

Impact of Routing and Traffic Distribution on the Performance of Network Admission Control

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Abstract—In contrast to link admission control (LAC), which limits the traffic on a single link, network admission control (NAC) methods limit the traffic within a network. In this paper we present four basic budget based NAC approaches that have different complexity. They categorize most resource management schemes from a performance point of view regarding the maximum bandwidth utilization. Our results show that the option of single- or multi-path routing has a significant impact on the NAC performance while it is rather independent of the structure of the traffic matrix.

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

I. INTRODUCTION

In a connection oriented network layer, admission control (AC) is easily combined with connection state management at each network node. Thus, it is performed link by link like in ATM or in the Integrated Services framework. AC for a single link – we call it *link* admission control (LAC) – can be done by flow descriptor based resource reservation assisted by effective bandwidths or by measurement based AC (MBAC), and it is well understood from research in the ATM context in the nineties [1]. In contrast, a connectionless network layer like IP does not deal with connection or resource management at the network nodes. Correspondingly, a *network* admission control (NAC) approach is advisable that admits reservations only at dedicated locations, e.g. at the borders of a network, without contacting individual routers for admission decisions. We present four basically different budget based NAC approaches. Their implementation complexity can be shown by running code like it is practice in the IETF. In contrast, we investigate their resource efficiency, i.e. we show how much bandwidth can be utilized on average in a well dimensioned network. This performance measure depends on many network parameters. The analytical results of this work show the impact of the traffic matrix and the routing protocol on the required capacity and the resource utilization.

The paper is structured as follows. Section 2 gives an overview of four basic budget based NAC categories. Section 3 reviews our performance evaluation framework [2] and Section 4 compares the performance of the different NAC methods. Section 5 summarizes this work.

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II. NETWORK ADMISSION CONTROL (NAC) METHODS

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

A. 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.

Network admission control (NAC) needs to protect more than one link with admission decisions. 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, the solutions have different efficiency, i.e. they require different amounts of network capacity to meet the same border-to-border (b2b) flow blocking probability p_{b2b} which affects the network operator's costs.

NAC and LAC can be combined, i.e. a flow's required capacity $c(f)$ may consist of an effective bandwidth to take burstiness and/or some overbooking in the presence of large traffic aggregates into account. In this investigation, we only focus on the combinatoric NAC problem, i.e. we work on effective bandwidth budgets and blind out the issues of determining the effective bandwidth for individual reservations or potential MBAC based overbooking.

In general, an AC entity records the demand of the admitted flows $\mathcal{F}(b)$ in place related to a budget b . When a new flow arrives, it checks whether its effective bandwidth together with the demand of already established flows fits within the capacity budget. If so, the flow is accepted, otherwise it is rejected. This principle is used in link based admission control, controlling one link, as well as as in NAC, where a number of network resources are covered by each budget and at the same time the utilization of one resource is affected by a number of budgets.

B. Link Budget Based Network Admission Control (LB NAC)

The link-by-link NAC is probably the most intuitive NAC approach. The capacity $c(l)$ of each link l in the network is managed by a single link budget LB_l (with size $c(LB_l)$)

that may be administered, e.g., at the router sending over that link or in a centralized database. 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 $u_l(g_{v,w})$ indicates the percentage of the traffic rate $c(g_{v,w})$ using link l . It is able to reflect both single- and multi-path routing. A new flow $f_{v,w}^{new}$ with ingress router v , egress router w , and bitrate $c(f_{v,w}^{new})$ must pass the AC procedure for the LBs of all links that are traversed in the network by $f_{v,w}^{new}$ (cf. Figure 1). The NAC procedure will be successful if the following inequality holds

$$\forall l \in \mathcal{E} : u_l(g_{v,w}) > 0 : \\ c(f_{v,w}^{new}) \cdot u_l(g_{v,w}) + \sum_{f_{x,y} \in \mathcal{F}(LB_l)} c(f_{x,y}) \cdot u_l(g_{x,y}) \leq c(LB_l). \quad (1)$$

There are many systems and protocols working according to that principle. The connection AC in ATM [3] and the Integrated Services [4] architecture proposed for IP adopt it in pure form and induce per flow reservation states in the core. Other architectures reveal the same behavior although the mechanism is not implemented as an explicit LB NAC. A bandwidth broker [5], [6], [7] administers the budgets in a central database. The stateless core approaches [8], [9], [10] 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 three 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 traffic rerouting is required and the QoS is maintained if sufficient backup capacity is available.

