j}(e) = 1\}$ *for connection* j *in class* i, *then path* $p_{i,j}$ *is the optimal path from* o *to* d *for connection* j *in class* i.

Proposition 3.3 *The end-to-end unit cost for bandwidth on the optimal path* $p_{i,j}$ *is*

$$\sum_{e\in p_{i,j}} c_e z^*_{i,j}(e)$$

for connection j *in class* i.

Proposition 3.4 *If link e belongs to the optimal path $p_{i,j}$, then the bandwidth by which the link e can offer for connection j in class i is the same. That is, $y^*_{i,j}(e) = y^*_{i,j}(e')$ for all $e,\ e' \in p_{i,j}$.*

Proposition 3.5 *A link e is the bottleneck link if $\sum_{i \in \mathbb{I}} \sum_{j \in \mathbb{J}_i} y^*_{i,j}(e) = U_e$.*

3.2 Blocking Probability with Predetermined Optimal Solutions

In this section, we study the blocking probability of an end-to-end transmission system with predetermined optimal solutions, including optimal bandwidth allocation, x^*_i, and K_i optimal end-to-end paths, $p_{i,j}$. At the source node o, connections arrive at random times to enter the core network. The predetermined number, K_i, in the optimization model, is used to denote the limit on the number of connections in class i. A new connection in class i can not enter the source node o and is lost when all K_i end-to-end path are busy. That is, for each class i, a connection gets dropped on its arrival when the number of connections occupying the end-to-end paths equals K_i. Otherwise, it will be routed through an end-to-end path $p_{i,j}$ with allocated bandwidth x^*_i. The principal quantity of interest is the blocking probability of different QoS classes, that is, the steady-state probability that all K_i end-to-end paths in class i are busy. Our objective is to estimate these blocking probabilities.

From outside this end-to-end transmission system, connections arrive to the source node o in accordance with independent Poisson processes at rate λ_i. For connections in class i, we assumed that successive inter-arrival times are independent and identically distributed (i.i.d.) and that the packet sizes to be transmitted have a general distribution G with mean θ_i. For each class i, we define $\mu_i = x^*_i/\theta_i$, where x^*_i is the optimal bandwidth allocation for each connection of class i. The average service time corresponds to the packet transmission time and is equal to mean pack size divided by bandwidth, that is,

$$\frac{1}{\mu_i} = \frac{\theta_i}{x^*_i}. \tag{18}$$

Hence, for each class i, the service times of connections occupying the end-to-end paths have a general distribution G with mean $1/\mu_i$. Suppose that connections occupy the end-to-end paths in the order they arrive and that packet sizes, which need to be transmitted from o to d, are identically distributed, mutually independent, and independent of the inter-arrival times. Under these assumptions, we analyze this end-to-end transmission system as $M/G/K_i/K_i$ loss systems [4], that is, Poisson arrivals, general service, K_i end-to-end paths with identical bandwidth allocation x^*_i, and no waiting space.

Let $\Pr_i(n_i)$ represent the limiting probability that there are n_i connections occupying the end-to-end paths for class $i = 1, \ldots, m$, and $n_i = 0, 1, \ldots, K_i$. For each class i, we can derive the steady-state occupancy probabilities from Erlang loss system [14]. Solving for $\Pr_i(0)$ in the equation $\sum_{n_i=0}^{K_i} \Pr_i(n_i) = 1$, we obtain

$$\Pr_i(0) = [\sum_{j=0}^{K_i} \frac{1}{j!} \cdot (\frac{\lambda_i}{\mu_i})^j]^{-1} = [\sum_{j=0}^{K_i} \frac{1}{j!} \cdot (\frac{\theta_i \cdot \lambda_i}{x_i^*})^j]^{-1} \tag{19}$$

and then

$$\Pr_i(n_i) = \frac{1}{n_i!} \cdot (\frac{\lambda_i}{\mu_i})^{n_i} \cdot [\sum_{j=0}^{K_i} \frac{1}{j!} (\frac{\lambda_i}{\mu_i})^j]^{-1} = \frac{1}{n_i!} \cdot (\frac{\theta_i \cdot \lambda_i}{x_i^*})^{n_i} \cdot [\sum_{j=0}^{K_i} \frac{1}{j!} (\frac{\theta_i \cdot \lambda_i}{x_i^*})^j]^{-1}, \tag{20}$$

