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Abstract

In this paper we consider the performance of different network admission control (NAC) methods. In contrast to link admission control (LAC), they limit the traffic within a network by distributed protocols. We introduce four basic budget based NAC approaches such that most resource management schemes can be classified by them from a performance point of view. Since they have different complexity and efficiency, we compare their resource utilization in different networking scenarios. Our results show that the performance is rather independent of the traffic matrix for realistic scenarios while the routing protocol – single- or multi-path routing – has a significant impact on the resource efficiency of the IB/EB NAC, ILB NAC, and ILB/ELB NAC. Thus, our investigation helps to understand the performance implications of different resource allocation protocols and eases the design of efficient next generation QoS networks.

Keywords: QoS, Admission Control, Resource Allocation, Performance Evaluation

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 traffic load [1] to meet the packet loss and delay requirements. This function is called admission control (AC). High quality transmission is guaranteed at the expense of control and management effort and 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 capacity which causes costs for the network provider. Therefore, AC mechanisms should

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be efficient but still simple. For reasons of robustness, they should not induce information states inside the network.

Link admission control (LAC) limits the transported traffic on a single link to avoid violations of the QoS requirements. *Network* admission control (NAC) is required when data are transported over several hops through a network instead just over a single link. This may be done by applying LAC on a link-by-link basis but this implies AC states in the core. However, it is desirable to control the load inside the network only at the border routers by performing AC based on resource budgets that are prereserved for certain traffic aggregates. In this work we identify four different NAC methods that reveal different resource utilization and that categorize most of today's implemented and investigated NAC approaches. NAC may be based on link budgets (LB), which is the conventional link-by-link NAC, on ingress and egress budgets (IB/EB), which is an idea known from the DiffServ context, on b2b budgets (BBB), which correspond to virtual tunnels, and on ingress and egress link budgets (ILB/ELB) which is a new concept. We explain how budget and link capacities can be dimensioned for the different NAC approaches based on a traffic matrix, a desired b2b flow blocking probability, and the routing.

The above mentioned NAC approaches and their protocols have different benefits and drawbacks. The implementation complexity can be shown by running code like it is practice in the IETF. The resource efficiency of NAC methods can be evaluated by performance investigations. We briefly review our NAC performance evaluation framework [2], where the achievable resource utilization is the performance measure for NAC methods, and apply it to the three basic concepts. Our analysis shows that the NAC methods differentiate clearly in resource efficiency, which depends mostly on the offered load in the network. Our results reveal that the performance is rather independent of the traffic matrix for realistic scenarios while the routing protocol – single- or multi-path (SP/MP) routing – has a significant impact on the resource efficiency of the IB/EB NAC, ILB NAC, and ILB/ELB NAC. Hence, our study gives input for the design of future NAC protocols since the resource utilization depends on the networking scenario.

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. Section 4 presents the performance comparison of the NAC methods. Section 5 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. 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 [3]. 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 to employing measurement based AC (MBAC), which can also take advantage of this fact [4, 5]. LAC takes all this into account and works, e.g., on the flow peak rates or their effective bandwidth if the bandwidth is large enough [6]. LAC records the demand of the admitted flows $\mathcal{F}_{admitted}$ in place. When a new flow arrives, it checks whether its effective bandwidth together with the demand of already established flows fits within a capacity budget. If so, the flow is accepted, otherwise it is rejected.

Network admission control (NAC) tries to avoid congestion on all links of the network and not just on a single link. 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 blocking probability p_{b2b} which affects the network operator's costs. Ususally, NAC and LAC can be combined, i.e. a flow's required capacity $f.c$[1] may consist of an effective bandwidth to take some overbooking in the presence of large traffic aggregates into account.

2.2 Link Budget Based Network Admission Control (LB NAC)

The link-by-link NAC is probably the most intuitive NAC approach. The capacity $l.c$ 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

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

There are many systems and protocols working according to that principle. The connection AC in ATM [7] and the Integrated Services [8] architecture in IP technology adopt it in pure form and induce per flow reservation states in the core. Other protocols reveal the same behavior although the mechanism is not implemented as an explicit LB NAC. A bandwidth broker [9, 10, 11] administers the budgets in a central database which represents a single point of failure but behaves the same way from the performance point of view. The stateless core

[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 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 set of all b2b traffic aggregates is $\mathcal{G}$. 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.

approaches [12, 13, 14] avoid reservation states in the core at the expense of measurements or increased response time. Reservation states in the core, measurements, or increased response times are a drawback if network resilience is required. 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 and the QoS is maintained if sufficient backup capacity is available.

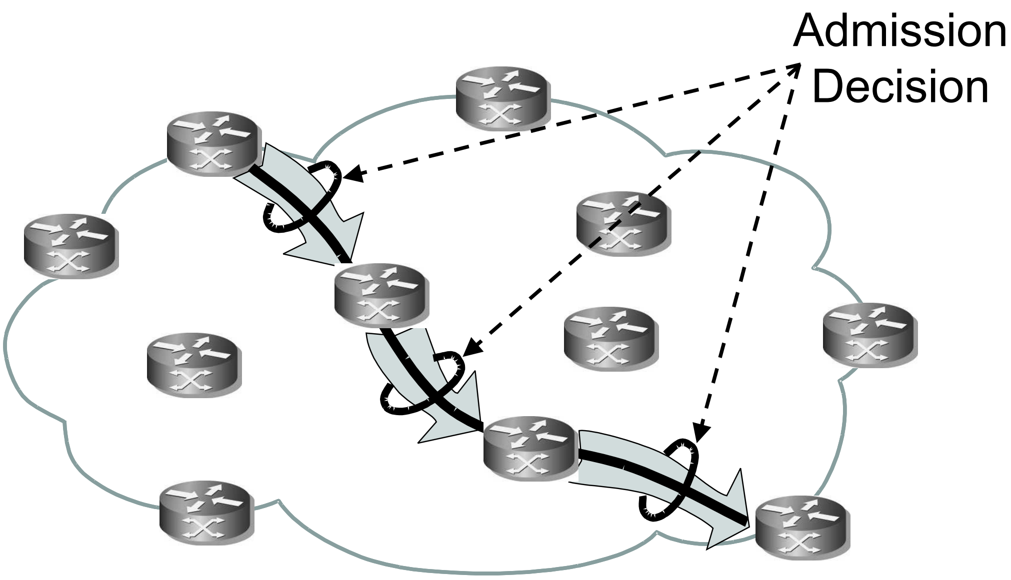

Figure 1: Network admission control based on link budgets.

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

$$f_{new}(v,w).c + \sum_{f \in \mathcal{F}^{ingress}_{admitted}(v)} f.c \leq IB(v).c \quad (2)$$

$$f_{new}(v,w).c + \sum_{f \in \mathcal{F}^{egress}_{admitted}(w)} f.c \leq EB(w).c \quad (3)$$

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 admissible by the IBs and EBs must be carried by the network with the required QoS. Therefore, enough capacity must be allocated on the network links.

If we leave the EBs aside, we get the simple IB NAC, so only Equation (2) must be met for the AC procedure. This idea originates from the DiffServ context [15, 16] where traffic is admitted only at the ingress routers without looking at the destination address of the flows. The QoS should be guaranteed by a sufficiently low utilization of the network resources by high quality traffic. To avoid any confusion: DiffServ is a mechanism for the forwarding differentiation of differently labelled packets while the IB NAC is just one concept among many others for the management of network resources within that context.

