University of Würzburg
Institute of Computer Science
Research Report Series

Impact of Resilience Requirements on the Performance of Network Admission Control Methods

Michael Menth[1], Stefan Kopf[1], Joachim Charzinski[2],

Report No. 309 February 2003

[1] Department of Distributed Systems
Institute of Computer Science, University of Würzburg
Am Hubland, D-97074 Würzburg, Germany
tel: (+49) 931-8886644, fax: (+49) 931-8886632
{menth|kopf}@informatik.uni-wuerzburg.de

[2] Siemens AG
Hofmannstraße, D-81359 München, Germany
tel: (+49) 89-72246803, fax: (+49) 89-72226877 Joachim.Charzinski@siemens.com

Impact of Resilience Requirements on the Performance of Network Admission Control Methods

Michael Menth[1], **Stefan Kopf**[1], **Joachim Charzinski**[2],

[1] Department of Distributed Systems
Institute of Computer Science, University of Würzburg
Am Hubland, D-97074 Würzburg, Germany
tel: (+49) 931-8886644, fax: (+49) 931-8886632
{menth|kopf}@informatik.uni-wuerzburg.de

[2] Siemens AG
Hofmannstraße, D-81359 München, Germany
tel: (+49) 89-72246803, fax: (+49) 89-72226877
Joachim.Charzinski@siemens.com

Abstract

In this paper, we review four fundamental approaches for different network admission control (NAC). We explain how budgets and links may be dimensioned to keep the blocking probability low. In order to provide resilience against link outages, fast rerouting may be done without involving any further real-time admission control decisions. However, quality of service (QoS) can only be maintained if the network has sufficient backup capacity. We explain appropriate resource dimensioning to satisfy resilience requirements for the different NAC categories. Finally, we show the resource utilization under different NAC mechanisms in networking scenarios with and without resilience requirements and for single- and multi-path routing.

Keywords: QoS, resource allocation, admission control, network dimensioning, rerouting, resilience

1 Introduction

The next generation of the Internet is expected to fully integrate all kinds of data and media communications. In contrast to today's telephone network, data connections have variable bitrates and the management of the individual nodes should be simpler. And in contrast to today's Internet, real-time multimedia applications expect mechanisms for increased Quality of Service (QoS). This implies that future networks need a limitation of the traffic load [1] to

---

This work was funded by the Bundesministerium für Bildung und Forschung of the Federal Republic of Germany (Förderkennzeichen 01AK045) and Siemens AG, Munich. The authors alone are responsible for the content of the paper.

meet packet loss and delay requirements. This function is called admission control (AC). High quality transmission is guaranteed at the expense of blocked reservation requests in overload situations. To realize a low border-to-border (b2b) flow blocking probability in transit networks, the networks are provided with sufficient transport capacities which causes costs for the network provider. Therefore, AC mechanisms should be efficient but still simple.

Residential and business users depend more and more on the reliability of communication services and for providers of communication networks, the steadiness of network operation is a crucial factor and an economic risk. This motivates the need for resilient network provisioning. Networks are provisioned with sufficient capacity that forseeable outages do not compromise the QoS of the carried premium traffic. Unlike physical layer protection, this backup capacity is used for low priority traffic in normal operation mode.

AC may be implemented using different concepts and protocols. We distinguish between link AC (LAC) which pertains to a single link and network AC (NAC) that covers an entire network. In [2] we have identified several fundamentally distinct NAC categories and they reveal different resource utilization. NAC may be performed link-by-link like in ATM or IntServ [3, 4], the ingress rate may be limited at the edge routers like in the DiffServ context [5], or virtual tunnels may be applied [6, 7].

In this work, we investigate the influence of the resilience requirements on the utilization of the network resources depending on the NAC approach. We evaluate how well they are suited for that objective. In case of a link failure, all flows whose paths run over the failed link must be rerouted. Conventional routing protocols like OSPF [8] converge anew after a failure has occurred and carry the traffic to its destination and there are also other mechanisms [9] that are specialized for that purpose. Single-path routing forces all flows with the same destination on a single path while multi-path routing has the ability to spread traffic over the network. This has some impact on the required backup capacities in failure scenarios. In this study, we use Shortest Path First routing as in the OSPF protocol and its multi-path variant Equal Cost Multi-Path (ECMP).

The paper is structured as follows. Section 2 gives an overview of four basic budget based NAC categories. Section 3 explains how suitable budget and link capacities can be dimensioned and Section 4 enhances these formulae for networks with resilience requirements. Section 5 compares the resource utilization of NAC methods for networks with and without backup capacity as well as for single- and multi-path routing. Section 6 summarizes this work and gives an outlook on further research.

2 Methods for Network Admission Control (NAC)

In this section we distinguish between link and network admission control and explain four basically different NAC concepts.

2.1 Link and Network Admission Control

QoS criteria are usually formulated in a probabilistic way, i.e., the packet loss probability and the probability that the transport delay of a packet exceeds a given delay budget must both be lower than certain thresholds (p_{loss}, p_{delay}). Link admission control (LAC) takes the queuing characteristics of the traffic into account and determines the required bandwidth to carry flows over a single link without QoS violations. This includes two different aspects. First, bursty traffic requires more bandwidth for transmission than its mean rate to keep the queuing delay low which can be predicted by queuing formulae [10]. Secondly, flows usually indicate a larger mean rate than required just to make sure that there is enough bandwidth available when needed. This leads to overbooking by the provider or employing measurement based AC (MBAC), which can also take advantage of this fact [11, 12]. LAC takes all this into account and works, e.g., on effective bandwidth instead of peak rates for flows or flow aggregates if the bandwidth is large enough [13]. It records the demand of the admitted flows $\mathcal{F}_{admitted}$ in place. When a new flow arrives, LAC checks whether its effective bandwidth together with the demand of already established flows fits within a capacity budget that pertains here to a single link. If so, the flow is accepted, otherwise it is rejected.

Network admission control (NAC) tries to avoid congestion on all links of the network at the same time and does not just protect one link with an admission decision. This is a distributed problem with various solutions differing in their degree of storage and processing demands, locality and achievable multiplexing gain due to the partitioning of resources into budgets administered in different locations. Moreover, their efficiency differs, i.e. they require different network capacity to meet the same b2b flow blocking probability p_{b2b} which affects the network operator's costs.

In this investigation, we only focus on NAC, i.e. we blind out potential overbooking in presence of large traffic aggregates and work only on the effective bandwidth for individual b2b flows.

2.2 Link Budget Based Network Admission Control (LB NAC)

The link-by-link NAC is probably the most intuitive NAC approach. The capacity $l.c$[1] of each link l in the network is managed by a single link budget $LB(l)$ (with size $LB(l).c$) that may be administered, e.g., at the ingress router of that link or in a centralized database. A new flow $f_{new}(v,w)$ with ingress router[2] v, egress router w, and bitrate $f_{new}.c$ must pass the AC procedure for the LBs of all links that are traversed in the network by f_{new} (cf. Figure 1). The NAC procedure will be successful if the following inequality holds

$$\begin{aligned} &\forall l \in \mathcal{E} | l.u(v,w) > 0 : f_{new}(v,w).c \cdot l.u(v,w) + \\ &\sum_{f(x,y) \in \mathcal{F}_{admitted}(l)} f(x,y).c \cdot l.u(x,y) \leq LB(l).c. \end{aligned} \tag{1}$$

There are many systems and protocols working according to that principle. The connection AC in ATM [3] and the Integrated Services [4]architecture in IP technology adopt it in pure

---

[1] We borrow parts of our notation from the object-oriented programming style: $x.y$ denotes a property y of an object x. We prefer $x.y$ to the conventional y_x since this is hard to read if the name of x is complex.

[2] A networking scenario $\mathcal{N} = (\mathcal{V}, \mathcal{E}, u)$ is given by a set of border routers $\mathcal{V}$ and set of links $\mathcal{E}$. The b2b traffic aggregate with ingress router v and egress router w is denoted by $g(v,w)$. The function $l.u(v,w)$ with $v,w \in \mathcal{V}$ and $l \in \mathcal{E}$ reflects the routing and it is able to cover both single- and multi-path routing by indicating the percentage of the traffic rate $g(v,w).c$ using link l.

form. Other protocols reveal the same behavior although the mechanism is not implemented as an explicit LB NAC. Most bandwidth broker approaches [14, 6, 15] behave the same way and so do some stateless-core approaches [16, 17, 18]. A drawback of most of theses approaches is that core routers need to hold AC states per flow. If network resilience is required, these states must be quickly restored in backup machines in case of partial network outage. This must be done before the traffic is rerouted, which entails a huge technical overhead and it is not clear whether it is feasible in real-time and for large systems. If the budgets are administered in a central entity like a bandwidth broker this represents a single point of failure. The following two basic NAC methods manage the network capacity in a distributed way, i.e. all budgets related to a flow can be consulted at its ingress or its egress border router. In a failure scenario, only fast local rerouting of the traffic is required if sufficient backup capacities are available.

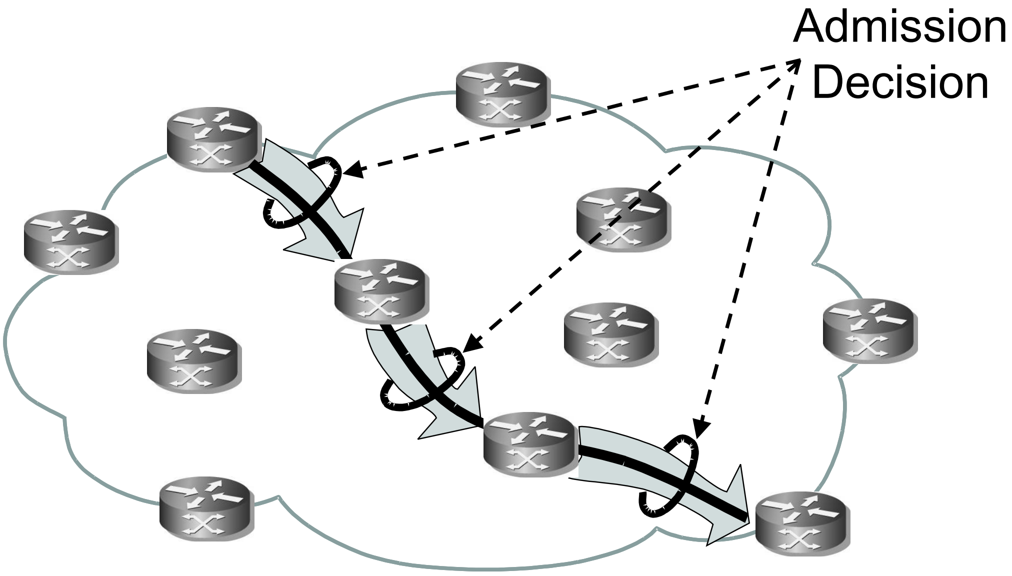

Figure 1: Network admission control based on link budgets.