C. 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 $f_{v,w}^{new}$ 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

$$c(f_{v,w}^{new}) + \sum_{f \in \mathcal{F}(IB_v)} c(f) \leq c(IB_v) \quad \text{and} \quad (2)$$

$$c(f_{v,w}^{new}) + \sum_{f \in \mathcal{F}(EB_w)} c(f) \leq c(EB_w) \quad (3)$$

Flows are admitted at the ingress irrespective of their egress router and at their egress router irrespective of their ingress routers, i.e. both AC decisions are decoupled. This entails that the capacity managed by an IB or EB can be used in a very flexible manner. However, the network must be able to carry all – also pathological – combinations of traffic patterns that are admissible by the IB s and EB s with the required QoS.

Hence, sufficient capacity must be allocated or the IB s and EB s must be set small enough.

If we leave the EB s aside, we get the simple IB NAC, so only the Equation (2) is checked for the AC procedure. This idea fits within the DiffServ context [11], [12] 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.

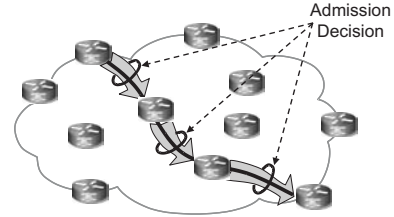


Fig. 1. LB NAC.

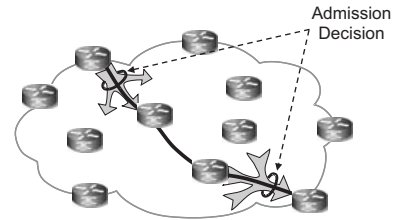


Fig. 2. IB/EB NAC.

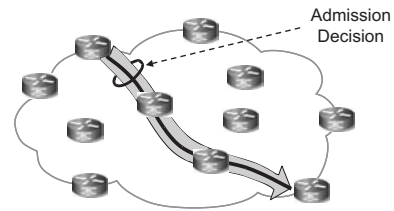


Fig. 3. BBB NAC.

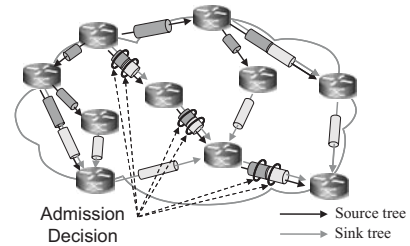


Fig. 4. ILB/ELB NAC.

D. 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 decision, i.e. a b2b budget $BBB_{v,w}$ manages the capacity of a virtual tunnel between v and w . This tunnel can consist of multiple b2b paths if multi-path routing is used. Figure 3 illustrates that a new flow $f_{v,w}^{new}$

passes only a single AC procedure for $BBB_{v,w}$. It is admitted if the following inequality holds

$$c(f_{v,w}^{new}) + \sum_{f \in \mathcal{F}(BBB_{v,w})} c(f) \leq c(BBB_{v,w}). \quad (4)$$

The BBB NAC can also avoid states inside the network because the $BBB_{v,w}$ may be controlled at the ingress or egress router. 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 [13], [14]. Tunnels may also be used hierarchically [15]. The tunnel capacity may be signaled using explicit reservation states in the network [16], [17], only in logical entities like bandwidth brokers [6], or it may be assigned by a central entity [18].