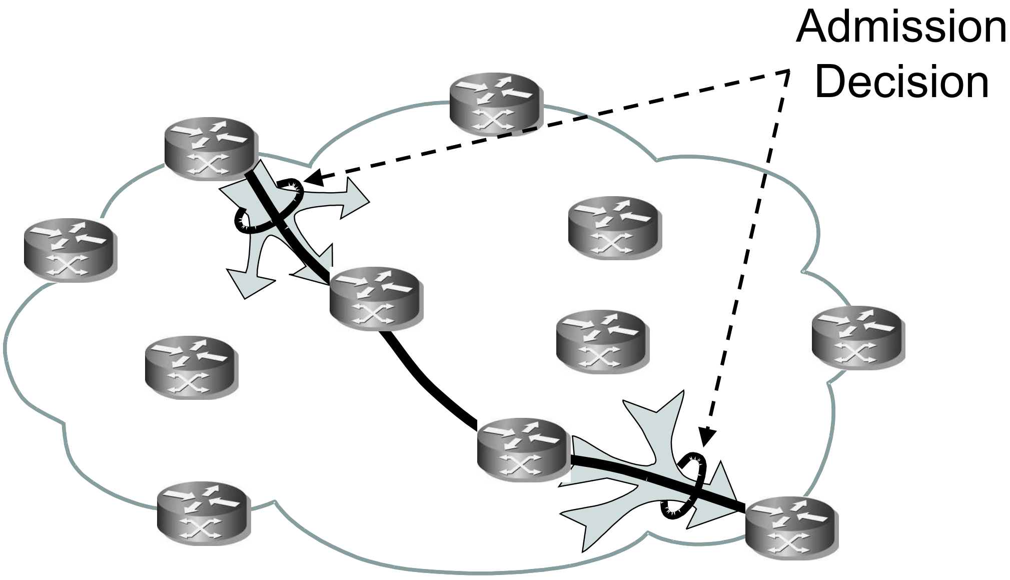

Figure 2: Network admission control based on ingress and egress budgets.

2.4 B2B Budget Based Network Admission Control (BBB NAC)

The TB 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. Figure 3 illustrates that a new flow $f_{new}(v, w)$ passes only the AC procedure for $BBB(v, w)$. It is admitted if this request is successful, i.e. if the following inequality holds

$$f_{new}(v, w).c + \sum_{f \in \mathcal{F}_{admitted}(v,w)} f.c \leq BBB(v, w).c. \tag{4}$$

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 also avoids 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 [17, 18]. Tunnels may also be used hierarchically [19]. The tunnel capacity may be signaled using explicit reservation states in the network [20, 21], only in logical entities like bandwidth brokers [10], or it may be assigned by a central entity [22].

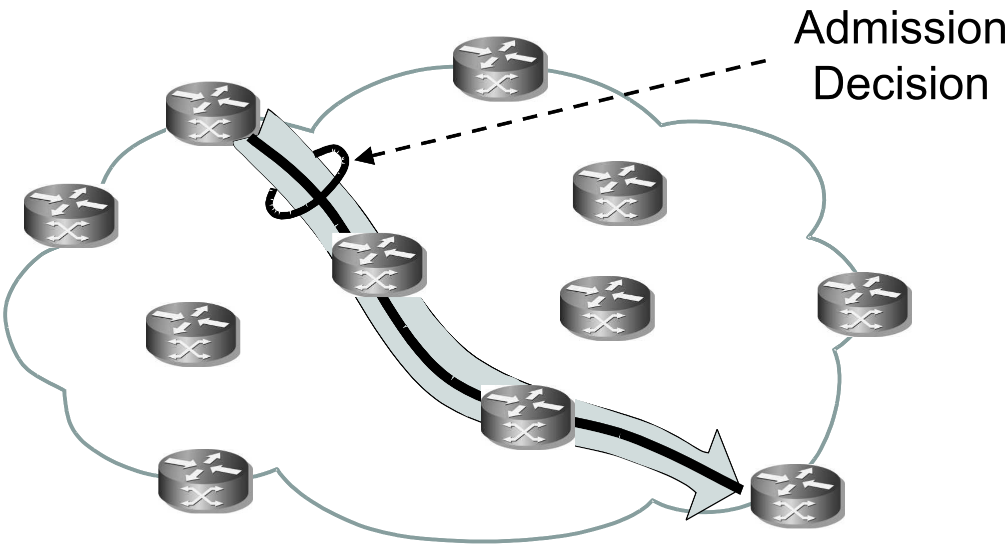

Figure 3: The BBB NAC corresponds to a logical tunnel.

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

The ILB/ELB NAC defines ingress link budgets (ILBs) $ILB(l, v)$ and egress link budgets (ELBs) $ELB(l, w)$ to manage the capacity of each $l \in \mathcal{E}$. They are administered by border routers v and w, i.e. the link capacity is partitioned among $|\mathcal{V}| - 1$ border routers. In case of single-path IP routing, 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 traversed in the network by f_{new} (cf. Figure 4). The NAC procedure will be successful if the following inequalities are fulfilled

$$\forall l \in \mathcal{E} : l.u(v, w) > 0 \quad : \quad f_{new}(v, w).c \cdot l.u(v, w) + \sum_{f(v,y) \in \mathcal{F}^{l,v,ingress}_{admitted}} f(v, y).c \cdot l.u(v, y) \leq ILB(l, v).c, \text{ and} \tag{5}$$

$$\forall l \in \mathcal{E} : l.u(v, w) > 0 \quad : \quad f_{new}(v, w).c \cdot l.u(v, w) + \sum_{f(x,w) \in \mathcal{F}^{l,w,egress}_{admitted}} f(x, w).c \cdot l.u(x, w) \leq ELB(l, w).c. \tag{6}$$

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) cover flows with the same source (destination) but different destinations (sources). Therefore, the ILB/ELB NAC is more flexible than the BBB NAC. The BBB NAC is simpler to implement because 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 but only in two different locations. Like with the IB/EB NAC, there is the option to use only ILBs or ELBs by applying only Equation (5) or Equation (6). The concept of ILB/ELB or ILB NAC can be viewed as local bandwidth brokers at the border routers, disposing over a fraction of the network capacity. These concepts are new and have not yet been implemented by any resource management protocol. The path of the sessions in BGRP [23] matches also a sink tree but BGRP works like the LB NAC on its entities.

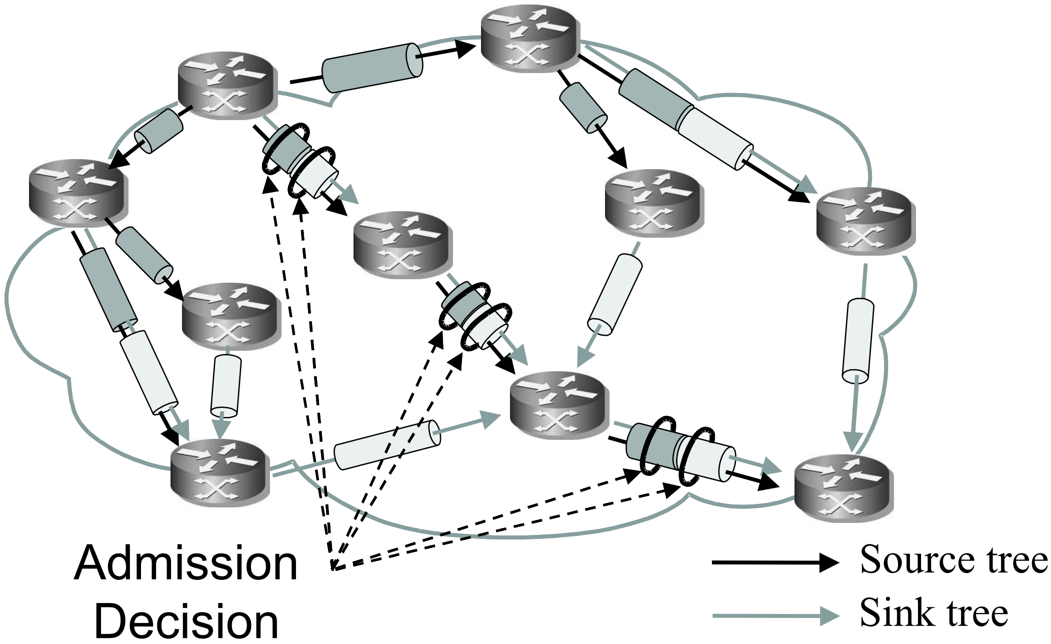

Figure 4: Network admission control based on ingress and egress link budgets.