2.3 Ingress and Egress Budget Based Network Admission Control (IB/EB NAC)

The IB/EB NAC defines for every ingress node $v \in \mathcal{V}$ an ingress budget $IB(v)$ and for every egress node $w \in \mathcal{V}$ an egress budget $EB(w)$ that must not be exceeded. A new flow $f_{new}(v,w)$ must pass the AC procedure for $IB(v)$ and $EB(w)$ and it is only admitted if both requests are successful (cf. Figure 2). Hence, the following inequalities must hold

$$\begin{aligned} f_{new}(v,w).c + \sum_{f \in \mathcal{F}^{ingress}_{admitted}(v)} f.c &\leq IB(v).c \\ f_{new}(v,w).c + \sum_{f \in \mathcal{F}^{egress}_{admitted}(w)} f.c &\leq EB(w).c \end{aligned} \tag{2}$$

Flows are admitted at the ingress and the egress irrespective of their egress or ingress routers. This entails that the capacity managed by an IB or EB can be used in a very flexible manner. However, all – also pathological – traffic patterns that are acceptable by the IBs and EBs must be carried by the network with the required QoS. Therefore, enough capacity must be allocated for the IBs and EBs such that also very unlikely scenarios with a strongly skewed traffic matrix can be supported.

This idea originates from the DiffServ context [19, 5] where traffic is admitted only at the border routers without looking at the destination address of the flows. It corresponds to a mere IB NAC, so only the first inequality of Equation (2) must be met for the AC procedure. The QoS should be guaranteed by a sufficiently low utilization of the network resources by high quality traffic.

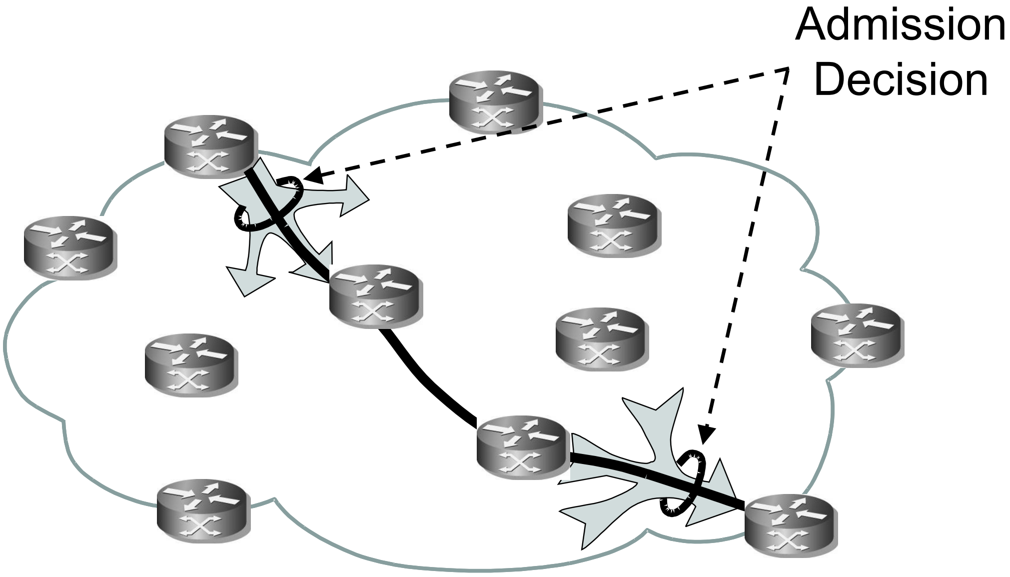

Figure 2: Network admission control based on ingress and egress budgets.

2.4 B2B Budget Based Network Admission Control (BBB NAC)

The BBB NAC is able to exclude pathological traffic patterns by taking both the ingress and the egress border router of a flow $f(v,w)$ into account for the AC procedure, i.e. a b2b budget $BBB(v,w)$ manages the capacity of a virtual tunnel between v and w. A new flow $f_{new}(v,w)$ passes only the AC procedure for $BBB(v,w)$ (cf. Figure 3). It is admitted if this request is successful, i.e. if the following inequality holds

$$f_{new}(v,w).c + \sum_{f \in \mathcal{F}_{admitted}(v,w)} f.c \leq BBB(v,w).c. \tag{3}$$

The $BBB(v,w)$ may be controlled, e.g., at the ingress router v or at the egress router w, i.e. the BBB NAC can also avoid states inside the network. The capacity of a tunnel is bound by the

BBB to one specific b2b aggregate and can not be used for other traffic with different source or destination. Hence, there is no flexibility for resource utilization. Therefore, the concept is often realized in a more flexible manner, such that the size of the BBBs can be rearranged [20, 21]. Tunnels may also be used hierarchically [22]. The tunnel capacity may be signaled using explicit reservation states in the network [7, 23], only in logical entities like bandwidth brokers [6], or it may be assigned by a central entity [24].

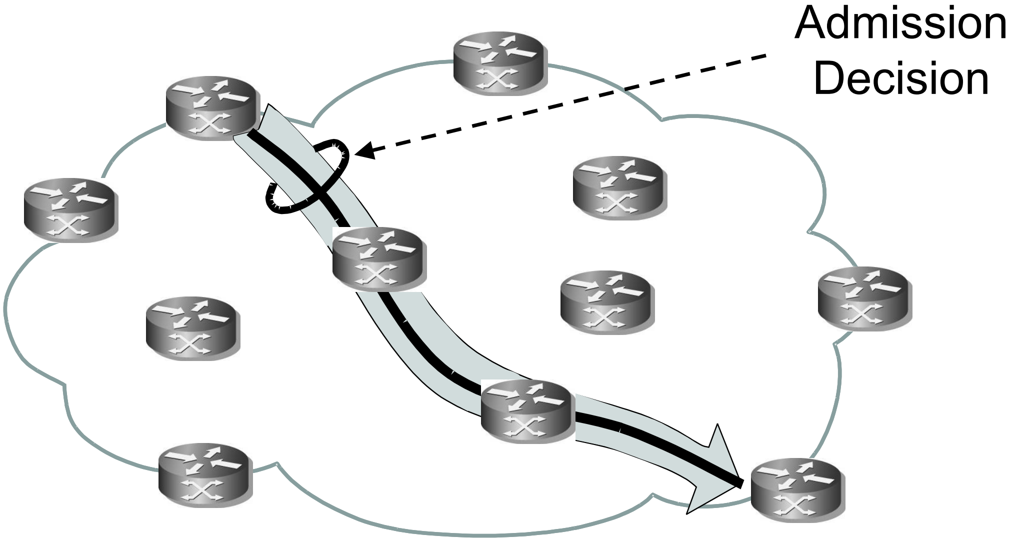

Figure 3: The BBB NAC corresponds to a logical tunnel.

2.5 Ingress Link Budget and Egress Link Budget Based Network Admission Control (ILB/ELB NAC)

The ILB/ELB NAC defines ingress link budgets $ILB(l,v)$ and egress link budgets $ELB(l,w)$ for each pair of ingress and egress routers $\{(v,w)|v,w \in \mathcal{V}, v \neq w\}$ to manage the capacity of link l. $ILB(l,v)$ can be administered at ingress router v and $ELB(l,w)$ at egress router w for each $l \in \mathcal{E}$. In case of single-path routing in IP, the links $\{l|ILB(l,v) > 0\}$ constitute a source tree and the links $\{l|ELB(l,w) > 0\}$ form a sink tree (cf. Figure 4). A new flow f_{new} must pass the AC procedure for the $ILB(.,v)$ and $ELB(.,w)$ of all links that are probably traversed in the network by f_{new} (cf. Figure 4). The NAC procedure will be successful if the following inequalities are fulfilled

$$\begin{aligned}
\forall l \in \mathcal{E}|l.u(v,w) > 0 \quad &: \quad f_{new}(v,w).c \cdot l.u(v,w) + \\
&\sum_{f(v,y) \in \mathcal{F}^{l,v,ingress}_{admitted}} f(v,y).c \cdot l.u(v,y) \leq ILB(l,v).c, \quad \text{and} \\
\forall l \in \mathcal{E}|l.u(v,w) > 0 \quad &: \quad f_{new}(v,w).c \cdot l.u(v,w) + \\
&\sum_{f(x,w) \in \mathcal{F}^{l,w,egress}_{admitted}} f(x,w).c \cdot l.u(x,w) \leq ELB(l,w).c. \qquad (4)
\end{aligned}$$

There are several significant differences to the BBB NAC. A BBB covers only an aggregate of flows with the same source and destination while the ILBs (ELBs) may cover flows with the same source but different destinations (sources). Therefore, the ILB/ELB NAC is more flexible than the BBB NAC. With the BBB NAC, only one $BBB(v, w)$ is checked while with ILB/ELB NAC, the number of budgets to be checked is twice the flow path lengths. In [25], a flexible version of the mere ILB NAC is applied and the ELBs map the structure of the aggregates in BGRP [26].