E. 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 $ELB_{l,w}$ 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 $\{l : ILB_{l,v} > 0\}$, that are administered in v , constitute a logical source tree and the links $\{l : ELB_{l,w} > 0\}$, that are administered in w , form a logical sink tree (cf. Figure 4) in case of single path routing. A new flow $f_{v,w}^{new}$ must pass the AC procedure for the $ILB_{l,v}$ and $ELB_{l,w}$ of all links l that are traversed in the network by $f_{v,w}^{new}$ (cf. Figure 4). The NAC procedure will be successful if the following inequalities are fulfilled

$$\forall l \in \mathcal{E} : u_l(g_{v,w}) > 0 : c(f_{v,w}^{new}) \cdot u_l(g_{v,w}) + \sum_{f_{v,y} \in \mathcal{F}(ILB_{l,v})} c(f_{v,y}) \cdot u_l(g_{v,y}) \leq c(ILB_{l,v}) \quad (5)$$

$$\forall l \in \mathcal{E} : u_l(g_{v,w}) > 0 : c(f_{v,w}^{new}) \cdot u_l(g_{v,w}) + \sum_{f_{x,w} \in \mathcal{F}(ELB_{l,w})} c(f_{x,w}) \cdot u_l(g_{x,w}) \leq c(ELB_{l,w}) \quad (6)$$

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 possibly 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's path length in hops. In contrast to the LB NAC, these budgets are controlled only at the border routers. 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 is new while the ILB NAC is similar to the hose model [19]. Both can be viewed as local bandwidth brokers at the border routers, disposing over a fraction of the network capacity. The path of the sessions in BGRP [20] matches also a sink tree but BGRP works like the LB NAC on its entities.

III. 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 $c(b)$ of a budget b must be dimensioned large enough. First, we consider budget dimensioning in general. Then, we explain how NAC specific budgets and link capacities are calculated. Finally, we define a performance measure for the comparison of NAC methods.

A. Capacity Dimensioning

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

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 Poisson arrivals of resource requests and a generally distributed holding time. Although typical Internet traffic has different characteristics on the packet level [21], the Poisson model is more realistic for the resource request level of end-user driven real-time applications. In addition, we are rather interested in a basic performance comparison of the NAC methods than in the capacity dimensioning for a specific network service with known traffic profiles. The offered load a is the mean number of active flows, if no flow blocking occurred. In a multi-service world, the request profile is multi-rate, so we take n_r different request types r_i , $0 \leq i < n_r$ with a bitrate $c(r_i)$. Given an offered load a , the respective request type specific offered load is $a(r_i) = p_a(r_i) \cdot a$. In our studies, we assume a simplified multimedia real-time communication scenario with $n_r = 3$, $c(r_0) = 64$ kbit/s, $c(r_1) = 256$ kbit/s, and $c(r_2) = 2048$ kbit/s, and a mean bitrate of $E[C] = \sum_{0 \leq i < n_r} c(r_i) \cdot p_a(r_i) = 256$ kbit/s. The recursive solution by Kaufman and Roberts [1] allows for the computation of request type specific blocking probabilities $p_b(r_i)$ if a certain capacity c is provided. We use Equation (7) to relate the blocking probability p_b to the traffic volume instead to the number of flows:

$$p_b = 1 - \left[\sum_{0 \leq i < n_r} (1 - p_b(r_i)) \cdot c(r_i) \cdot p_a(r_i) \right] / E[C]. \quad (7)$$

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

2) *From B2B Blocking Probabilities to Budget Blocking Probabilities:* Budget sizes are dimensioned for a desired budget blocking probability $p_b(b)$. The set \mathcal{B}_g consists of all 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

$$p_{b2b}(g) = 1 - \prod_{b \in \mathcal{B}_g} (1 - p_b(b)). \quad (8)$$

under the assumption that flow blocking at different budgets is independent. Since flow blocking at different budgets tends to be positively correlated, the computation of $p_{b2b}(g)$ according to Equation (8) is rather conservative.

In [2] we have proposed three different methods for setting the budget blocking probabilities $p_b(b)$ 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 $p_b(b)$ are equal for all budgets $b \in \mathcal{B}_g$. We denote by $m(b)$ the maximum number of budgets to be checked for any flow controlled by b . Then the required $p_b(b)$ is determined by

$$p_b(b) \leq 1 - \sqrt[m(b)]{1 - p_{b2b}} \quad (9)$$

B. Resource Allocation for Budget Based NAC Methods

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

For a possible traffic pattern $C_G \in \mathbb{R}_0^+^{|\mathcal{V}|^2}$ the following formulae hold

$$\forall v, w \in \mathcal{V} : c(g_{v,w}) \geq 0 \quad \text{and} \quad \forall v \in \mathcal{V} : c(g_{v,v}) = 0. \quad (10)$$