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 specifi c budget and link capacities are calculated. Finally, we defi ne 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 $n_r = 3$, $r_0.c = 64$ Kbit/s, $r_1.c = 256$ Kbit/s, and $r_2.c = 2048$ 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 [3] for the computation of the blocking probabilities $r_i.p$ of request types r_i if a certain capacity c is provided. We use Equation (7) to relate the blocking probability p to the traffic volume instead to the number of flows.

$$p \;=\; 1 - \frac{\sum_{0 \leq i < n_r} (1 - r_i.p) \cdot r_i.c \cdot r_i.prob}{E[C]}. \tag{7}$$

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 $\mathcal{D}(g)$ consists of the budgets whose capacity needs to be checked if a flow of the traffic aggregate g asks for admission. The b2b blocking probability associated with this aggregate g is then

$$g.p_{b2b} \;=\; 1 - \Pi_{b \in \mathcal{D}(f)} (1 - b.p). \tag{8}$$

under the assumption that the $b.p$ are independent of each other. Since the blocking probabilities of different budgets tend to be positively correlated if the network is well provisioned, the computation of $g.p_{b2b}$ according to Equation (8) is rather conservative.

In [2] 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 $b \in \mathcal{D}(g)$. 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

$$b.p \;\leq\; 1 - \sqrt[b.m]{1 - p_{b2b}} \tag{9}$$

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

$$\begin{aligned} \forall v, w \in \mathcal{V} &: \quad g(v,w).c \geq 0 \\ \forall v \in \mathcal{V} &: \quad g(v,v).c = 0. \end{aligned} \tag{10}$$

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:

$$l.c \quad \geq \quad \max_{g.c \in \mathbb{R}_0^{+|\mathcal{V}|^2}} \sum_{v,w \in \mathcal{V}} g(v,w).c \cdot l.u(v,w). \tag{11}$$

This is used to determine the minimum required capacity $l.c$ of that link. Since the aggregate rates have real values, the maximization can be performed by the Simplex algorithm [24] 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 $LB(l)$ for every link l of its path for admission, hence, the maximum number of passed NAC budgets is

$$LB(l).m \; = \; max_{\{v,w \in \mathcal{V}: l.u(v,w)>0\}} len_{paths}^{max}(v,w,l) \tag{12}$$

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

$$LB(l).a \quad = \quad \sum_{v,w \in \mathcal{V}} g(v,w).a \cdot l.u(v,w). \tag{13}$$

According to Equation (1)

$$\forall l \in \mathcal{E} : \sum_{v,w \in \mathcal{V}} g(v,w).c \cdot l.u(v,w) \leq LB(l).c \tag{14}$$

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

$$l.c \quad \geq \quad LB(l).c. \tag{15}$$

[3]We denote the offered load for a b2b aggregate $g(v,w)$ by $g(v,w).a$. 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 $IB(v).m = EB(w).m = 2$. The IB/EB NAC subsumes all flows with the same ingress router v under $IB(v)$ and all flows with the same egress router w under $EB(w)$. The offered load of the respective budgets is

$$IB(v).a = \sum_{w \in \mathcal{V}} g(v,w).a, \text{ and} \tag{16}$$

$$EB(w).a = \sum_{v \in \mathcal{V}} g(v,w).a. \tag{17}$$

Here we use the inequalities from Equation (2) and Equation (3) as side conditions in Simplex method for the computation of the capacity $l.c$:

$$\forall v \in \mathcal{V} : \sum_{w \in \mathcal{V}} g(v,w).c \leq IB(v).c, \text{ and} \tag{18}$$

$$\forall w \in \mathcal{V} : \sum_{v \in \mathcal{V}} g(v,w).c \leq EB(w).c. \tag{19}$$

In case of the mere IB NAC, $IB(v).m = 1$. 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 $l.c$:

$$l.c \geq \sum_{v \in \mathcal{V}} IB(v).c \cdot \sum_{w \in \mathcal{V}} l.u(v,w) \tag{20}$$

3.2.3 BBB NAC

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

$$BBB(v,w).a = g(v,w).a. \tag{21}$$

Since Equation (4) is checked for admission

$$\forall v,w \in \mathcal{V} : g(v,w).c \leq BBB(v,w).c \tag{22}$$

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

$$l.c \geq \sum_{v,w \in \mathcal{V}} BBB(v,w).c \cdot l.u(v,w) \tag{23}$$

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

$$ILB(l, v).m = 2 \cdot \max_{\{w \in \mathcal{V}: l.u(v,w)>0\}} len^{max}_{paths}(v, w, l), \text{ and} \tag{24}$$

$$ELB(l, w).m = 2 \cdot \max_{\{v \in \mathcal{V}: l.u(v,w)>0\}} len^{max}_{paths}(v, w, l). \tag{25}$$

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

$$ILB(l, v).a = \sum_{w \in \mathcal{V}} g(v, w).a \cdot l.u(v, w), \text{ and} \tag{26}$$

$$ELB(l, w).a = \sum_{v \in \mathcal{V}} g(v, w).a \cdot l.u(v, w). \tag{27}$$

Due to Equation (5) and Equation (6), the side conditions

$$\forall v \in \mathcal{V}: \sum_{w \in \mathcal{V}} g(v, w).c \cdot l.u(v, w) \leq ILB(l, v).c, \text{ and} \tag{28}$$

$$\forall w \in \mathcal{V}: \sum_{v \in \mathcal{V}} g(v, w).c \cdot l.u(v, w) \leq ELB(l, w).c \tag{29}$$

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

$$l.c \geq \min\left(\sum_{v \in \mathcal{V}} ILB(l, v).c, \sum_{w \in \mathcal{V}} ELB(l, w).c\right). \tag{30}$$

In case of the mere ILB NAC, we have instead

$$ILB(l, v).m = \max_{\{w \in \mathcal{V}: l.u(v,w)>0\}} len^{max}_{paths}(v, w, l), \text{ and} \tag{31}$$

$$l.c \geq \sum_{v \in \mathcal{V}} ILB(l, v).c \tag{32}$$

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 can neglect the fact that requests with a larger rate have a higher blocking probability due to the construction in Equation (7).

$$\mathcal{N}.c = \sum_{l \in \mathcal{E}} l.c \tag{33}$$

$$\mathcal{N}.c_{trans} = (1 - p_{b2b}) \cdot E[C] \cdot \sum_{\{(v,w):v,w \in \mathcal{V}, v \neq w\}} g(v,w).a \cdot g(v,w).avgPathLen \tag{34}$$

$$\mathcal{N}.\rho = \frac{\mathcal{N}.c_{trans}}{\mathcal{N}.c}. \tag{35}$$

The overall resource utilization $\mathcal{N}.\rho$ is the fraction of the transmitted traffi c 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 Performance Comparison of NAC Approaches

In this section, we compare the performance of the presented basic NAC approaches. First, we illustrate the capacity requirements and the resource utilization on a single link. Then we compare the performance of the NAC methods depending on the offered load and test its sensitivity to the traffi c matrix and the routing.

4.1 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 [2] we have shown that the b2b blocking probability has a minor impact on the required capacity and the resource utilization compared to the influence of the offered load. We set it in all our studies to $p_{b2b} = 10^{-3}$.

Figure 5 shows that both 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. The fact that resources can be used more economically at large scale is called economy of scale.

4.2 Influence of the Offered Load

To study the impact of the offered load on the NAC performance, we take the test network depicted in Figure 6. Its topology is based on the UUNET in 1994 [25] where nodes connected by only one or two links were successively removed. Finally, the network has $|\mathcal{V}| = 20$ routers, $|\mathcal{E}| = 51$ bidirectional links, and an average path length of 2.15 hops.