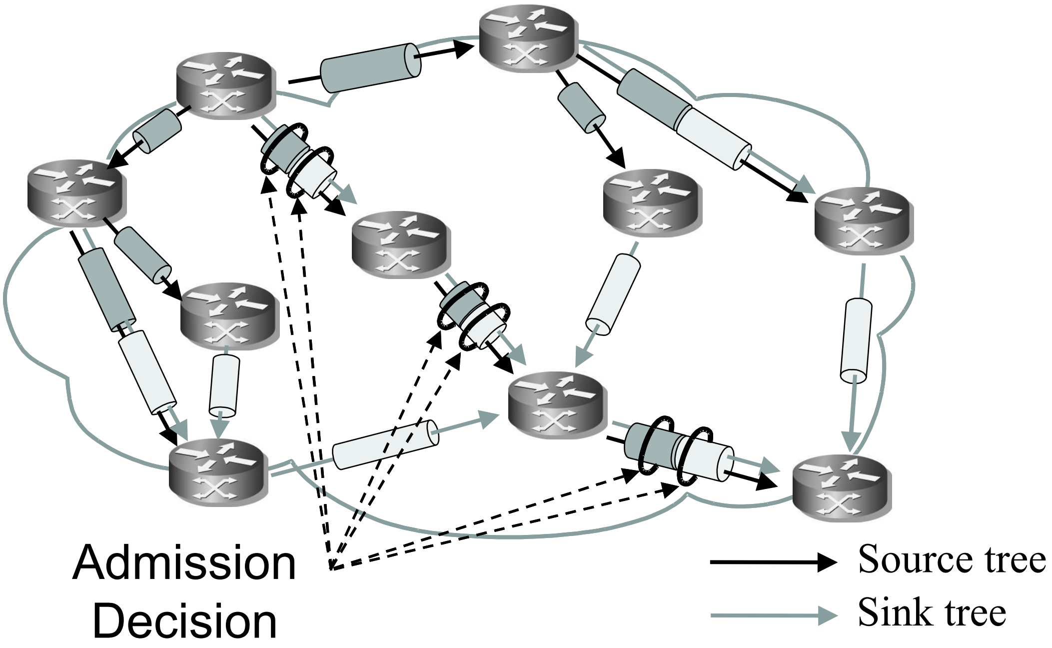

Figure 4: Network admission control based on ingress and egress link budgets.

3 Capacity Dimensioning for Budgets and Links

AC guarantees QoS for admitted flows at the expense of flow blocking if the budget capacity is exhausted. Since this applies to all budgets mentioned before, we abstract from special budgets to a general one denoted by b. To keep the blocking probability small, the capacity $b.c$ of a budget b must be dimensioned large enough. First, we consider budget dimensioning in general. Then, we explain how NAC specific budget and link capacities are calculated. Finally, we define a performance measure for the comparison of NAC methods.

3.1 Capacity Dimensioning

We review a general approach for capacity dimensioning and derive the required blocking probabilities.

3.1.1 Capacity Dimensioning for a Single Budget

Capacity dimensioning is a function calculating the required bandwidth for given traffic characteristics and a desired blocking probability. The specific implementation of that function depends on the underlying traffic model. We assume a Poisson model like in the telephone world. However, in a multi-service world, e.g. the future Internet, the request profile will be multi-rate, so we take n_r different request types r_i, $0 \leq i < n_r$ with a bitrate $r_i.c$ and a probability $r_i.prob$ into account. In our studies, we assume a simplified multimedia real-time communication scenario with $n_r = 2$, $r_0.c = 64$ Kbit/s, $r_1.c = 2048$ Kbit/s, and a mean bitrate of $E[C] = \sum_{0 \leq i < n_r} r_i.c \cdot r_i.prob = 256$ Kbit/s. The offered load a is the mean number of active flows, provided that no flow blocking occurs. Given an a, the respective offered load per request type is $r_i.a = r_i.prob \cdot a$. We assume that the requests arrive according to a Poisson process and have a generally distributed holding time. Therefore, we can use the recursive solution by Kaufman and Roberts [10] for the computation of the blocking probability $r_i.p$ of request type r_i if a certain capacity c is provided. We use Equation (5) to relate the blocking probability p to the traffic volume instead of to the number of flows.

$$p = 1 - \frac{\sum_{0 \leq i < n_r} (1 - r_i.p) \cdot r_i.c \cdot r_i.prob}{E[C]}. \tag{5}$$

An adaptation of the Kaufman and Roberts algorithm yields the required capacity for a desired blocking probability p. After all, we can compute the required budget capacity $b.c$ if the offered load $b.a$ and the desired budget blocking probability $b.p$ is given.

3.1.2 From B2B Blocking Probabilities to Budget Blocking Probabilities

Budget sizes are dimensioned using a desired budget blocking probability $b.p$. The set $\mathcal{D}(f)$ consists of the budgets whose capacity needs to be checked for the NAC of a flow f. This flow's b2b blocking probability is then

$$f.p_{b2b} = 1 - \Pi_{b \in \mathcal{D}(f)} (1 - b.p). \tag{6}$$

under the assumption that the $b.p$ are independent of each other and that the blocking probability of f is independent of its request size. Since the blocking probabilities of different budgets tend to be positively correlated if the network is well provisioned, the computation of $f.p_{b2b}$ according to Equation (6) is rather conservative.

In [27] we have proposed three different methods for setting the budget blocking probabilities $b.p$ to achieve a desired b2b flow blocking probability p_{b2b}. They have hardly any effect on the NAC performance, therefore, we stick with the simple approach that all $b.p$ are equal for all budgets $b \in \mathcal{D}(f)$. We denote by $b.m$ the maximum number of budgets to be checked for any flow controlled by b. Then the required $b.p$ is determined by

$$b.p \leq 1 - \sqrt[b.m]{1 - p_{b2b}} \quad \text{and} \tag{7}$$

$$b.p_{b2b} = 1 - (1 - (b.p))^{b.m}. \tag{8}$$

3.2 Resource Allocation for Budget Based NAC Methods

For a possible traffic pattern[3] $g.c \in {\mathbb{R}_0^+}^{|\mathcal{V}|^2}$ the following formulae hold

$$\begin{aligned} \forall v, w \in \mathcal{V} &: \; g(v,w).c \geq 0 \\ \forall v \in \mathcal{V} &: \; g(v,v).c = 0. \end{aligned} \tag{9}$$

If NAC is applied in the network, each traffic pattern $g.c$ satisfies the constraints defined by the NAC budgets. These constraints lead to linear equations, too, serving as side conditions for the worst case scenario in terms of rate maximization on a link l to determine its minimum capacity $l.c$

$$l.c \;\; \geq \;\; \max_{g.c \in {\mathbb{R}_0^+}^{|\mathcal{V}|^2}} \sum_{v,w \in \mathcal{V}} g(v,w).c \cdot l.u(v,w). \tag{10}$$

Since the aggregate rates have real values, the maximization can be performed by the Simplex algorithm [28] in polynomial time. However, for some NACs there are more efficient solutions that we will point out in the following.

3.2.1 LB NAC

The LB NAC requires that transit flows need to check a budget $\mathcal{LB}(l)$ for every link l for admission, hence, the maximum number of passed NAC budgets is

$$\mathcal{LB}(l).m \;\; = \;\; max_{\{v,w \in \mathcal{V} | l.u(v,w) > 0\}} len_{paths}^{max}(v,w,l)$$

whereby $len_{paths}^{max}(v,w,l)$ is the maximum length of the paths from v to w that contain l. The LB NAC covers all flows traversing link l. Hence, the expected offered load for budget $\mathcal{LB}(l)$ is

$$\mathcal{LB}(l).a \;\; = \;\; \sum_{v,w \in \mathcal{V}} g(v,w).a \cdot l.u(v,w). \tag{11}$$

According to Equation (1)

$$\forall l \in \mathcal{E} : \sum_{v,w \in \mathcal{V}} g(v,w).c \cdot l.u(v,w) \leq LB(l).c \tag{12}$$

must be fulfilled, so the minimum capacity $l.c$ of link l is constrained by

$$l.c \;\; \geq \;\; \mathcal{LB}(l).c. \tag{13}$$

---

[3] We denote the offered load for a b2b aggregate $g(v,w)$ by $g(v,w).a$ and the resulting matrix $g.a = \big(g(v,w).a\big)_{v,w \in \mathcal{V}}$ is the traffic matrix. In contrast, the current requested rate of an aggregate is $g(v,w).c$ and the matrix $g.c = \big(g(v,w).c\big)_{v,w \in \mathcal{V}}$ describes an instantaneous traffic pattern.

3.2.2 IB/EB NAC

With the IB/EB NAC, a flow is admitted by checking both the ingress and the egress budget, hence, we get $\mathit{IB}(v).m = \mathit{EB}(w).m = 2$. The IB/EB NAC subsumes all flows with the same ingress router v under $\mathit{IB}(v)$ and all flows with the same egress router w under $\mathit{EB}(w)$. The offered load of the respective budgets is

$$\begin{aligned} \mathit{IB}(v).a &= \sum_{w \in \mathcal{V}} g(v,w).a, \text{ and} \\ \mathit{EB}(w).a &= \sum_{v \in \mathcal{V}} g(v,w).a. \end{aligned} \tag{14}$$

Here we use the inequalities from Equation (2) as side conditions in Simplex method for the computation of the capacity $l.c$:

$$\begin{aligned} \forall v \in \mathcal{V} &: \sum_{w \in \mathcal{V}} g(v,w).c \leq \mathit{IB}(v).c, \text{ and} \\ \forall w \in \mathcal{V} &: \sum_{v \in \mathcal{V}} g(v,w).c \leq \mathit{EB}(w).c. \end{aligned} \tag{15}$$

In case of the mere IB NAC, $\mathit{IB}(v).m = 1$. The IBs are computed in the same way like above, however, there is a computational shortcut to the Simplex method for the calculation of the required link capacity $l.c$:

$$l.c \geq \sum_{v \in \mathcal{V}} \mathit{IB}(v).c \cdot \sum_{w \in \mathcal{V}} l.u(v,w) \tag{16}$$

3.2.3 BBB NAC

With the BBB NAC, only one budget is checked, therefore, $\mathit{BBB}(v,w).m = 1$. The BBB NAC subsumes under $\mathit{BBB}(v,w)$ all flows with ingress router v and egress router w. The offered load for $\mathit{BBB}(v,w)$ is simply

$$\mathit{BBB}(v,w).a = g(v,w).a. \tag{17}$$

Since Equation (3) is checked for admission

$$\forall v,w \in \mathcal{V} : g(v,w).c \leq \mathit{BBB}(v,w).c \tag{18}$$

must be fulfilled and the minimum capacity $l.c$ of link l is constrained by

$$l.c \geq \sum_{v,w \in \mathcal{V}} \mathit{BBB}(v,w).c \cdot l.u(v,w) \tag{19}$$