If NAC is applied in the network, each traffic pattern C_G satisfies the constraints defined by the NAC budgets. These constraints lead to linear equations, too, serving as side conditions for the calculation of the worst case scenario on each link $l \in \mathcal{E}$ by the following rate maximization:

$$c(l) \geq \max_{C_G \in \mathbb{R}_0^+^{|\mathcal{V}|^2}} \sum_{g \in \mathcal{G}} c(g) \cdot u_l(g). \quad (11)$$

This determines the minimum required capacity $c(l)$ of link l . Since the aggregate rates have real values, the maximization can be performed by the Simplex algorithm in polynomial time. However, for some NAC methods there are more efficient solutions that we will point out in the following.

1) *LB NAC*: The LB NAC requires that a transit flow needs to check a budget LB_l for every link l of its path for admission, hence, the maximum number of passed NAC budgets is

$$m(LB_l) = \max_{\{g \in \mathcal{G} : u_l(g) > 0\}} \text{len}_{path}^{max}(g, l) \quad (12)$$

whereby $\text{len}_{path}^{max}(g, l)$ is the maximum length of a path containing l used by g . As the budget LB_l covers all flows traversing link l , its expected offered load is

$$a(LB_l) = \sum_{g \in \mathcal{G}} a(g) \cdot u_l(g). \quad (13)$$

According to Equation (1)

$$\forall l \in \mathcal{E} : \sum_{g \in \mathcal{G}} c(g) \cdot u_l(g) \leq c(LB_l) \quad (14)$$

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

$$c(l) \geq c(LB_l). \quad (15)$$

2) *IB/EB NAC*: With the IB/EB NAC, a flow is admitted by checking both the ingress and the egress budget. Thus, we get $m(IB_v) = m(EB_w) = 2$. 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

$$a(IB_v) = \sum_{w \in \mathcal{V}} a(g_{v,w}) \quad \text{and} \quad a(EB_w) = \sum_{v \in \mathcal{V}} a(g_{v,w}). \quad (16)$$

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

$$\begin{aligned} \forall v \in \mathcal{V} : \sum_{w \in \mathcal{V}} c(g_{v,w}) &\leq c(IB_v) \quad \text{and} \\ \forall w \in \mathcal{V} : \sum_{v \in \mathcal{V}} c(g_{v,w}) &\leq c(EB_w). \end{aligned} \quad (17)$$

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

$$c(l) \geq \sum_{v \in \mathcal{V}} c(IB_v) \cdot \sum_{w \in \mathcal{V}} u_l(g_{v,w}) \quad (18)$$

3) *BBB NAC*: With the BBB NAC, only one budget is checked, therefore, $m(BBB_{v,w}) = 1$. 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

$$a(BBB_{v,w}) = a(g_{v,w}). \quad (19)$$

Since Equation (4) is checked for admission

$$\forall v, w \in \mathcal{V} : c(g_{v,w}) \leq c(BBB_{v,w}) \quad (20)$$

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

$$c(l) \geq \sum_{v,w \in \mathcal{V}} c(BBB_{v,w}) \cdot u_l(g_{v,w}) \quad (21)$$

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

$$\begin{aligned} m(ILB_{l,v}) &= 2 \cdot \max_{\{w \in \mathcal{V} : u_l(g_{v,w}) > 0\}} \text{len}_{path}^{max}(g_{v,w}, l) \quad \text{and} \\ m(ELB_{l,w}) &= 2 \cdot \max_{\{v \in \mathcal{V} : u_l(g_{v,w}) > 0\}} \text{len}_{path}^{max}(g_{v,w}, l). \end{aligned} \quad (22)$$

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

$$\begin{aligned} a(ILB_{l,v}) &= \sum_{w \in \mathcal{V}} a(g_{v,w}) \cdot u_l(g_{v,w}) \quad \text{and} \\ a(ELB_{l,w}) &= \sum_{v \in \mathcal{V}} a(g_{v,w}) \cdot u_l(g_{v,w}). \end{aligned} \quad (23)$$