The overall offered load in the network is $a_{tot} = \sum_{\{v,w \in \mathcal{V} | v \neq w\}} g(v,w).a$. We use the average b2b load $a_{b2b} = \frac{a_{tot}}{|\mathcal{V}| \cdot (|\mathcal{V}| - 1)}$ to scale the overall load a_{tot}. We construct the traffi c matrix

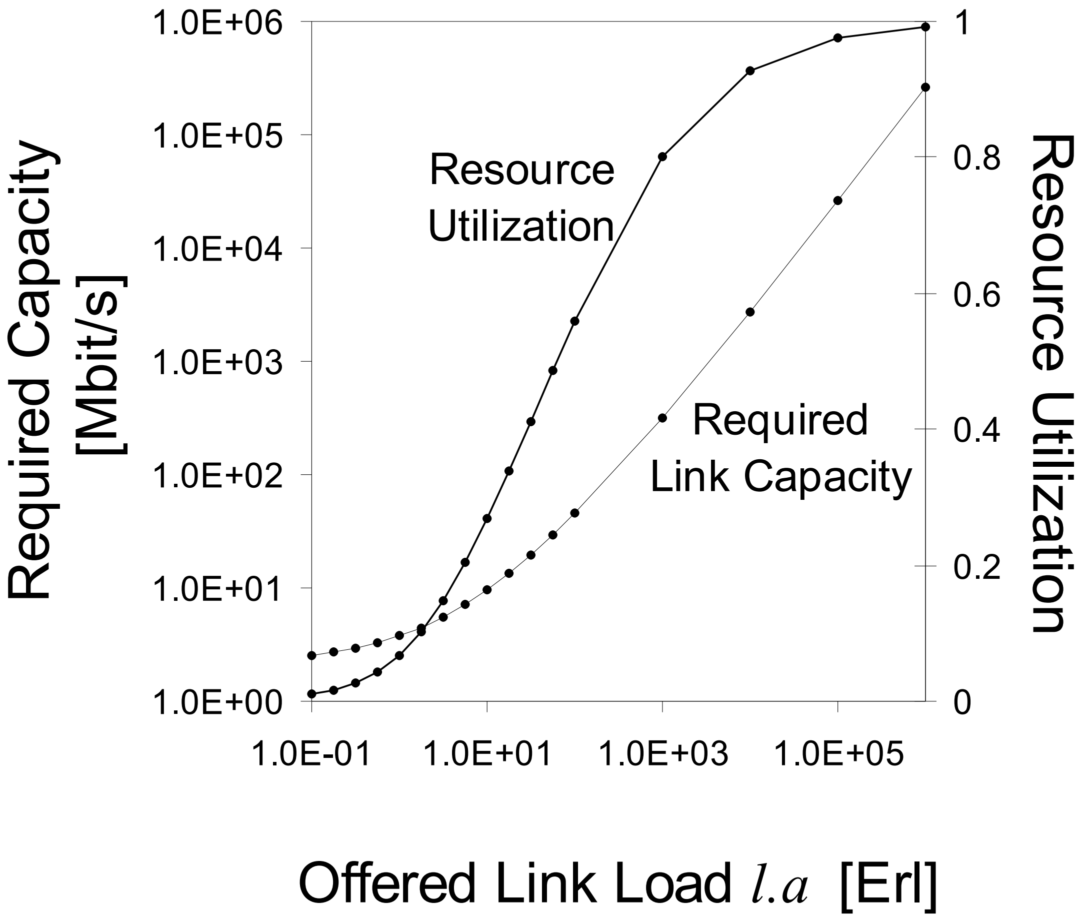

Figure 5: Impact of offered load on required link capacity and resource utilization on a single link.

in terms of offered load $g.a$ proportionally to the city sizes π which are given in Figure 7

$$g(v,w).a = \begin{cases} \frac{a_{tot} \cdot \pi(v) \cdot \pi(w)}{\sum_{x,y \in \mathcal{V}, x \neq y} \pi(x) \cdot \pi(y)} & \text{for } v \neq w, \\ 0 & \text{for } v = w. \end{cases} \quad (36)$$

Figure 8 shows the resource utilization depending on the offered b2b load a_{b2b} for all NAC methods. The LB NAC uses the network resources most effi ciently. A budget $LB(l)$ controls a maximum possible amount of traffi c on link l and takes most advantage from economy of scale. The ILB/ELB, ILB, and BBB NAC are less effi cient because the same offered load $g(v,w).a \cdot l.u(v,w)$ is partitioned among up to $|\mathcal{V}|$ budgets in case of ILB NAC or $|\mathcal{V}| \cdot (|\mathcal{V}| - 1)$ different budgets in case of BBB NAC. This yields a worse utilization of the budget capacities due to reduced economy of scale and leads to more required bandwidth. However, for suffi ciently high offered load, the utilization of all these NAC methods tends towards 100%. The ILB/ELB NAC is a new concept and it is not yet implemented in any standardized protocol or system. It does not induce any information states in the network but achieves 16 percent

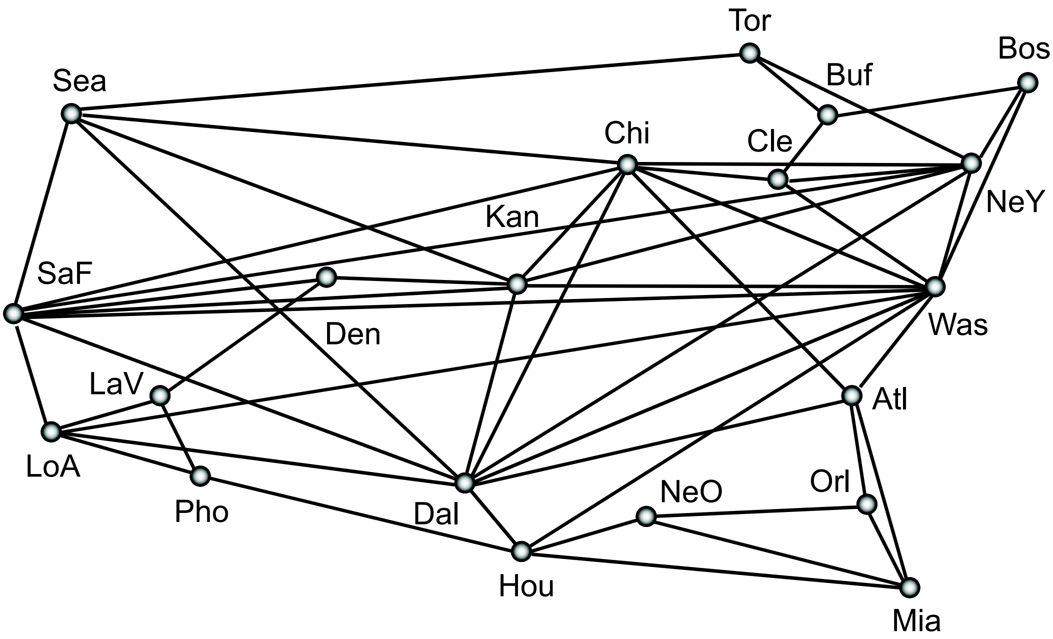

Figure 6: Topology of the test network.

points more resource utilization than the BBB NAC for a load of $a_{b2b} = 100$ Erlang. Therefore, it is a good approximation of the stateful LB NAC in our test network.

Some NACs are not able to exclude unlikely traffi c patterns which force to allocate high link capacities to an extent that reduces the achievable resource utilization to 30% for the IB/EB NAC and to 10% for the IB NAC. Hence, the IB NAC has the worst performance and our IB/EB NAC achieves a three times larger resource utilization by applying the limitation of the traffi c volume in a symmetric way.

We have shown that the presented results depend on the network topology [26] but also that the trend remains the same under changed topological conditions.

4.3 Influence of the Traffic Matrix

We study the impact of a skewed traffi c matrix in our test network. We achieve that by modifying the city population π by an exponential extrapolation

$$\pi(v,t) \;=\; |\mathcal{V}| \cdot \overline{\pi} \cdot \frac{\exp(\delta(v) \cdot t)}{\sum_{w \in \mathcal{V}} \exp(\delta(w) \cdot t)}, \tag{37}$$

where $\overline{\pi}$ is the mean population of all border router areas. The value $\delta(v)$ is determined by $\pi(v,1) = \pi(v)$, i.e. $\delta(v) = \ln(\frac{\pi(v)}{\overline{\pi}})$. According to that construction, the traffi c matrix for the original population π and $\pi(t=1)$ are the same. If a city is larger than the average city size $\overline{\pi}$, it is scaled up for a positive value of t and it is scaled down by a negative value of t. The coeffi cient of variation of the city sizes $c_{var}[city\ sizes]$ given in Table 1 characterizes the variation of the city sizes due to extrapolation.