3.2.4 ILB/ELB NAC

The ILB/ELB NAC requires that transit flows need to ask for admission for every link as with the LB NAC. Therefore, we set

$$\begin{aligned} \mathit{ILB}(l,v).m &= 2 \cdot \max_{\{w \in \mathcal{V} | l.u(v,w)>0\}} len_{paths}^{max}(v,w,l), \text{ and} \\ \mathit{ELB}(l,w).m &= 2 \cdot \max_{\{v \in \mathcal{V} | l.u(v,w)>0\}} len_{paths}^{max}(v,w,l). \end{aligned} \tag{20}$$

The ILB/ELB NAC subsumes all flows with the same ingress router v on the link l under the $\mathit{ILB}(l,v)$ and all flows with the same egress router w under $\mathit{ELB}(l,w)$. The offered load for the budgets is

$$\begin{aligned} \mathit{ILB}(l,v).a &= \sum_{w \in \mathcal{V}} g(v,w).a \cdot l.u(v,w), \text{ and} \\ \mathit{ELB}(l,w).a &= \sum_{v \in \mathcal{V}} g(v,w).a \cdot l.u(v,w). \end{aligned} \tag{21}$$

Due to Equation (4), the side conditions

$$\begin{aligned} \forall v \in \mathcal{V} &: \sum_{w \in \mathcal{V}} g(v,w).c \cdot l.u(v,w) \leq ILB(l,v).c, \text{ and} \\ \forall w \in \mathcal{V} &: \sum_{v \in \mathcal{V}} g(v,w).c \cdot l.u(v,w) \leq ELB(l,w).c \end{aligned} \tag{22}$$

must be respected which constrains the minimum capacity $l.c$ by

$$l.c \geq \min\left(\sum_{v \in \mathcal{V}} \mathit{ILB}(l,v).c, \sum_{w \in \mathcal{V}} \mathit{ELB}(l,w).c\right). \tag{23}$$

In case of the mere ILB NAC, we have instead

$$\begin{aligned} \mathit{ILB}(l,v).m &= \max_{\{w \in \mathcal{V} | l.u(v,w)>0\}} len_{paths}^{max}(v,w,l), \text{ and} \\ l.c &\geq \sum_{v \in \mathcal{V}} \mathit{ILB}(l,v).c \end{aligned} \tag{24}$$

3.3 Performance Measure for NAC Comparison

We compute the required link capacities for all NAC methods according to the equations above. The required network capacity $\mathcal{N}.c$ is the sum of all link capacities in the network. The overall transmitted traffic rate $\mathcal{N}.c_{trans}$ is the sum of the offered load of all b2b aggregates weighted by their average path lengths $g(v,w).avgPathLen$, their acceptance probability $(1-p_{b2b})$, and the mean request rate $E[C]$. We neglect the fact that requests with a larger rate have a higher blocking probability due to the construction in Equation (5).

$$\begin{aligned}
\mathcal{N}.c &= \sum_{l\in\mathcal{E}} l.c \\
\mathcal{N}.c_{trans} &= (1-p_{b2b})\cdot E[C]\cdot \\
&\sum_{\{(v,w)|v,w\in\mathcal{V},v\neq w\}} g(v,w).a\cdot g(v,w).avgPathLen \\
\mathcal{N}.\rho &= \frac{\mathcal{N}.c_{trans}}{\mathcal{N}.c}. \qquad (25)
\end{aligned}$$

The overall resource utilization $\mathcal{N}.\rho$ is the fraction of the transmitted traffic rate and the overall network capacity. We use it in the next section as the performance measure for the performance comparison of NAC methods.

4 Capacity Dimensioning under Resilience Requirements

A local outage in a network – even with properly assigned resources – leads to severe QoS problems. Either, the transmission of the concerned flows in place is stalled, or rerouting takes place which may cause severe congestion on detour links. A solution for small local network failures is rerouting of the concerned traffic in combination with sufficient capacity provisioning in the network beforehand. Hence, appropriate dimensioning for possible outage scenarios is required which takes care of the rerouted traffic in that case. To that aim, the set $\mathcal{S}$ of protected failure scenarios $\mathcal{P}$ must be known. Each $\mathcal{P}\in\mathcal{S}$ reflects a set of failed network elements $\mathcal{P}.\mathcal{V}_F\subseteq\mathcal{V}$ and $\mathcal{P}.\mathcal{E}_F\subseteq\mathcal{E}$, i.e. the set of working routers $\mathcal{P}.\mathcal{V}_W\subseteq\mathcal{V}$ and the set of working links $\mathcal{P}.\mathcal{E}_W\subseteq\mathcal{E}$ are different from $\mathcal{V}$ and $\mathcal{E}$ which yields a new routing function $l.u_{\mathcal{P}}(v,w)$. After all, we have a new networking scenario $\mathcal{P}.\mathcal{N}$ for every protected failure scenario $\mathcal{P}\in\mathcal{S}$. We denote $\mathcal{P}$ with $\mathcal{P}.\mathcal{V}_F=\emptyset$ and $\mathcal{P}.\mathcal{E}_F=\emptyset$ by $\mathcal{P}^*$ and define that it is always contained in $\mathcal{S}$ to facilitate the handling of the normal operation mode in the following. Each link $l\in\mathcal{E}$ must be provided with sufficient capacity to carry the premium traffic in all $\mathcal{P}\in\mathcal{S}$. Hence, the required link capacity is

$$l.c \geq \max_{\mathcal{P}\in\mathcal{S}} \mathcal{P}.l.c. \qquad (26)$$

As outlined before, the NAC limits the traffic in the networks by Equations (1) and (4) which leads to the inequalities in Equation (12), Equation (15), Equation (18), and Equation (22) that can be used in a linear program to evaluate the required link capacities. In an outage scenario $\mathcal{P}$, the routing function $l.u(v,w)$ becomes $l.u_{\mathcal{P}}(v,w)$ which must be respected in the traffic maximization step in Equation (10). As long as the budgets are not changed, the side conditions are still based on the old routing function $l.u_{\mathcal{P}^*}(v,w)$. Due to this change, the shortcuts for the calculation of the link capacities for the LB NAC in Equation (13), for the ILB NAC in Equation (24), and for the ILB/ELB NAC in Equation (23) do not work anymore and the time consuming Simplex method must be applied.

5 NAC Performance Under Resilience Requirements

The number of failure scenarios with n link failures is $\binom{|\mathcal{E}|}{n}$. The more links fail, the less likely is that scenario and the more expensive is its protection. Therefore, we restrict our numerical studies to all single bi-directional link failure scenarios.

We investigate the performance of each NAC method with and without resilience requirements, and with single-path (SP) and multi-path routing (MP) for which we choose the shortest single-path routing and the shortest equal cost multi-path (ECMP) routing. We take SP and MP routing as the routing mechanisms in normal operation mode and use their convergence as reroute mechanism. Therefore, the routing in a failure scenario $\mathcal{P}$ equals the conventional SP or MP routing in the resulting networking scenario.

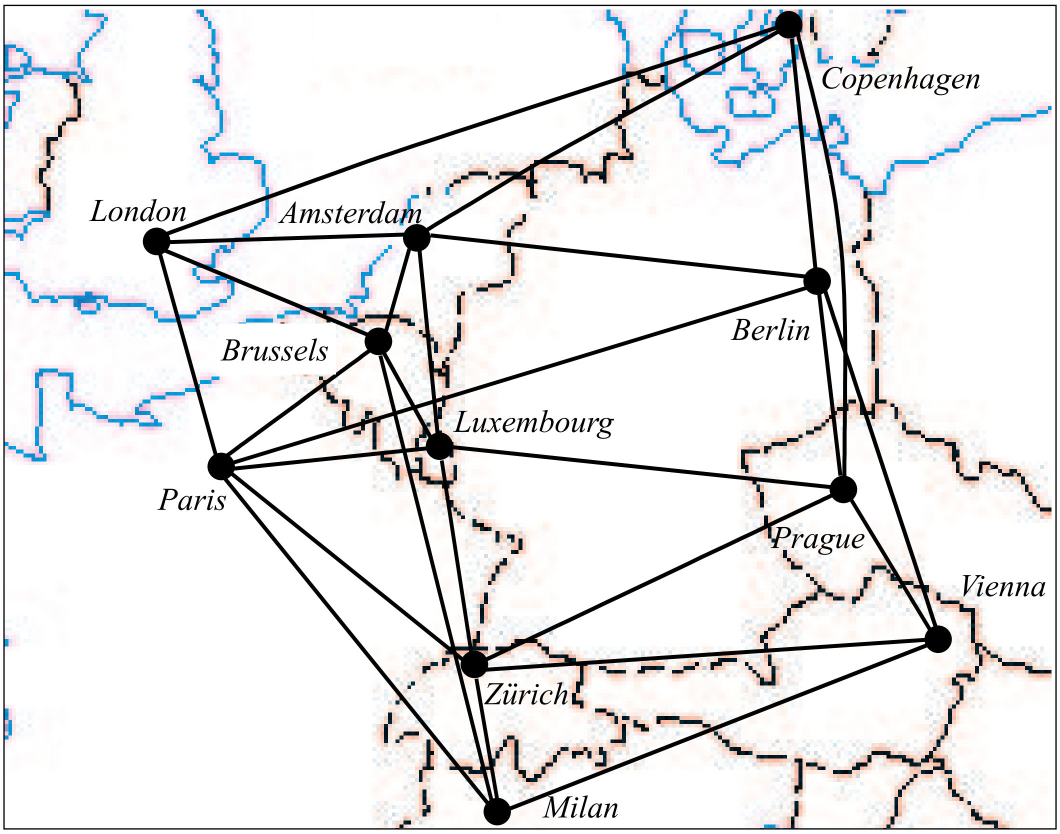

Figure 5: The topology of the COST239 network.

We study the NAC performance in the COST 239 network (cf. Figure 5, [29]) since it allows many shortest equal cost multi-paths and can well illustrate the influence of MP routing.