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

$$\forall v \in \mathcal{V}: \sum_{w \in \mathcal{V}} c(g_{v,w}) \cdot u_l(g_{v,w}) \leq c(ILB_{l,v}) \text{ and} \quad (24)$$

$$\forall w \in \mathcal{V}: \sum_{v \in \mathcal{V}} c(g_{v,w}) \cdot u_l(g_{v,w}) \leq c(ELB_{l,w}) \quad (25)$$

must be respected constraining the minimum capacity by

$$c(l) \geq \min \left(\sum_{v \in \mathcal{V}} c(ILB_{l,v}), \sum_{w \in \mathcal{V}} c(ELB_{l,w}) \right). \quad (26)$$

In case of the mere ILB NAC this simplifies to

$$m(ILB_{l,v}) = \max_{\{w \in \mathcal{V}: u_l(g_{v,w}) > 0\}} len_{path}^{max}(g_{v,w}, l) \text{ and} \quad (27)$$

$$c(l) \geq \sum_{v \in \mathcal{V}} c(ILB_{l,v}) \quad (28)$$

C. Performance Measure for NAC Comparison

We compute the required link capacities for all NAC methods according to the equations above. The required network capacity $c(\mathcal{N})$ is the sum of all link capacities in the network. The overall transmitted traffic rate $\hat{c}(\mathcal{N})$ is the sum of the offered load of all b2b aggregates g weighted by their average path lengths $len_{path}^{avg}(g)$, 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).

$$c(\mathcal{N}) = \sum_{l \in \mathcal{E}} c(l) \quad (29)$$

$$\hat{c}(\mathcal{N}) = (1-p_{b2b}) \cdot E[C] \cdot \sum_{\{g \in \mathcal{G}\}} a(g) \cdot len_{path}^{avg}(g) \quad (30)$$

$$\rho(\mathcal{N}) = \frac{\hat{c}(\mathcal{N})}{c(\mathcal{N})}. \quad (31)$$

The overall resource utilization $\rho(\mathcal{N})$ 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.

IV. PERFORMANCE COMPARISON OF NAC APPROACHES

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

A. Economy of Scale Illustrated on a Single Link

Economy of scale or multiplexing gain is the key for understanding the performance of NAC methods and can be best illustrated on a single link. The traffic offered to that link has a load of $a(l)$ and it is subject to AC. We set the desired b2b blocking probability 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 $a(l)$. The resource utilization increases drastically up to an

offered load of $a(l) = 1000$ 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.

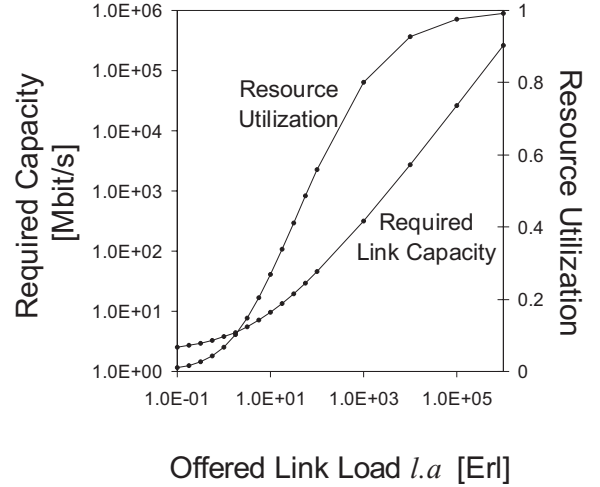


Fig. 5. Impact of offered load on required link capacity and resource utilization on a single link.

B. Influence of the Offered Load

To study the impact of the offered load on the NAC performance, we take the test network from [2] which 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 $a_{tot} = \sum_{g \in \mathcal{G}} a(g)$. 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 traffic matrix in terms of offered load $a(g)$ proportionally to the city sizes π which are also given in [2].

$$a(g_{v,w}) = \begin{cases} \frac{a_{tot} \cdot \pi(v) \cdot \pi(w)}{\sum_{x,y \in \mathcal{V}, x \neq y} \pi(x) \cdot \pi(y)} & \text{for } v \neq w, \\ 0 & \text{for } v = w. \end{cases} \quad (32)$$