Name(v)	(v) [10³]	Name(v)	(v) [10³]
Atlanta	4112	Los Angeles	9519
Boston	3407	Miami	2253
Buffalo	1170	New Orleans	1338
Chicago	8273	New York	9314
Cleveland	2250	Orlando	1645
Dallas	3519	Phoenix	3252
Denver	2109	San Francisco	1731
Houston	4177	Seattle	2414
Kansas	1776	Toronto	4680
Las Vegas	1536	Washington	4923

Figure 7: Population of the cities and their surroundings.

Table 1: Properties of extrapolated city sizes.

t	-3	-2	-1	0	1	2	3
$c_{var}[city\ sizes]$	7.88	2.62	0.78	0	0.69	2.02	5.29
avg. path length	2.91	2.68	2.43	2.15	1.91	1.77	1.72

We observe that the average of the path lengths weighted by the transported traffic volume decreases with increasing values of t. To understand the effect of the t-extrapolation on the average path length, we consider the two largest cities Los Angeles and New York. For $t = 0$ all cities have the same size $\pi(v, 0)$ and all $g(v, w).a$ are the same, i.e. the overall offered load a_{tot} is well distributed over the entire network. For increasing t, the city sizes for LA and NY go up and increase the offered load between them by Equation (36). For extremely large t this traffic volume is the major traffic in the network and its path length dominates the average. Networks are usually designed that cities with large traffic volumes are closely connected among each other (e.g. Chicago) to keep the average path length short. This causes that this explanation takes already effect for small t. For negative values of t, we get the contrary phenomenon because the small cities (with respect to π) produce then most traffic. They have longer average path lengths which impacts the overall average path length weighted by the traffic volume.

Figure 9 shows the required network capacity depending on the traffic matrix extrapolation parameter t for $a_{b2b} = 10$. The increased average path length weighted by the traffic volume has a significant impact on the required capacity. However, this behavior is only clearly visible

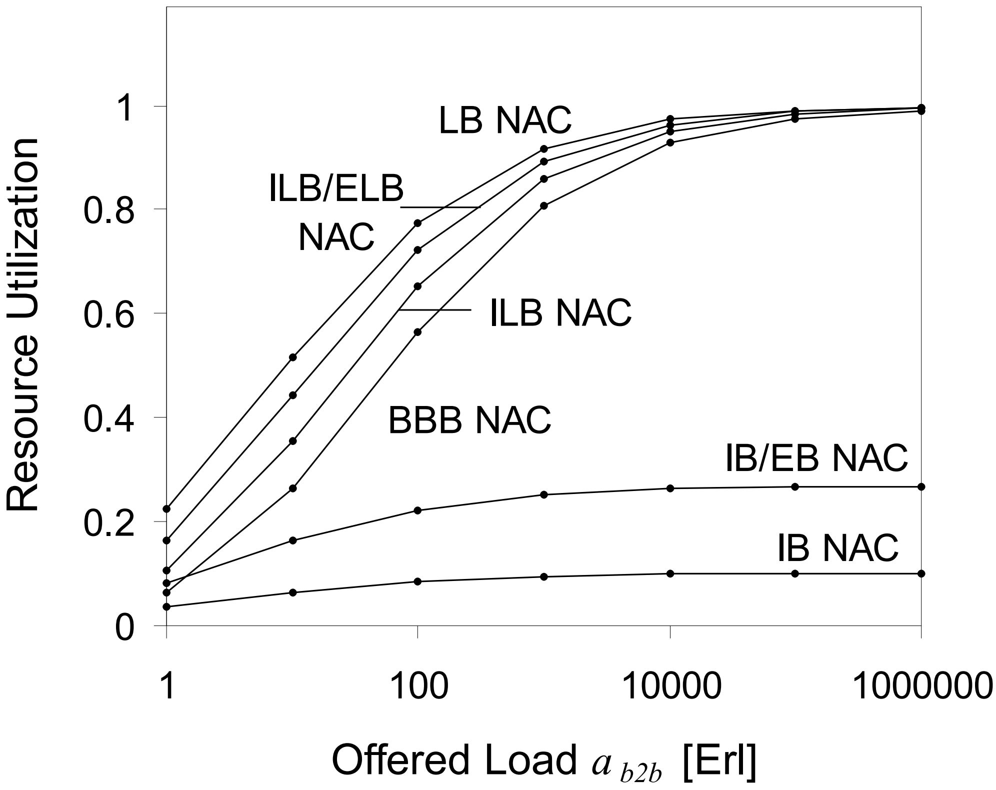

Figure 8: Impact of offered load on the resource utilization.

for the LB NAC. The other NAC methods need more bandwidth for homogeneous traffic matrices. For $|t| > 0$, the city sizes become more variable, and so does the offered load of the traffic aggregates between them. Since most of the traffic is shifted by the extrapolation into larger traffic aggregates, this yields on average larger budgets for all NAC methods, which can be dimensioned more efficiently. This leads to less required capacity for large absolute values of $|t|$. Figure 10 underpins this reasoning by showing a larger resource utilization for larger absolute values of t.

The IB NAC is an exception. The budget size $IB(v).c$ must be allocated on all links of a routing tree in case of SP routing, i.e. exactly $(|\mathcal{V}|-1)$ times. For MP routing this is similar. So, $\mathcal{N}.c$ depends only on $\sum_{v\in\mathcal{V}} IB(v).c$ and not on the average path length. Since $\mathcal{N}.c_{trans}$ takes the average path length into account (cf. Equation (34)), the average resource utilization decreases when the average path length is increased by t according to Equation (35). We try to blind out the influence of the economy of scale to a certain extent by increasing the offered load in the network to $a_{b2b} = 1000$. As expected in accordance with the above given arguments, Figure 11 shows that the required capacity for the IB NAC is independent of t and that the required capacity for the LB, ILB, ILB/ELB, and BBB NAC follow the trend of the

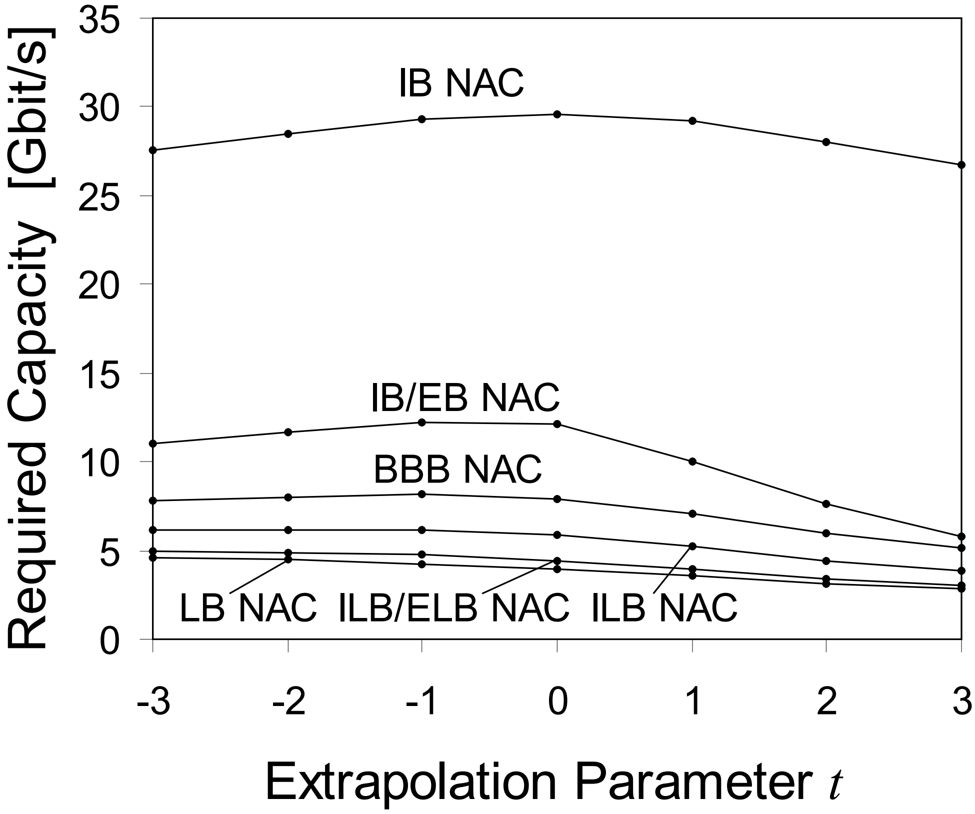

Figure 9: Impact of the city size variation on the required capacity ($a_{b2b} = 10$).

average path length.