for $n_i = 1, 2, \ldots, K_i$. Therefore, for each class i, the blocking probability is

$$\Pr_i(K_i) = \frac{1}{K_i!} \cdot (\frac{\theta_i \cdot \lambda_i}{x_i^*})^{K_i} \cdot [\sum_{j=0}^{K_i} \frac{1}{j!} (\frac{\theta_i \cdot \lambda_i}{x_i^*})^j]^{-1}. \tag{21}$$

Equation (21) is referred to as Erlang's loss formula (known as Erlang B) [14]. It is valid for all service distributions and only depends on the traffic load, $\theta_i \cdot \lambda_i / x_i^*$.

If we denote $\rho_i = \theta_i \cdot \lambda_i / x_i^*$, then equation (21) can be rewritten as

$$\begin{aligned} \Pr_i(K_i) &= \tfrac{(\rho_i)^{K_i}}{K_i!} \cdot [\textstyle\sum_{j=0}^{K_i} \tfrac{(\rho_i)^j}{j!}]^{-1} \\ &= \tfrac{(\rho_i)^{K_i}}{K_i!} \cdot [\exp(\rho_i) - R_i(K_i)]^{-1}, \end{aligned} \tag{22}$$

where $R_i(K_i)$ is the K_ith-degree Taylor remainder term of $\exp(\rho_i)$ [1]. From Taylor's formula with remainder [1], we have the following results.

Proposition 3.6 *There exists a real number* $\xi_i \in (0, \rho_i)$*, such that* $\exp(\rho_i) = \sum_{j=0}^{K_i} \frac{(\rho_i)^j}{j!} + R_i(K_i)$ *as*

$$R_i(K_i) = \frac{\exp(\xi_i) \cdot (\rho_i)^{K_i+1}}{(K_i+1)!}.$$

Moreover,

$$\lim_{K_i \to \infty} R_i(K_i) = 0.$$

Readers may refer to Wang et al. [17] for detailed derivation.

4 Numerical Results

Consider a sample network (shown in Figure 1) from [16] where $\mathbb{N}$ ={node o, ..., node d} and $\mathbb{A} = \{e_k,\ k = 1, \ldots, 26\}$ denote the set of nodes and the set of links in the network respectively. Characteristics of each link is listed in Table 1. Three different QoS classes are given in [16], characterized and shown in Table 2, where class 1 has the highest priority and class 3 has the lowest priority. Each connection is delivered from o to d. We assume connections of class i arrive to the source node o in accordance with independent Poisson processes at rate λ_i, and the packet sizes to be transmitted have general distributions with mean θ_i. We also assume every connection in class i has the same aspiration level a_i kbps (i.e. kilobits/sec), reservation level r_i kbps, mean packet size θ_i kb, maximal end-to-end delay D_i, and bandwidth requirement b_i kbps.

For each class i, we consider the achievement function $f_i(x_i)$ in (1). Given positive weight w_i, we have the objective function (2), where $\sum_{i=1}^{3} w_i = 1$. Under the total available budget B, we plan to allocate the bandwidths in order to provide each class with maximal utility (1). The mathematical model is programmed in a MILP form and ready to be solved by CPLEX.

We now explore how changes in the weight to each class will change the optimal allocation. All numerical results are presented in Table 3. We observe the sensitivity to the weight w_i assigned to each class. Given $(K_1, K_2, K_3) = (80, 120, 150)$, we compare it by changing the weight assigned to each class. Table 3 shows the computational result. Observe that enlarging the difference of weights will increase the total satisfaction. The increase is dominated by class 1 because there is almost no change in ratio of class 3. The reason is that it is easy to satisfy every connection in class 3 with minimum requirements. It shows enlarging the difference between classes 1 and 3 will increase the total satisfaction. However, the increase is mainly contributed by class 1 since w_1, the weight assigned to class 1, is larger than the others. Interestingly, bandwidth allocated to each connection and budget ratio do not reflect significantly any pattern versus the difference of weights $(w_1 - w_3)$.