In the following, we illustrate first the concept of economy of scale on a single link. Then, we investigate the influence of the routing scheme and the resilience requirements on the resource utilization depending on the NAC method, and finally, we compare these methods in the different scenarios.

5.1 Economy of Scale Illustrated on a Single Link

Economy of scale or multiplexing gain is the key for understanding the performance behavior of NAC approaches and can be best illustrated on a single link. In [27] we have shown that the b2b blocking probability has a minor impact on the required capacity and the resource utilization compared to the offered load. We set it in all our studies to $p_{b2b} = 10^{-3}$.

Figure 6 shows that the required link capacity and the resource utilization depend heavily on the offered link load $l.a$. The resource utilization increases drastically up to an offered load of $l.a = 1000$ Erlang. Then the required link capacity rises almost linearly with the offered link load.

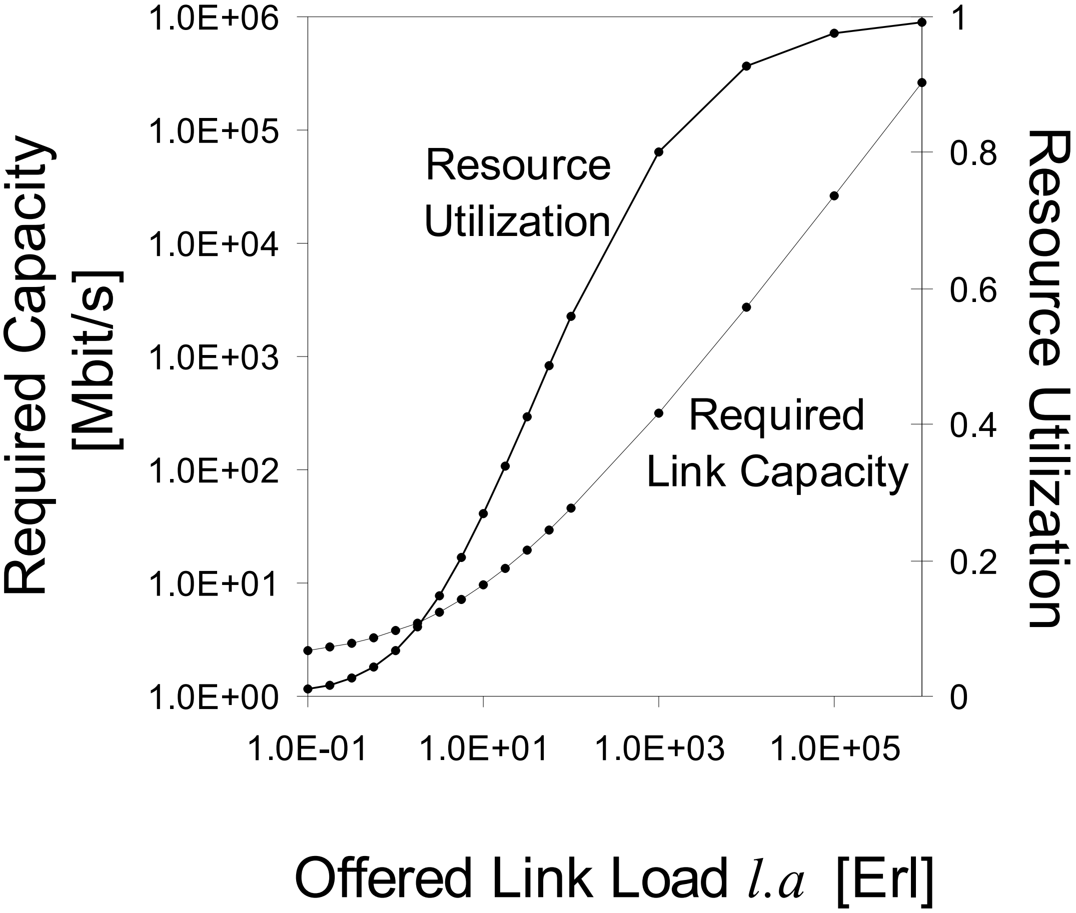

Figure 6: The impact of offered load on the required link capacity and the resource utilization on a single link under link admission control.

5.2 Impact of Resilience Requirements and Routing on the NAC Methods

We compare the resource utilization of the NAC methods with and without resilience requirements both with SP and MP routing.

5.2.1 BBB NAC

Figure 7 shows the resource utilization of the BBB NAC. The average offered load $g(v, w).a$ of all b2b aggregates $g(v, w)$ is given by our system parameter a_{b2b}. Since the BBBs cover exactly that traffic, the performance of the BBB NAC without resilience requirements equals exactly the above discussed single link scenario. The routing does not influence the offered load $BBB(v, w).a = a_{b2b}$ of a budget (cf. Equation (17)) and the resulting required capacity $BBB(v, w).c$ has an additive impact on the link capacities (cf. Equation (19)). Therefore, the overall required network capacity $\mathcal{N}.c$ for the BBB NAC is the same regardless of the routing as long as packets are forwarded on a shortest path.

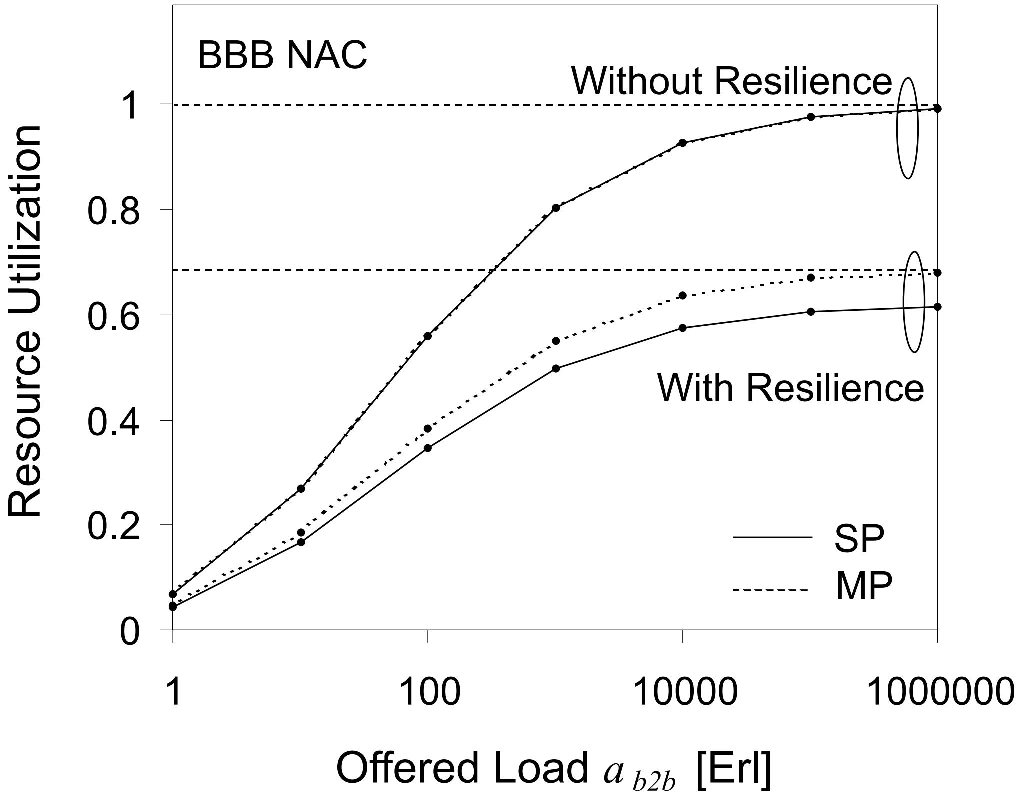

Figure 7: Resource utilization in the COST Network for BBB NAC.

With resilience requirements only 60% and 68% resource utilization can be achieved in the limit for SP and MP routing, respectively. Without resilience requirements, the resource utilization is almost 100%, so the reciprocal value $\frac{1}{0.6} \approx 1.67$ is the average degree of overdimensioning required for the survivability in outage scenarios. This corresponds to 67% additional backup capacity. Hence, clearly less than the double amount of capacity is required to achieve 100% resilience for all outage scenarios because the backup capacity is shared by different flows in different link failure scenarios. MP routing reduces this value even further to less than 50% ($\frac{1}{0.68} \approx 1.47$) since the rerouted traffic is distributed equally to more links which need in turn less backup capacity for resilience purposes. This observation is very important and applies to the performance of other NAC methods under resilience requirements, too.

5.2.2 LB NAC

Figure 7 illustrates the resource utilization of the LB NAC. Again, the LB NAC performance hardly depends on the routing scheme in the non-resilience case because the resource utilization depends only on the traffic concentration on the links. Apparently, the routing options SP and MP do not affect the resource utilization sufficiently to achieve clearly visible effects. With resilience requirements, the resource utilization decreases to 40% for SP routing and 48% for MP routing. Although, the absolute utilization values are smaller, the effect explained above applies here, too.