The solid lines in Figure 6 show the resource utilization depending on the offered b2b load a_{b2b} for single-path routing and all NAC methods. The LB NAC uses the network resources most efficiently. A budget LB_l controls a maximum possible amount of traffic on link l and takes most advantage from economy of scale. The ILB/ELB, ILB, and BBB NAC are less efficient because the same offered load $\sum_{g \in \mathcal{G}} a(g) \cdot u_l(g_{v,w})$ 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 sufficiently high offered load, the utilization of all these NAC methods tends towards 100%. The ILB/ELB NAC achieves 16 percent points more resource utilization than the BBB NAC for a load of $a_{b2b} = 100$ Erlang. Some NAC methods are not able to exclude unlikely traffic 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 the IB/EB NAC achieves a three times larger resource utilization by applying the limitation of the traffic volume in a symmetric way.

In [22] we have shown that the presented results depend on the network topology but also that the relative performance of the NAC methods remains the same.

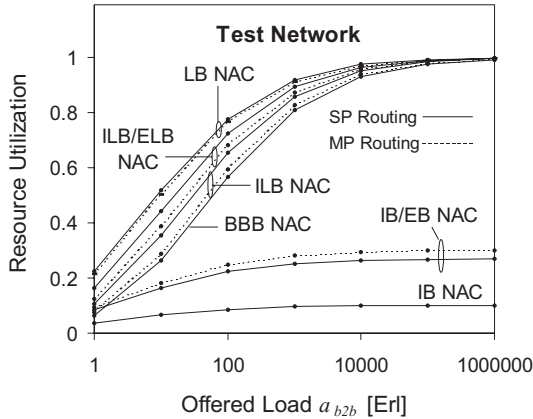


Fig. 6. Impact of the routing on the resource utilization in the test network.

C. Influence of the Routing

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 an alternative to conventional single-path routing. For our study we use OSPF [23]. 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.

The dashed lines in Figure 6 illustrate the performance of different NAC types in the test network for MP routing. The performance of the IB NAC and the BBB NAC is identical for SP and MP routing because their budgets are dimensioned independently of the routing information $u_l(g_{v,w})$ (cf. Equation (16) and Equation (19)). The resulting required budget capacity induces capacity demands on the links towards any possible destination (cf. Equation (18) and Equation (21)) whereby the capacity demand is distributed only along shortest paths. Therefore, ECMP does not affect the overall required capacity of the network for IB and BBB NAC.

According to Equation (16), the capacity of the EBs is not influenced by the routing, either. But the resource utilization is increased by 3 percent points for the IB/EB NAC due to MP routing. This is not due to multiplexing gain. The IB/EB NAC allows for a flexible use of the bandwidth by various flows but precludes some traffic patterns compared to IB NAC. As these flows share more links with MP than with SP routing, they induce lower capacity demands on each single link. This

reduces the required overall capacity as these link capacities can be commonly used by mutually exclusive flows.

The traffic concentrates on fewer links with SP routing than with MP routing. The LB NAC can take advantage of that traffic concentration and leads to a slightly better resource utilization for SP routing than for MP routing. In contrast, the resource utilization of the ILB/ELB NAC suffers 4 percent points and the ILB NAC suffers 6 percent points at a load of $a_{b2b} = 100$. With MP routing the offered load from a single source is spread out over significantly more links than with SP routing. This leads to a lower traffic concentration for $a(ILB_{l,v})$ and $a(ELB_{l,w})$ and yields a worse utilization of these budgets. This effect can be so strong that ECMP routing makes the ILB NAC less efficient than the BBB NAC.