The IB/EB NAC is an exception and the explanation for its behavior gives insight into its increase of efficiency compared with the IB NAC. We take $a \cdot E[C]$ instead of a dimensioned capacity c in our rough calculations. For the IB NAC, we get a required overall capacity of $\mathcal{N}.c = \sum_{v \in \mathcal{V}} IB(v).a \cdot (|\mathcal{V}| - 1) \cdot E[C] = a_{tot} \cdot (|\mathcal{V}| - 1) \cdot E[C]$. For the IB/EB NAC there is an upper bound on the required capacity $\mathcal{N}.c \leq \sum_{v,w \in \mathcal{V}} \min(IB(v).c, EB(w).c) \cdot E[C]$, which is also about $a_{tot} \cdot (|\mathcal{V}| - 1) \cdot E[C]$ for $t = 0$. As we get the same result for the IB NAC, we conclude that the difference in the required capacity between IB NAC and IB/EB NAC comes from the use of the Simplex algorithm in the dimensioning method. The application of both IBs and EBs avoids multiple capacity allocation on a single link for traffic with the same destination. The efficiency of that mechanisms depends on the network topology [27]. But there is another reason for the decrease of the required capacity for heterogeneous traffic matrices. We denote the average offered load per node by $a_{|\mathcal{V}|} = \frac{a_{tot}}{|\mathcal{V}|}$ and assume that $\frac{|\mathcal{V}|}{3}$ nodes have an offered load of $2 \cdot a_{|\mathcal{V}|}$ and that $\frac{2|\mathcal{V}|}{3}$ nodes have an offered load of $\frac{a_{|\mathcal{V}|}}{2}$. The restriction of the IBs and EBs leads to $\frac{|\mathcal{V}|}{3} \cdot (\frac{|\mathcal{V}|}{3} - 1)$ b2b aggregates that can send or receive at most $2 \cdot a_{|\mathcal{V}|}$

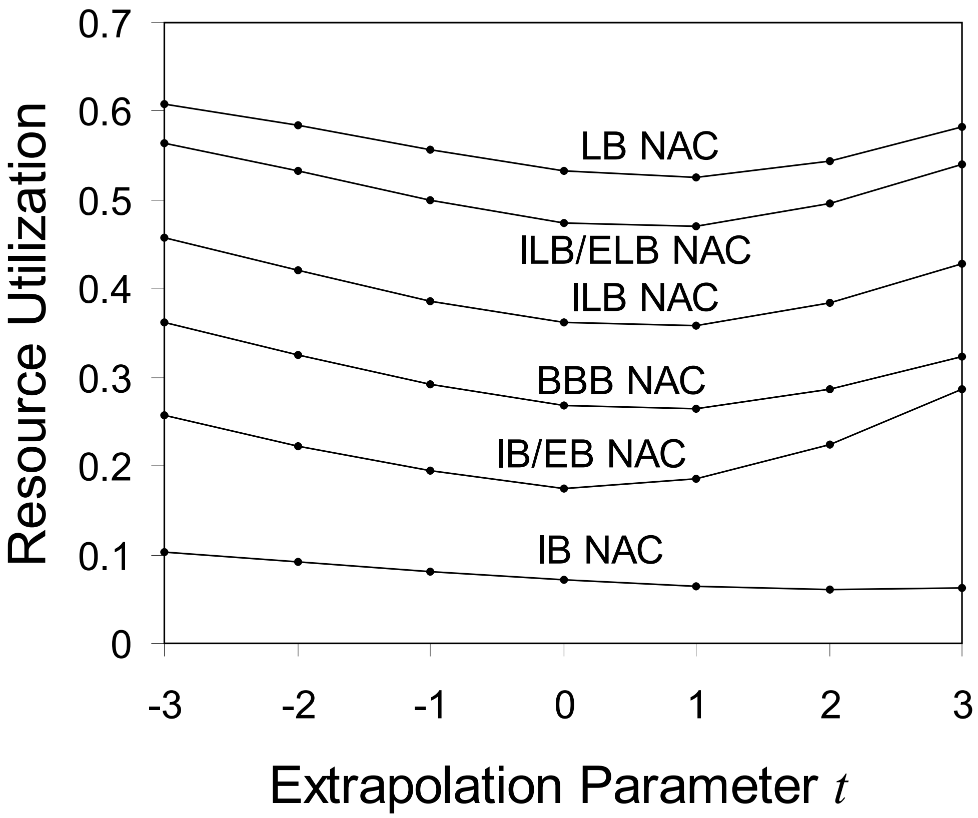

Figure 10: Impact of the city size variation on the resource utilization ($a_{b2b}=10$).

traffic and to $|\mathcal{V}| \cdot (|\mathcal{V}|-1) - \frac{|\mathcal{V}|}{3} \cdot (\frac{|\mathcal{V}|}{3} - 1)$ aggregates with an offered load of at most $\frac{a_{|\mathcal{V}|}}{2}$. This reduces the upper bound to $\frac{2}{3} \cdot a_{tot} \cdot (|\mathcal{V}|-1) \cdot E[C]$. This explains why the required capacity for the IB/EB NAC reduces for increasing absolute values of t. The effect is not symmetric in t according to Figure 11 because we observe it with a superposition of the fact that the average of the path lengths weighted by the traffic volume reduces with increasing t.

After all, the traffic matrix has only a minor impact on the NAC performance in realistic networking scenarios, i.e. for $a \geq 100$ and for $|t| \leq 1$. The effects are mainly due to the modified average of the path length weighted by the traffic volume. The IB/EB NAC is an exception from that rule and this consideration led to a deeper understanding of that mechanism. For future experiments we learn that the choice of the traffic matrix is not so crucial if the efficiency of a NAC method is evaluated.

4.4 Influence of the Routing

In the second part of this work we test the influence of the routing on the NAC performance. In the pursuit of robust and self-healing networks, multi-path (MP) routing is considered as

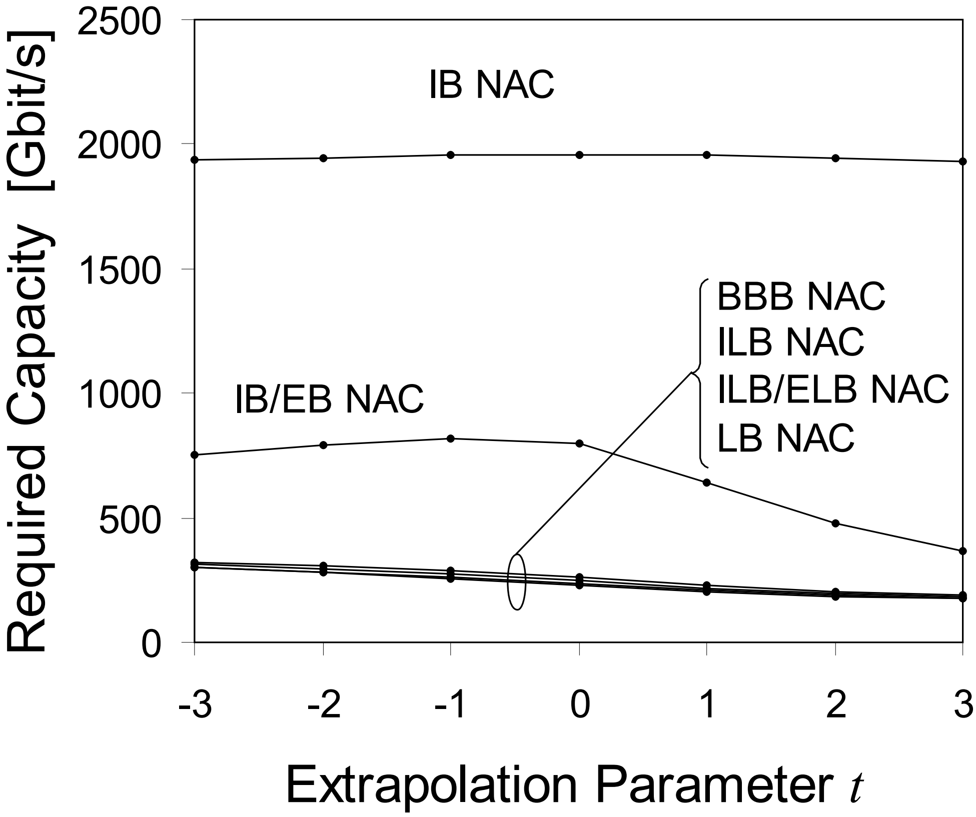

Figure 11: Impact of the city size variation on the required capacity ($a_{b2b} = 1000$).