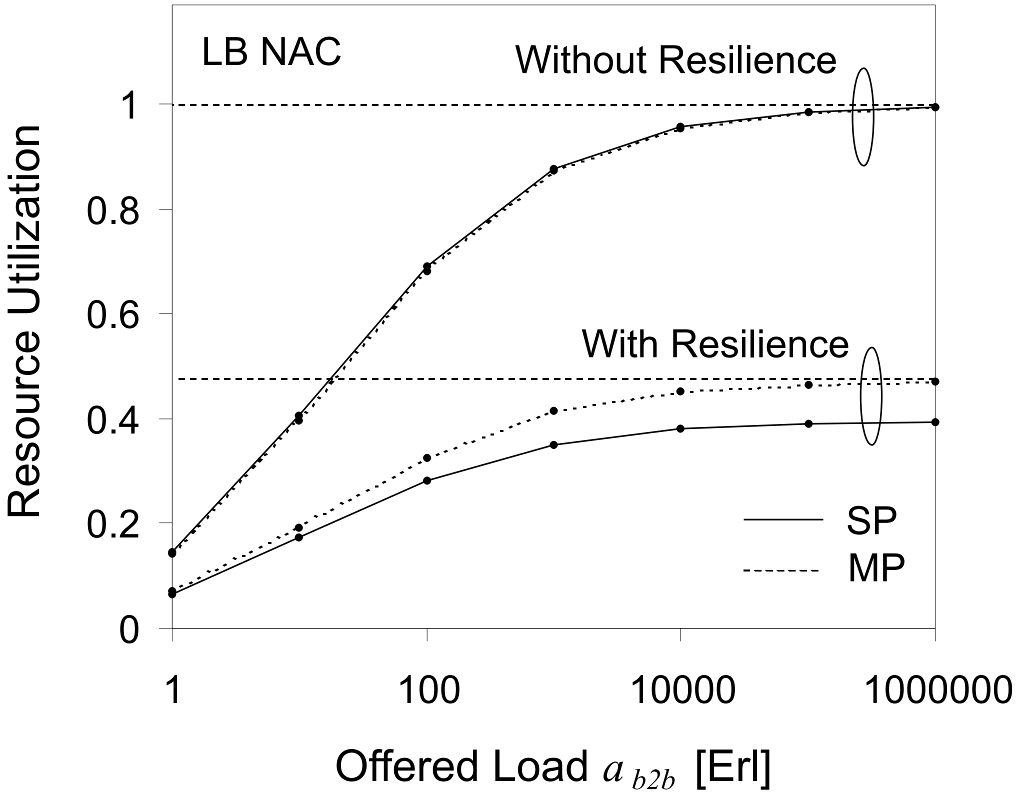

Figure 8: Resource utilization in the COST Network for LB NAC.

5.2.3 ILB/ELB NAC

The motivation for the ILBs and ELBs is the fact that they are able to aggregate the traffic on a link that stems from different b2b aggregates with the same ingress or egress router. This leads to a higher traffic concentration for a budget and to a higher utilization of its capacity. For SP routing, this works quite well because the traffic of a single b2b aggregate is forwarded over a single path so that the offered traffic for ILBs and ELBs are clearly larger than or equal to the offered load of the corresponding BBBs. With MP routing the traffic of a BBB is spread out over the network. As a consequence, the ILBs and ELBs are smaller which reduces the utilization of their capacities [2]. This explains why the resource utilization for the ILB/ELB NAC is smaller with MP routing than with SP routing in the non-resilience case (cf. Figure 9). With resilience requirements, the resource utilization is clearly smaller and now MP routing improves the NAC performance like above.

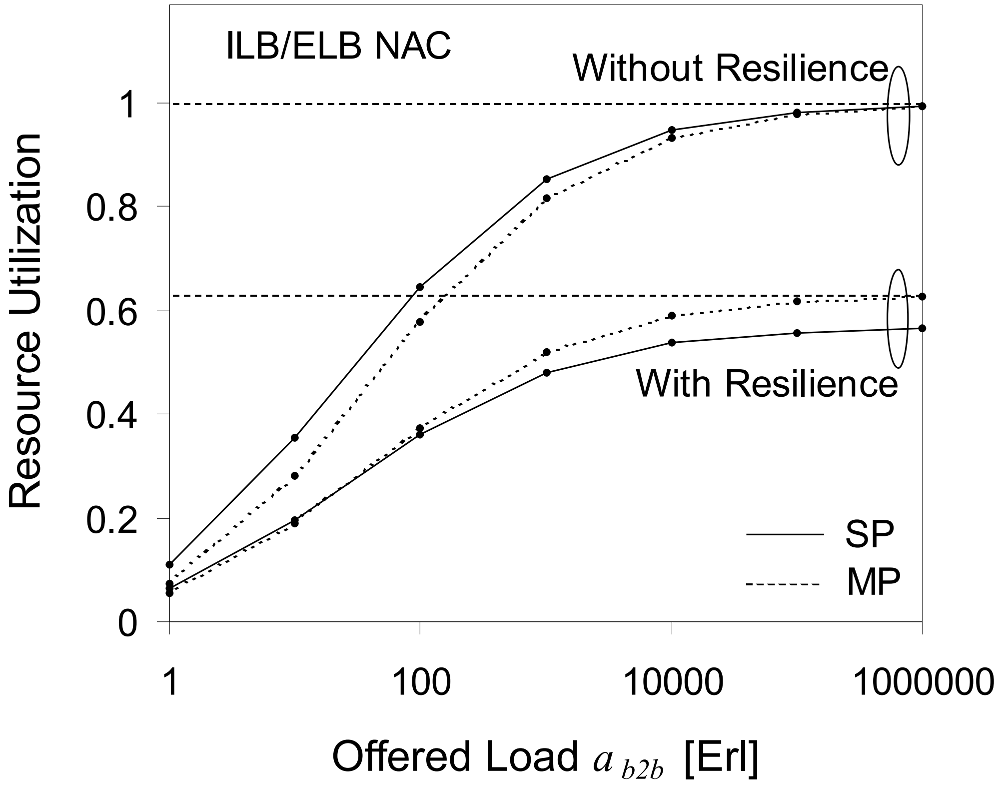

Figure 9: Resource utilization in the COST Network for ILB/ELB NAC.

5.2.4 IB/EB NAC

Figure 10 illustrates the performance of the IB/EB NAC. It is at most 22% for SP routing without resilience requirements and 16% with resilience requirements which leads to only 37.5% additional backup capacities. MP routing also improves the NAC performance under resilience requirements due to the reasons given above. It is remarkable that the performance is also increased for the normal operation mode. However, this kind of NAC is still not able to achieve high utilization values. The performance of the IB/EB NAC is discussed in more detail in [**?**, 30].

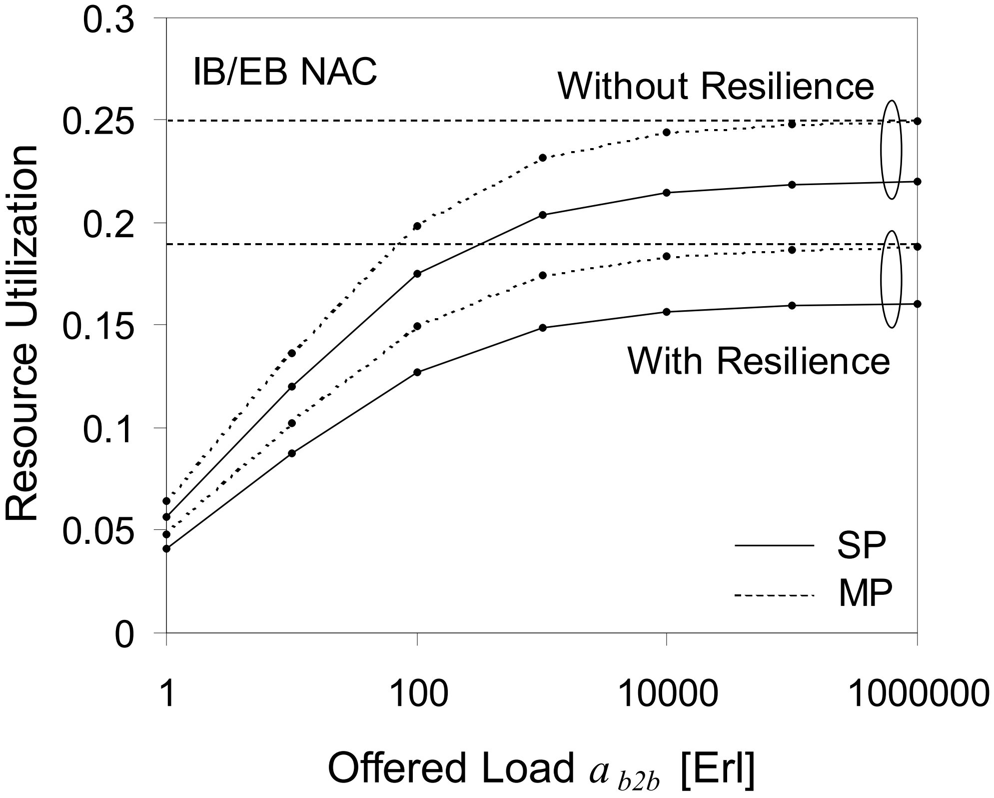

Figure 10: Resource utilization in the COST Network for IB/EB NAC. Note the reduced scale on the vertical axis.

5.3 Performance Comparison of the NAC Methods

We compare the performance of different NACs in different networking scenarios.

5.3.1 Single-Path Routing without Resilience Requirements

Figure 11 shows the performance of all NAC types that we have discussed previously for SP routing and without resilience requirements. The LB NAC, ILB/ELB NAC, ILB NAC, and BBB NAC can all achieve 100% resource utilization in the limit. The LB NAC has the highest resource utilization, in particular for low and medium size offered load while the performance of the BBB NAC is clearly lower. The reason for that phenomenon is the different flexibility of the NAC methods. The BBBs can allocate their capacity only to flows from a single b2b aggregate while the LB NAC admits more various traffic patterns. Therefore, the network resources can be better utilized with the LB NAC. The ILB NAC and the ILB/ELB NAC can be viewed as an interpolation of the BBB NAC and the LB NAC. The IB/EB NAC has a better performance than the IB NAC but their corresponding curves both converge to network topology specific asymptotes between only 10% and 20%. For low and medium size offered load, the LB NAC is the best NAC option but its implementation requires either reservation states in the network, a centralized bandwidth broker solution, or any other sophisticated mechanisms that depend on core router interaction.