Next, we observe the relationship between blocking probability, $\Pr_i(K_i)$, and mean arrival rate, λ_i, under conditions of $B = \$2,000,000$, $(K_1, K_2, K_3) = (80, 120, 150)$, and $(w_1, w_2, w_3) = (0.6, 0.3, 0.1)$. The optimal bandwidth allocation (x_1^*, x_2^*, x_3^*)=(334,156,46) can be easily found in Table 3. From equation (21), we can determine the blocking probabilities $\Pr_1(80)$, $\Pr_2(120)$, and $\Pr_1(150)$. Figure 2 shows enlarging the mean arrival rate, λ_i, will increase the blocking probability, $\Pr_i(K_i)$.

5 Conclusions

We present an approach for the bandwidth allocation and QoS routing in class-based networks. This scheme determines QoS routing under the network constraints. Users' utility functions are summarized by means of achievement functions. We can find an optimal allocation of bandwidth on the network under a limited budget, and this allocation can provide the proportional fairness to every class. Our approach is executed in advance, and its purpose is to establish a database, selecting one of the solutions when connections arrive. The on-line algorithm may select a path with the maximum reservable bandwidth among all feasible paths in this database. We also study the blocking probability of an end-to-end transmission system with predetermined optimal solutions, which is an important performance measurement of network systems. The blocking is due to the failure of setting up the number of end-to-end paths for each class.

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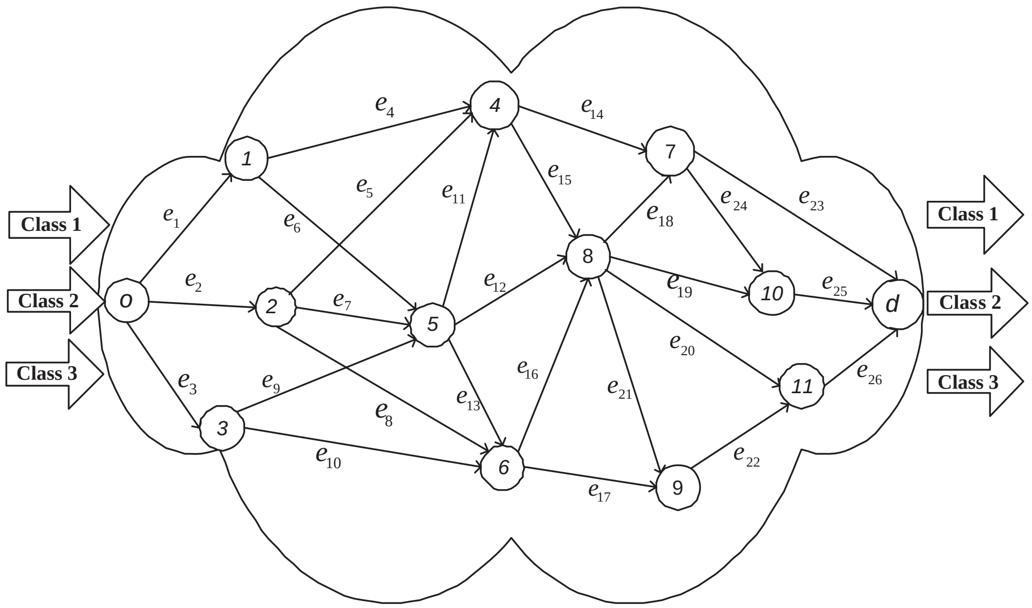