an alternative to conventional single-path routing since if one path fails others may still be running. For our study we use OSPF [28]. It takes either a single shortest path for packet forwarding or – if the Equal Cost Multi-Path (ECMP) option is set – it distributes the traffic load uniformly over all outgoing interfaces leading to a path of shortest length. Although there may be solutions having un-equal cost MP and more MP than ECMP, we content ourselves with this simple representant of MP routing. In addition to our test network, we use the COST239 network which is depicted in Figure 12 [29]. With $|\mathcal{V}| = 11$ routers, $|\mathcal{E}| = 26$ bidirectional links, and an average path length of 1.43 hops it is smaller than the test network and it has multiple shortest paths for many source-destination pairs (v, w).

Figures 13–14 illustrate the performance of different NAC types in the test network and the COST239 network for SP and MP routing depending on the offered traffic. In both cases the performance of the IB NAC and the BBB NAC are identical. Theses budgets are dimensioned independently of the routing information $l.u(v, w)$ (cf. Equation (16) and Equation (21)). The resulting required budget capacity induces capacity demands on the links towards any possible destination (cf. Equation (20) and Equation (23)) whereby the capacity demand is distributed only along shortest paths. Therefore, this does not affect the overall required capacity of the

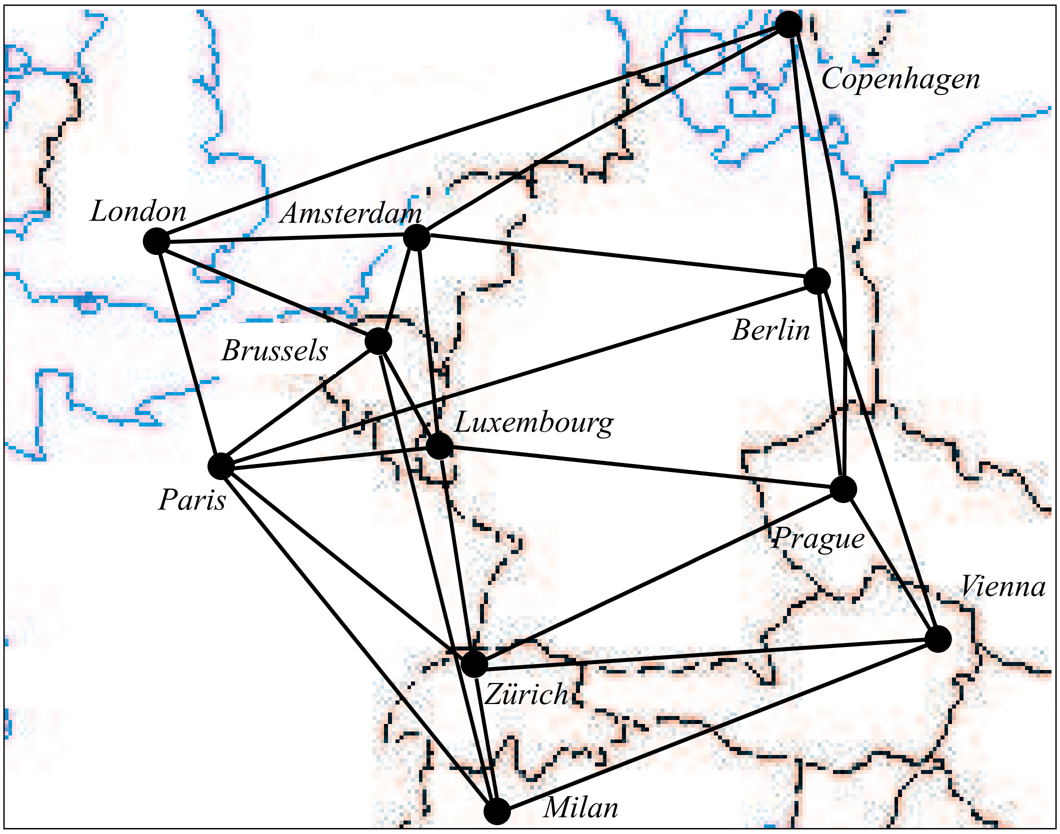

Figure 12: Topology of the COST239 network.

network. According to Equation (16), the capacity of the EBs is not influenced by the routing, either, but in both networks we observe for the IB/EB NAC a resource utilization increased by 3 percent points due to MP routing. The IB/EB NAC allows for a flexible use of the bandwidth by various flows that can not be active simultaneously due NAC limitations. By using MP routing, theses flows share the capacity of commonly used links instead of requiring their full rate on the links of their own single shortest path, which reduces the required bandwidth.

The performance of the LB NAC is hardly reduced with MP routing compared to SP routing. In the test network, the resource utilization of the ILB/ELB NAC suffers 4 percent points and the ILB NAC suffers 6 percent points at a load of $a_{b2b} = 100$. In the COST239 network, the performance of the ILB/ELB NAC degrades by 7 percent points down to the performance of the BBB NAC, i.e. the advantage of this approach – the increased utilization without reservation states – is lost. With MP routing the ILB NAC becomes even slightly worse than the BBB NAC. In all cases, the negative impact of MP routing on the performance decreases with increasing offered load.

Hence, the performance of all NAC methods based on link budgets is adversely affected by MP routing. These NAC approaches take the routing information $l.u(v, w)$ for the computation of the offered load of the budgets into account (cf. Equation (13), Equation (26), and Equation (27)). If MP routing leads to a more equal traffi c distribution, the LBs can not be