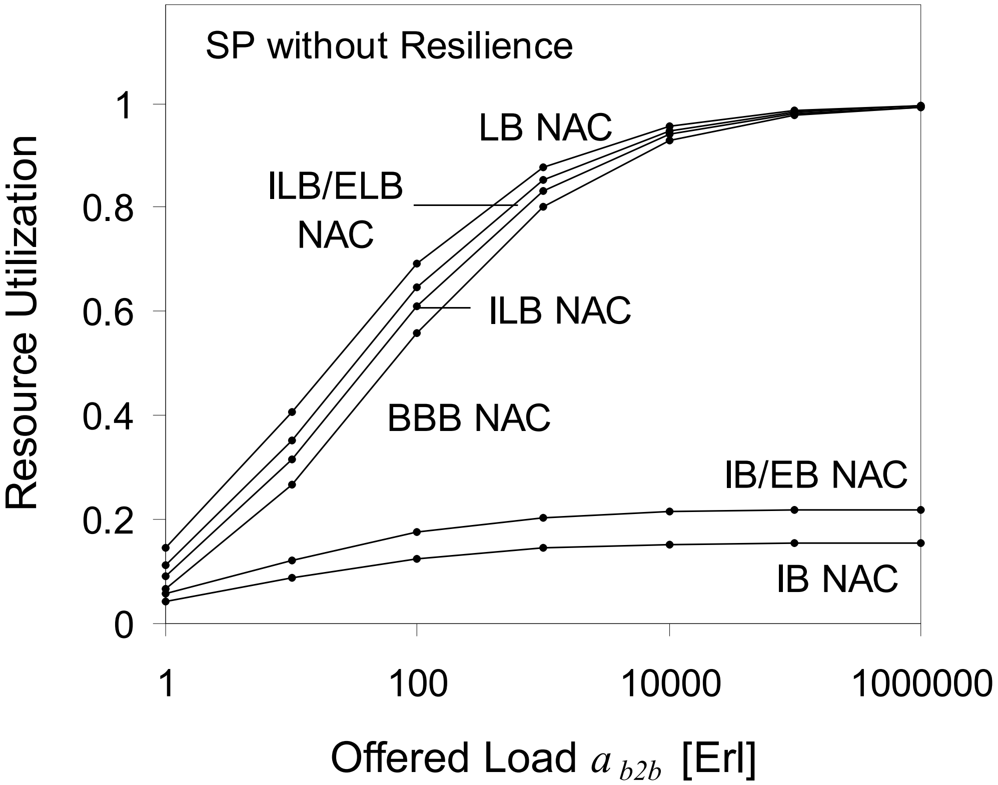

Figure 11: Resource utilization in the COST Network for SP routing without resilience requirements.

5.3.2 Multi-Path Routing without Resilience Requirements

Figure 12 illustrates the performance of all NAC approaches for MP routing and without resilience requirements. First, we realize that the performance advantage of the ILB and ILB/ELB NAC compared to the BBB almost vanishes. Hence, these NAC approaches clearly benefit from SP routing. Second, the performance of the LB NAC and the BBB NAC is about the same as with SP routing, and third, the resource utilization for both the IB NAC and the IB/EB NAC is slightly increased.

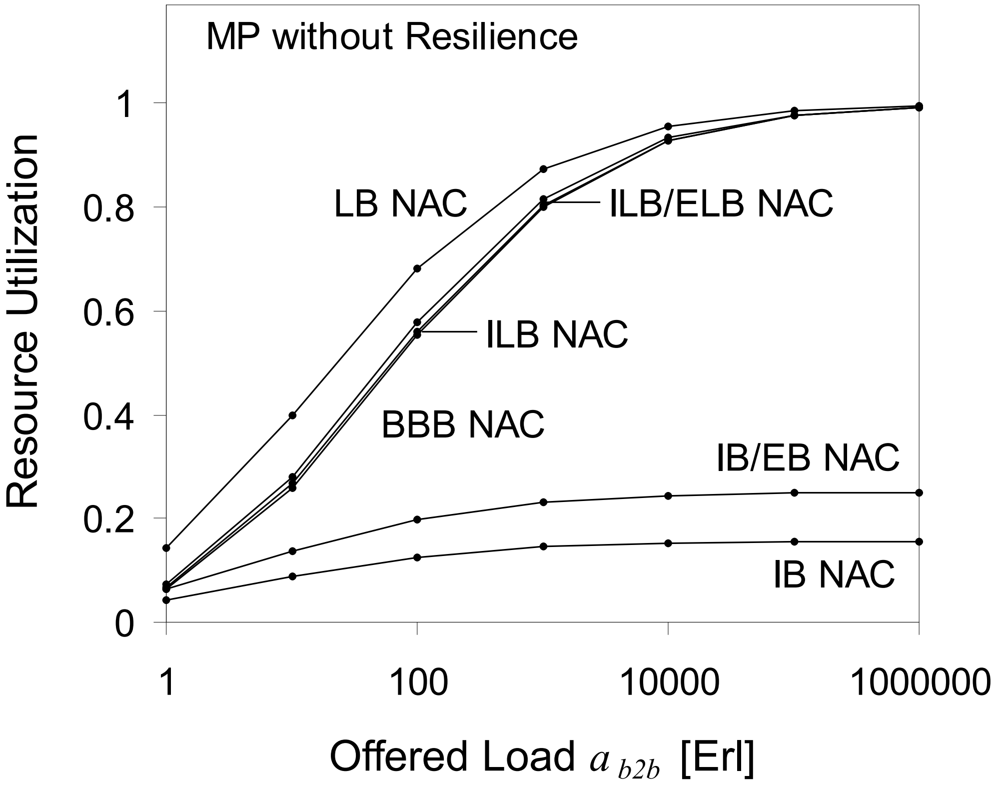

Figure 12: Resource utilization in the COST Network for MP routing without resilience requirements.

5.3.3 Single-Path Routing with Resilience Requirements

Figure 13 reveals a completely different performance behavior of the NAC methods for SP routing in case of resilience requirements. All NAC types have network specific asymptotes for their resource utilization. The most important finding is that the BBB NAC outperforms the ILB/ELB NAC, the ILB NAC, and the LB NAC. Except for ILB NAC and ILB/ELB NAC, this is the reversed order from the scenario without resilience. The flexibility of the

NAC methods is a drawback under resilience requirements since all admissible traffic patterns must be protected by backup capacity. Although the traffic patterns that are accepted by the LB NAC but not by the BBB NAC are unlikely, they are more extreme and demand more backup capacity in failure scenarios. Since the admitted traffic is about the same, the resource utilization of the LB NAC is smaller than with the BBB NAC. The ILB and the ILB/ELB NAC can be viewed again as an interpolation of the LB NAC and the BBB NAC. The resource utilization for the IB NAC and the IB/EB NAC is still clearly lower and slightly decreased compared to the normal operation mode.

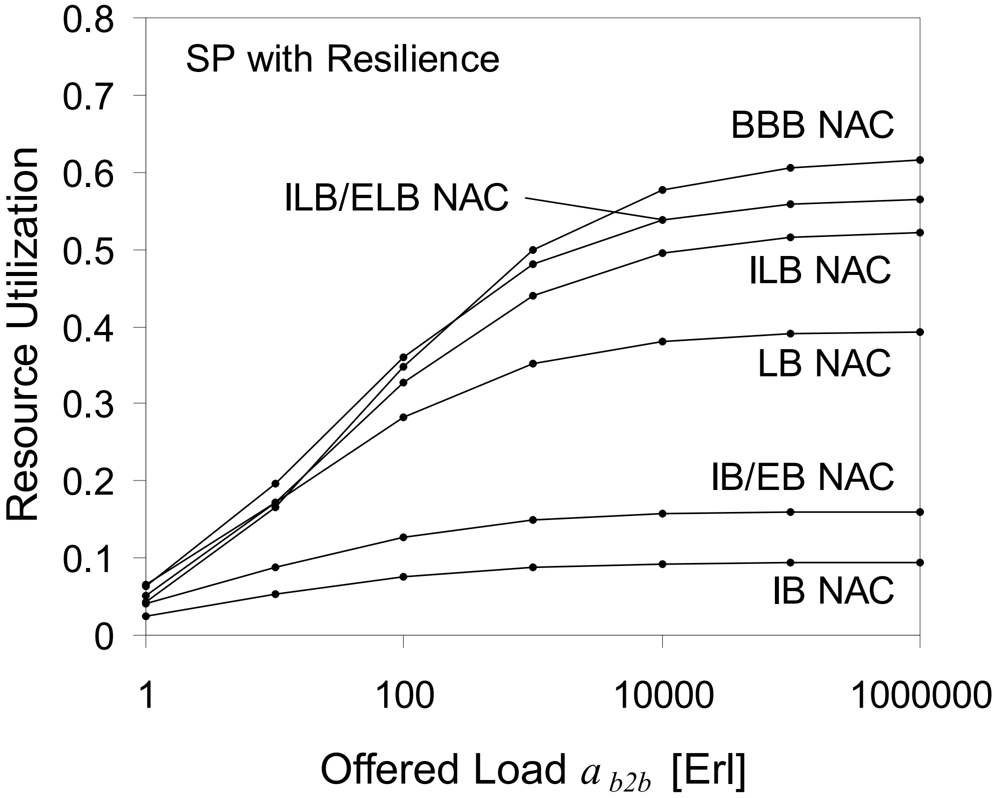

Figure 13: Resource utilization in the COST Network for SP routing with resilience requirements.

5.3.4 Multi-Path Routing with Resilience Requirements

Finally, we consider MP routing in case of resilience requirements as depicted in Figure 14. The curves look very similar to the SP routing case before but they are all increased by about 5% to 10%. Although the difference between ILB NAC, ILB/ELB NAC, and BBB NAC almost vanishes for MP routing without resilience requirements, with resilience requirements it is clearly visible.

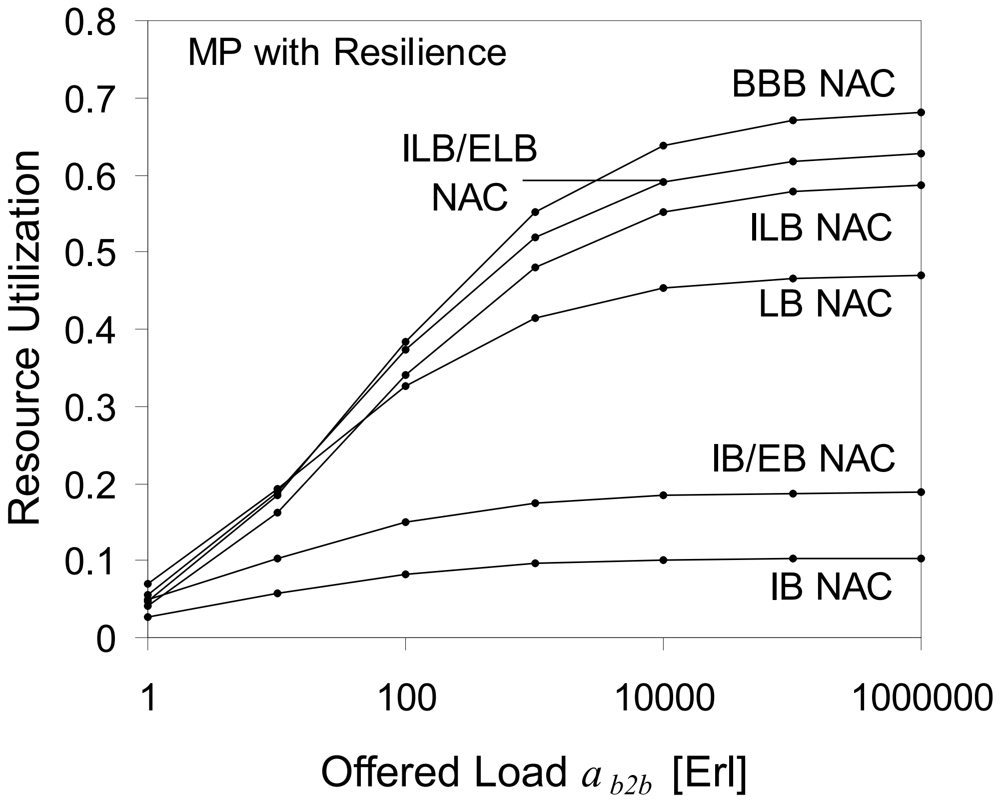

Figure 14: Resource utilization in the COST Network for MP routing with resilience requirements.