D. Influence of the Traffic Matrix

In the second part of this work we study the impact of a skewed traffic matrix in our test network. We achieve that by modifying the city population π by an exponential extrapolation

$$\pi(v, t) = |\mathcal{V}| \cdot \bar{\pi} \cdot \frac{\exp(\delta(v) \cdot t)}{\sum_{w \in \mathcal{V}} \exp(\delta(w) \cdot t)}, \quad (33)$$

using the extrapolation parameter t where $\bar{\pi}$ is the mean population of all border router areas. The value $\delta(v)$ is determined by $\pi(v, 1) = \pi(v)$, i.e. $\delta(v) = \ln(\frac{\pi(v)}{\bar{\pi}})$. According to that construction, the traffic matrix $\pi(t=1)$ is the original population π . If a city size $\pi(v)$ is larger than the average city size $\bar{\pi}$, $\pi(v, t)$ is scaled up for a positive value of t and it is scaled down by a negative value of t . The coefficient of variation of the city sizes $c_{var}[city\ sizes]$ given in Table I characterizes the variation of the city sizes depending on the extrapolation parameter t . We observe that the average of the path lengths weighted by the transported traffic volume decreases with increasing values of t .

TABLE I
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 (weighted by load)	2.91	2.68	2.43	2.15	1.91	1.77	1.72

For $t = 0$ all cities have the same size $\pi(v, 0)$ and all $a(g_{v,w})$ are the same, i.e. the overall offered load a_{tot} is well distributed over the entire network. We consider the two largest cities (no matter which) in the traffic matrix. For increasing t , their extrapolated city sizes go up and Equation (32) increases the offered load between them. 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 such that cities with large traffic volumes are closely connected among each other to keep the average path length short. For increasingly positive values of t , most traffic flows result from communication among large cities (with respect to π) which decreases the average path length

weighted by the traffic volume. For negative values of t we get the contrary phenomenon because then most traffic is produced by the cities that are small and badly connected in reality.

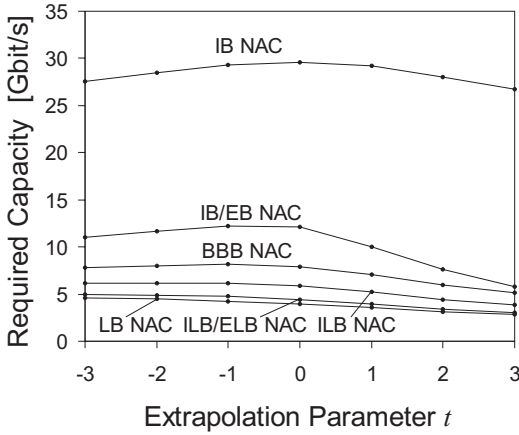


Fig. 7. Impact of the city size variation on the required capacity ($a_{b2b} = 10$).

Figure 7 shows the required network capacity depending on the 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 for the LB and ILB/ELB 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 that can be dimensioned more efficiently. This leads to less required capacity for large absolute values of $|t|$. Figure 8 underpins this reasoning by showing a larger resource utilization for larger absolute values of t .

The IB NAC is an exception. The budget size $c(IB_v)$ must be allocated on all links of a routing tree in case of single-path (SP) routing, i.e. exactly $(|\mathcal{V}| - 1)$ times. For multi-path (MP) routing this is similar. So, $c(\mathcal{N})$ depends only on $\sum_{v \in \mathcal{V}} c(IB_v)$ and not on the average path length. Since the overall transmitted traffic rate $\hat{c}(\mathcal{N})$ takes the average path length into account (cf. Equation (30)), the average resource utilization decreases when the average path length is increased by t according to Equation (31).

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 $a_{b2b} = 1000$. In accordance with the above given arguments, Figure 9 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 average path length. The IB/EB NAC behaves differently. The explanation gives insight into its functioning and gives reasons for its superiority over IB NAC.

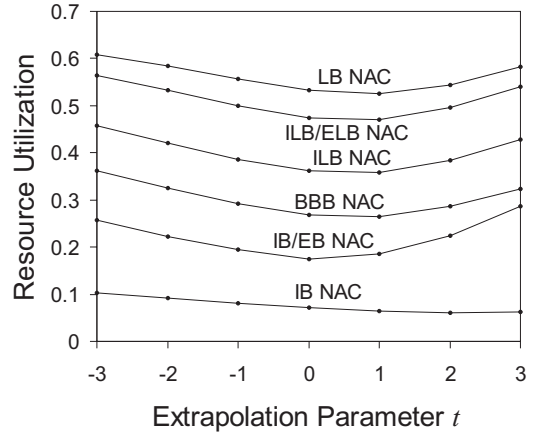


Fig. 8. Impact of the city size variation on the resource utilization ($a_{b2b} = 10$).