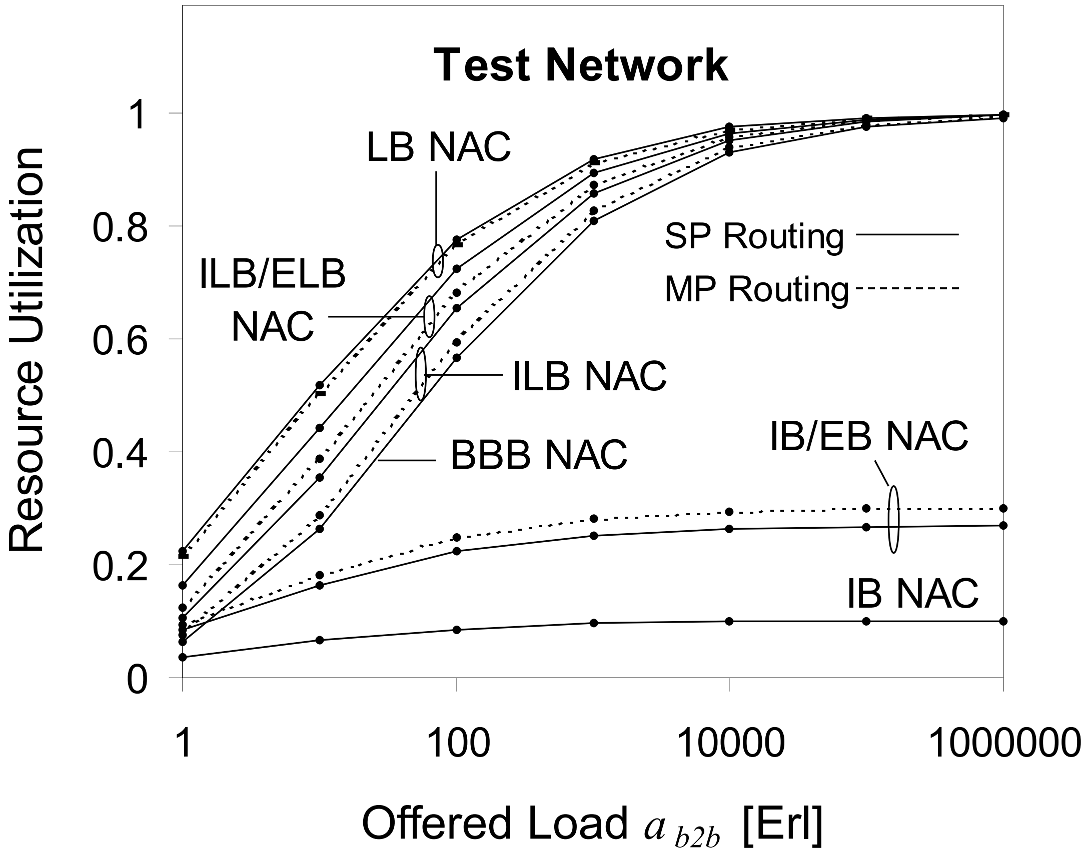

Figure 13: Impact of the routing on the resource utilization in the test network.

dimensioned as efficiently as with SP routing when the traffic concentrates on a few links. However, according to the results, this has hardly any impact for the LB NAC with MP routing. We consider the ILB and ILB/ELB NAC. The offered load induced by a single source or destination is spread out over significantly more links than with SP routing. This leads to a lower traffic concentration for $ILB(l, v).a$ and $ELB(l, w).a$ and yields a worse utilization of these budgets. In the COST239 network this effect is so strong that ECMP routing makes the ILB NAC less efficient than the BBB NAC.

The effects illustrated in this study show that the choice of SP or MP routing has some impact on the NAC performance. We used ECMP for our experiments but the effects will be more distinct when MP routing is enforced by taking more than just additional shortest paths if available. A future network architecture should avoid the combination of components that do not play well together if a high resource utilization is desired. Such a disadvantageous combination would be, e.g., local bandwidth brokers at the border routers – working essentially like the ILB NAC – and MP routing.

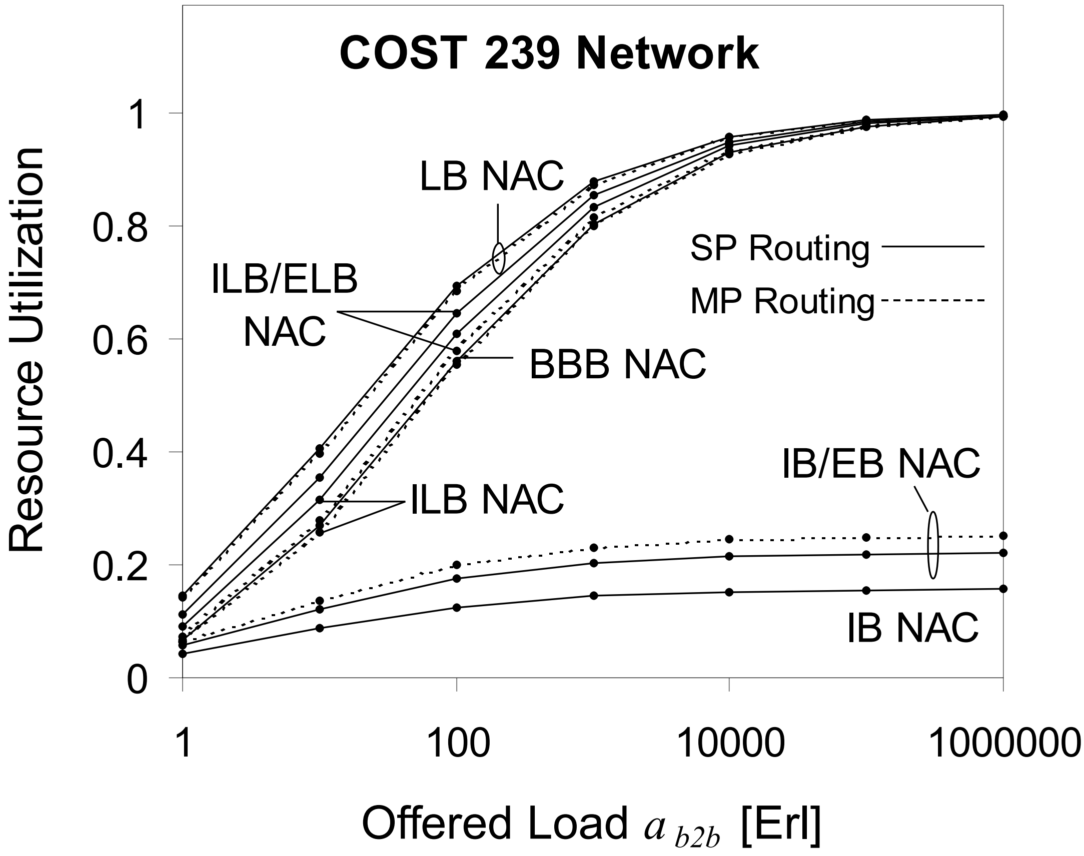

Figure 14: Impact of the routing on the resource utilization in the COST239 network.

5 Conclusion

We distinguished between *link* admission control (LAC) and *network* admission control (NAC). LAC limits the number of flows on a single link to assure their QoS requirements while NAC limits the number of flows in a network. We presented four basic NAC methods: the link budget (LB) based NAC, the border-to-border (b2b) budget (BBB) based NAC, which consists of virtual tunnels, the ingress and egress budget (IB/EB) based NAC, known from the Differentiated Services context, and the ingress and egress link budget (ILB/ELB) based NAC. The ILB/ELB NAC is a new concept and works like local bandwidth brokers at the border routers. Many research projects implement admission control (AC) schemes that can be classified by these categories.

For each NAC method, we dimensioned the capacity of sample networks to meet a desired blocking probability in presence of a given traffic matrix. The NAC types revealed a significantly different resource efficiency which is mainly due to their ability for taking advantage of economy of scale. The LB NAC exhibits the best resource utilization, followed by the ILB/ELB NAC, the ILB NAC, and the BBB NAC. They all achieve a resource utilization close to 100% if the offered traffic load is sufficiently high. The IB and IB/EB NAC are less economic with a resource efficiency in the order of 10 to 30%. In this study we concentrated on the impact of the traffic matrix and the routing on the resource efficiency of the NAC methods.

The variation in the traffic matrix influences the average of the path lengths weighted by the traffic volume, and the required capacity for most NAC approaches follows this trend. The required capacity of the IB NAC is independent of the traffic matrix – as long as it is constant – and the IB/EB NAC takes advantage of skewed traffic matrices to reduce the needed resources. The considerations also led to a deeper understanding of the NAC methods. In addition, we learned that the resource utilization results are rather robust against variations in the traffic matrix which simplifies future experiments.

The second part of the investigation showed the dependency of the NAC performance on the routing mechanism. The resource efficiency of the IB and the BBB NAC is independent of the routing and the resource efficiency of the IB/EB NAC profits from multi-path (MP) routing compared to single-path (SP) routing. The LB NAC suffers hardly from MP routing while the resource utilization of the ILB and ILB/ELB NAC is significantly reduced to such an extent that the ILB NAC looses its superiority to the BBB NAC.

Hence, the new ILB and ILB/ELB NAC methods are very appealing because they are stateless concepts with a clearly higher resource efficiency than the BBB NAC in case of SP routing but they should not be used in combination with MP routing.

Another challenge in future networks is the integration of resilience requirements in QoS real-time networks. To maintain the connectivity in case of local network outages, rerouting is used. With some modifications of our approach, we compute the required backup capacities to preserve QoS [30]. This leads to new optimization objectives since backup capacities are costly.

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