6 Conclusion

In this paper we have distinguished between link admission control (LAC) and network admission control (NAC). We reviewed four fundamentally different NAC categories and proposed formulae for their budget and link dimensioning. The novelty in this paper is the consideration of backup capacities for link failure scenarios such that rerouted traffic is still carried with a desired QoS.

The measure for the performance investigation is the average resource utilization, i.e. the average offered traffic weighted by its path length and divided by the sum of all link capacities. We tested the performance of each NAC method with and without resilience requirements, and with single-path (SP) and multi-path routing (MP) for which we chose the shortest single-path routing and the shortest equal cost multi-path (ECMP) routing.

The direct comparison of the NAC methods without resilience requirements and SP routing showed that the LB NAC is most efficient for low and medium size offered load, followed by the ILB/ELB NAC, the ILB NAC, and the BBB NAC. These NAC types achieve a resource utilization close to 100% for sufficiently high offered load. In contrast, the performance IB NAC and the IB/EB NAC converges to a network specific asymptote between 10% and 20%. Without resilience requirements, LB NAC, BBB NAC and IB NAC are not influenced by the routing scheme, the performance of IB/EB NAC is improved by MP routing while it is conversely affected for the ILB and ILB/ELB NAC. Under resilience requirements, the efficient NAC methods achieve a lower resource utilization between 40% and 70%. They have different utilization limits and the order of efficiency is reversed, i.e. the BBB NAC is most efficient and the LB NAC is least efficient. Under resilience requirements, all NAC methods profit from MP routing. We have observed the same effects in different network topologies with different utilization limits but the trend is the same.

Hence, networks resilient against partial network outages should implement the BBB NAC for two reasons. First, the network has a stateless core and no resource reservation signalling is needed when traffic is rerouted. Second, the BBB NAC requires less backup capacity than any other NAC approach. In addition, the capacity calculation for BBB NAC is easier and its implementation is less complex compared with the other NAC methods.

With MP routing, the resource utilization is about 10% larger than with SP routing. This shows that the mechanism for rerouting in failure scenarios holds some optimization potential with regard to the amount of the required backup capacity. Both MPLS and enhanced MP routing schemes may be used to increase the resource utilization and to reduce the required backup capacity in resilient networks.

References

[1] S. Shenker, “Fundamental Design Issues for the Future Internet,” *IEEE JSAC*, vol. 13, pp. 1176–1188, Sep. 1995.

[2] M. Menth, S. Gehrsitz, and J. Milbrandt, “Fair Assignment of Efficient Network Admission Control Budgets,” Technical Report, No. 306, University of Würzburg, Institute of Computer Science, Feb. 2003.

[3] The ATM Forum, *Traffic Management Specification, Version 4.0,* April 1996.

[4] B. Braden, D. Clark, and S. Shenker, “RFC1633: Integrated Services in the Internet Architecture: an Overview.” http://www.ietf.org/rfc/rfc1633.txt, June 1994.

[5] X. Xiao and L. M. Ni, “Internet QoS: A Big Picture,” *IEEE Network Magazine*, vol. 13, pp. 8–18, Mar. 1999.

[6] B. Teitelbaum, S. Hares, L. Dunn, V. Narayan, R. Neilson, and F. Reichmeyer, “Internet2 QBone: Building a Testbed for Differentiated Services,” *IEEE Network Magazine*, Sep. 1999.

[7] F. Baker, C. Iturralde, F. Le Faucheur, and B. Davie, “RFC3175: Aggregation of RSVP for IPv4 and IPv6 Reservations.” http://www.ietf.org/rfc/rfc3175.txt, Sept. 2001.

[8] J. Moy, "RFC2328: OSPF Version 2." ftp://ftp.isi.edu/in-notes/rfc2212.txt, April 1998.

[9] P. Pan, D.-H. Gan, G. Swallow, J. P. Vasseur, D. Cooper, A. Atlas, and M. Jork, "Fast Reroute Extensions to RSVP-TE for LSP Tunnels." http://www.ietf.org/internet-drafts/draft-ietf-mpls-rsvp-lsp-fastreroute-01.txt, Nov. 2002.

[10] J. Roberts, U. Mocci, and J. Virtamo, *Broadband Network Teletraffic - Final Report of Action COST 242*. Berlin, Heidelberg: Springer, 1996.

[11] L. Breslau, E. W. Knightly, S. Shenker, and H. Zhang, "Endpoint Admission Control: Architectural Issues and Performance," in *ACM SIGCOMM*, Aug. 2000.

[12] L. Breslau, S. Jamin, and S. Shenker, "Comments on the Performance of Measurement-Based Admission Control Algorithms," in *Infocom*, pp. 1233–1242, March 2000. ISBN 0-7803-5880-5.

[13] F. P. Kelly, "Notes on Effective Bandwidths," *Stochastic Networks: Theory and Applications*, vol. 4, pp. 141–168, 1996.

[14] A. Terzis, J. Wang, J. Ogawa, and L. Zhang, "A Two-Tier Resource Management Model for the Internet," in *Global Internet Symposium'99*, Dec. 1999.

[15] Z.-L. Z. Zhang, Z. Duan, and Y. T. Hou, "On Scalable Design of Bandwidth Brokers," *IEICE Transaction on Communications*, vol. E84-B, pp. 2011–2025, Aug 2001.

[16] I. Stoica and H. Zhang, "Providing Guaranteed Services Without Per Flow Management," *Computer Communication Review*, vol. 29, October 1999.

[17] S. Bhatnagar and B. Nath, "Distributed Admission Control to Support Guaranteed Services in Core-Stateless Networks," in *IEEE INFOCOM 2003*, (San Francisco, USA), April 2003.

[18] R. Szábó, T. Henk, V. Rexhepi, and G. Karagiannis, "Resource Management in Differentiated Services (RMD) IP Networks," in *International Conference on Emerging Telecommunications Technologies and Applications (ICETA 2001)*, (Kosice, Slovak Republic), Oct. 2001.

[19] S. Blake, D. L. Black, M. A. Carlson, E. Davies, Z. Wang, and W. Weiss, "RFC2475: An Architecture for Differentiated Services." ftp://ftp.isi.edu/in-notes/rfc2475.txt, Dec. 1998.

[20] T. Engel, E. Nikolouzou, F. Ricciato, and P. Sampatakos, "Analysis of Adaptive Resource Distribution Algorithsm in the Framework of a Dynamic DiffServ IP Network," in 8^{th} *International Conference on Advances in Communications and Control (ComCon8)*, (Crete, Greece), June 2001.

[21] H. Fu and E. Knightly, "Aggregation and Scalable QoS: A Performance Study," in *Proceedings of IWQoS 2001*, (Karlsruhe, Germany), June 2001.

[22] K. Kompella and Y. Rekhter, “LSP Hierarchy with Generalized MPLS TE.” http://www.ietf.org/internet-drafts/draft-ietf-mpls-lsp-hierarchy-08.txt, March 2002.

[23] D. O. Awduche, L. Berger, D.-H. Gan, T. Li, V. Srinivasan, and G. Swallow, “RFC3209: RSVP-TE: Extensions to RSVP for LSP Tunnels.” http://www.ietf.org/rfc/rfc3209.txt, Dec. 2001.

[24] P. Trimintzios, T. Bauge, G. Pavlou, L. Georgiadis, P. Flegkas, and R. Egan, “Quality of Service Provisioning for Supporting Premium Services in IP Networks,” in *IEEE Globecom 2002*, (Taipei, Taiwan), Nov. 2002.

[25] G. A. Politis, P. Sampatakos, and I. Venieris, “Design of a Multi-Layer Bandwidth Broker Architecture,” in *Interworking*, (Bergen, Norway), 2000.

[26] P. Pan and H. Schulzrinne, “BGRP: A Tree-Based Aggregation Protocol for Inter-domain Reservations,” *Journal of Communications and Networks*, vol. 2, pp. 157–167, June 2000.

[27] M. Menth, S. Kopf, and J. Milbrandt, “A Performance Evaluation Framework for Network Admission Control Methods,” Technical Report, No. 305, University of Würzburg, Institute of Computer Science, Feb. 2003.

[28] J. Stoer, *Numerische Mathematik 1*. New York, Berlin, Heidelberg: Springer, 5th ed., June 1989.

[29] P. Batchelor et al., “Ultra High Capacity Optical Transmission Networks. Final report of Action COST 239.” http://www.cnlab.ch/cost239/, 1999.

[30] M. Menth, S. Kopf, and J. Milbrandt, “Impact of Traffic Matrix and Routing on the Performance of Network Admission Control Methods,” Technical Report, No. 307, University of Würzburg, Institute of Computer Science, Feb. 2003.

[31] M. Menth, S. Kopf, and J. Charzinski, “Impact of Network Topology on the Performance of Network Admission Control Methods,” Technical Report, No. 308, University of Würzburg, Institute of Computer Science, Feb. 2003.