Figure 1: A sample network

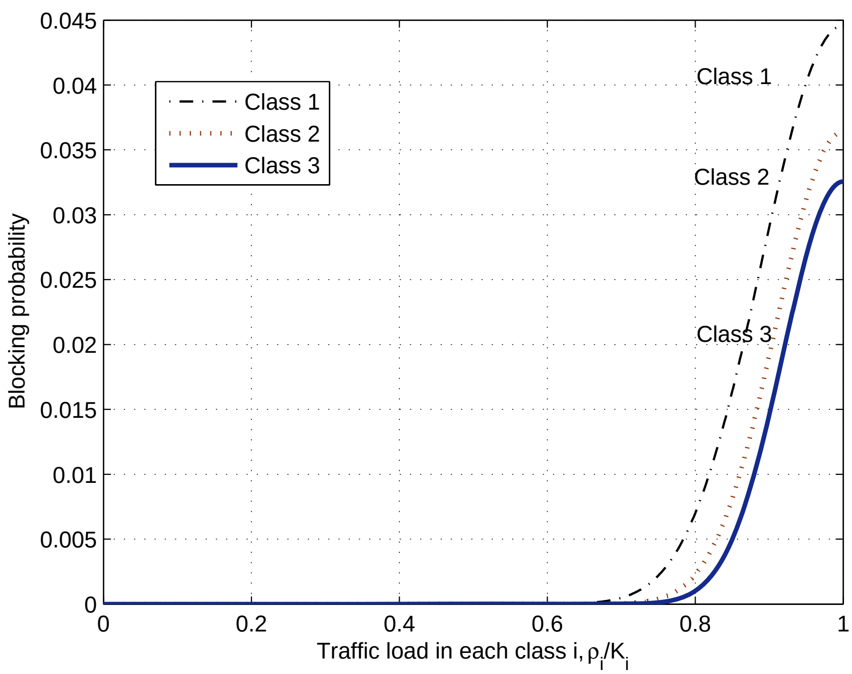

Figure 2: Blocking probability versus traffic load with 3 classes.

Table 1: Characteristics of each link.

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9
U_e (10^3 kbps)	35	45	55	53	47	36	37	45	40
c_e (\$)	7	6	5	14	11	14	7	13	8
d_e (ms)	3	3.2	3.5	1.2	2	1.2	3	1.5	2.7
	e_{10}	e_{11}	e_{12}	e_{13}	e_{14}	e_{15}	e_{16}	e_{17}	e_{18}
U_e (10^3 kbps)	50	45	46	45	44	46	36	35	54
c_e (\$)	14	7	11	5	5	10	5	7	5
d_e (ms)	1.2	3	2	3.5	3.5	2.2	3.5	3	3.5
	e_{19}	e_{20}	e_{21}	e_{22}	e_{23}	e_{24}	e_{25}	e_{26}	
U_e (10^3 kbps)	40	53	41	40	52	44	42	50	
c_e (\$)	7	9	6	8	13	6	8	6	
d_e (ms)	3	2.5	3.2	2.7	1.5	3.2	2.7	3.2	

Table 2: Characteristics of each QoS class

Class i	b_i (kbps)	a_i (kbps)	r_i (kbps)	θ_i (kb)	D_i (sec)
1	160	334	167	35	0.89
2	80	166	83	16.6	1.02
3	25	56	28	12.5	2.34

Table 3: Change in the weight

Weight (w_1, w_2, w_3)	Bandwidth (x_1^*, x_2^*, x_3^*)	Utility (f_1, f_2, f_3)	Total Utility $\sum_{i=1}^3 w_i f_i$	Budget Ratio (%)
$(\frac{1}{3}, \frac{1}{3}, \frac{1}{3})$	(300,166,56)	(0.84,1,1)	0.947	(45.8,37.9,16.0)
$(0.4, 0.3, 0.3)$	(313,158,56)	(0.91,0.93,1)	0.942	(47.8,36.2,16.0)
$(0.4, 0.4, 0.2)$	(300,165,56)	(0.84,0.99,1)	0.935	(45.7,37.9,16.0)
$(0.5, 0.3, 0.2)$	(334,142,56)	(1,0.77,1)	0.931	(51.1,32.3,16.0)
$(0.6, 0.2, 0.2)$	(334,144,56)	(1,0.80,1)	0.959	(51.1,32.9,16.0)
$(0.5, 0.4, 0.1)$	(334,166,37)	(1,1,0.41)	0.941	(50.9,44.3,10.6)
$(0.6, 0.3, 0.1)$	(334,156,46)	(1,0.91,0.70)	0.943	(51.0,35.7,13.0)
$(0.7, 0.2, 0.1)$	(334,147,53)	(1,0.82,0.91)	0.955	(51.0,33.5,15.0)
$(0.8, 0.1, 0.1)$	(334,144,56)	(1,0.80,1)	0.979	(51.0,32.9,16.0)