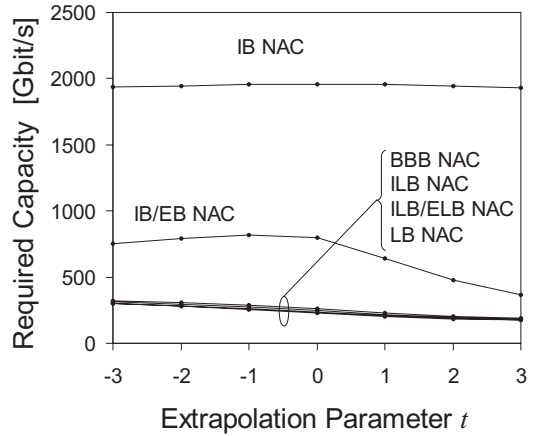


Fig. 9. Impact of the city size variation on the required capacity ($a_{b2b} = 1000$).

In the following calculations we neglect economy of scale and take $a \cdot E[C]$ as an approximation of a dimensioned capacity c . The overall network capacity for the IB NAC is $c(\mathcal{N}) = \sum_{v \in \mathcal{V}} a(IB_v) \cdot (|\mathcal{V}| - 1) \cdot E[C] = a_{tot} \cdot (|\mathcal{V}| - 1) \cdot E[C]$. For the IB/EB NAC we can calculate an upper bound $c(\mathcal{N}) \leq \sum_{v, w \in \mathcal{V}} \min(c(IB_v), c(EB_w)) \cdot E[C]$, which is also about $a_{tot} \cdot (|\mathcal{V}| - 1) \cdot E[C]$ for $t = 0$. There are two reasons for the increased efficiency of the IB/EB NAC. (1) The application of both IBs and EBs avoids multiple capacity allocation on a single link for traffic streams with the same sources or destinations, which are mutually exclusive due to the budget restrictions. This effect depends on the network topology and is further elaborated in [22]. (2) IB/EB NAC becomes more efficient for heterogeneous traffic matrices. We denote the average offered load per node by $a_{|\mathcal{V}|} = \frac{a_{tot}}{|\mathcal{V}|}$. We 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 $2 \cdot a|\mathcal{V}|$ 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 above upper bound to $\frac{2}{3} \cdot a_{tot} \cdot (|\mathcal{V}| - 1) \cdot E[C]$ and explains why the required capacity for the IB/EB NAC decreases for increasing absolute values of t . The effect is not symmetric in t according to Figure 9 as we observe it with a superposition of increasing path lengths for 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 $|t| \leq 1$. Hence, the choice of the traffic matrix is not so crucial if the efficiency of NAC methods is compared. 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.

V. CONCLUSION

We distinguished between *link* admission control (LAC) and *network* admission control (NAC) and presented four basic budget based NAC methods: LB NAC, IB/EB NAC, BBB NAC, and ILB/ELB NAC. They classify most of today's NAC implementations.

The bandwidth of a single link, which is required to meet a desired flow blocking probability for a specific offered traffic load, can be used more efficiently if the offered load is large. This fact is called economy of scale. We showed its impact on the resource efficiency of the NAC methods. Our results regarding routing alternatives showed that the resource efficiency of the IB and the BBB NAC is independent of the routing mechanism and that the resource efficiency of the IB/EB NAC profits from multi-path (MP) routing compared to single-path (SP) routing. Although the stateless-core ILB and ILB/ELB NAC are very attractive due to their high resource utilization with SP routing, they lose this advantage over the BBB NAC to a large extent in combination with MP routing.

The second part of this work we considered the influence of the structure of the traffic matrix on the NAC performance, i.e. we increased the variation in the traffic matrix while keeping the overall offered load constant. This influences the average of the path lengths weighted by the traffic volume, and the required capacity follows this trend for most NAC approaches. The required capacity of the IB NAC is independent of the structure of the traffic matrix and the IB/EB NAC takes advantage of skewed traffic matrices to reduce the needed resources. These considerations led to a deeper understanding of the NAC methods. In general, resource utilization results are rather robust against variations in the traffic matrix which simplifies future experiments.

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