

**Fair Assignment of Efficient Network
Admission Control Budgets**

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Report No. 306

February 2003

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Abstract

In this paper, we review several network admission control (NAC) methods. We explain how the NAC budgets and the required link capacities can be dimensioned based on a traffic matrix, a desired blocking probability, and the routing. The content of this work is the inversion of that process. Based on a traffic matrix, the routing, and given link capacities, the budgets are to be assigned such that their blocking probabilities are as low as possible. We present an algorithm for fair resource sharing and illustrate its effect on a single link. We extend this mechanism to entire networks, such that it is adaptable to all budget-based NAC approaches. The evaluation of our concept shows that it is most effective in real networking scenarios where heterogeneous traffic patterns occur.

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

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 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. 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

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

are transported over several hops through a network instead over a single link. In [28] we identify four different NAC methods that have fundamentally different performance in terms of resource utilization, and that categorize most of today’s implemented and investigated NAC approaches [2, 3]. NAC may be based on link budgets (LB), which is the conventional link-by-link NAC, on ingress and egress budgets (IB/EB), which has been discussed in the DiffServ context, and on b2b budgets (BBB), that correspond to virtual tunnels. We review these concepts, explain how budget and link capacities are assigned based on a traffic matrix, a desired b2b flow blocking probability, and the routing.

The goal of this work is the inversion of the dimensioning process. Based on a traffic matrix, the routing, and given link capacities, the budgets are to be assigned such that their blocking probabilities are as low as possible. We present an algorithm for fair resource sharing and illustrate its effect on a single link. This leads to a definition of unfairness regarding the assignment of budget capacities with respect to the flow blocking probabilities. We extend this mechanism to entire networks, such that it is adaptable to all budget-based NAC approaches. The evaluation of our concept shows that it is most effective in real networking scenarios where heterogeneous traffic patterns occur.

The paper is structured as follows. Section 2 gives an overview of several budget-based NAC categories and explain how budget and link capacities can be dimensioned. Section 3 proposes two methods for the assignment of the capacity of a single link to several budgets. Section 4 extends this method from a single link to an entire network. 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, we explain three basically different NAC concepts and show how the required budget and link capacities may be dimensioned.

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 level of aggregation 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 [4]. 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 [5, 6]. 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 [7]. It records the demand of the admitted flows $\mathcal{F}_{admitted}$ in place. When a new flow arrives, LAC checks whether its effective bandwidth to-

gether 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 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. This is a reasonable approach since the economy of scale is saturated for sufficiently large b2b aggregates [8], which will be the case in core networks.

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 v^2 , 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

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

There are many systems and protocols working according to that principle. The connection AC in ATM [9] and the Integrated Services [10, 11] architecture in IP technology adopt it in pure form. Other protocols reveal the same behavior although the mechanism is not implemented as an explicit LB NAC. Most bandwidth broker approaches [12, 13, 14] behave the same way and so do some stateless-core approaches [15, 16, 17]. A drawback of most of these 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

¹We lend 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.

²A 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 .

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.

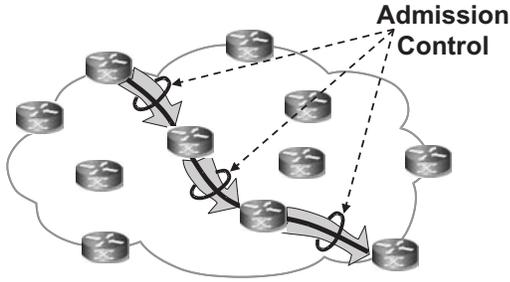


Figure 1: Network admission control based on link budgets.

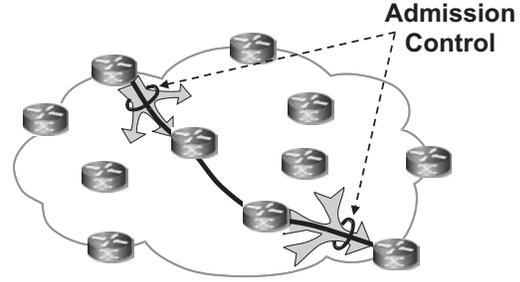


Figure 2: Network admission control based on ingress and egress budgets.

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

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

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

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 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 [18, 19] 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 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.

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

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

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 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, 22]. Tunnels may also be used hierarchically [23, 24]. The tunnel capacity may be signaled using explicit reservation states in the network [25, 26], only in logical entities like bandwidth brokers [13], or it may be assigned by a central entity [27].

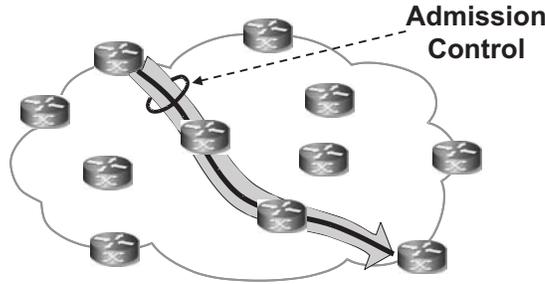


Figure 3: The BBB NAC corresponds to a logical tunnel.

2.5 Dimensioning of Budget and Link Capacities

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. We assume that no overbooking is desired, so each link must support the maximum admissible traffic.

2.5.1 Capacity Dimensioning for a Single Budget

Capacity dimensioning is a function calculating the required bandwidth for given traffic characteristics and 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 the Internet world it 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 [4] 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.

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

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.

2.5.2 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

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

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 [28] 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

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

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

2.6 Resource Allocation for Budget Based NAC Methods

For a possible traffic pattern³ $g.c \in \mathbb{R}_0^{+|\mathcal{V}|^2}$ the following formulae hold

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

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

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

for the worst case scenario in terms of rate maximization on a link l to determine its minimum capacity $l.c$

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

Since the aggregate rates have real values, the maximization can be performed by the Simplex algorithm [29] in polynomial time. However, for some NACs there are more efficient solutions that we will point out in the following.

2.6.1 LB NAC

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

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

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 $LB(l)$ is

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

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

$$l.c \geq LB(l).c. \quad (12)$$

2.6.2 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

$$IB(v).a = \sum_{w \in \mathcal{V}} g(v,w).a, \text{ and } EB(w).a = \sum_{v \in \mathcal{V}} g(v,w).a. \quad (13)$$

Here we use the Simplex method for the computation of the capacity $l.c$ with the side conditions

$$\forall v \in \mathcal{V} : \sum_{w \in \mathcal{V}} g(v,w).c \leq IB(v).c, \text{ and } \forall w \in \mathcal{V} : \sum_{v \in \mathcal{V}} g(v,w).c \leq EB(w).c. \quad (14)$$

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 $l.c$:

$$l.c \geq \sum_{v \in \mathcal{V}} IB(v).c \cdot \sum_{w \in \mathcal{V}} l.u(v,w) \quad (15)$$

2.6.3 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

$$BBB(v, w).a = g(v, w).a. \quad (16)$$

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

$$l.c \geq \sum_{v, w \in \mathcal{V}} BBB(v, w).c \cdot l.u(v, w) \quad (17)$$

3 Fair Assignment of a Single Resource to AC Budgets

In the last section, we have explained how suitable budget capacities are computed to achieve a desired b2b flow blocking probability and how the required link capacities are derived based on these budgets. However, the practical problem is vice versa. The bandwidth is given and budgets are determined such that the link capacity is not unintentionally overbooked.

3.1 Assignment Alternatives

We illustrate two different methods for the assignment of the network bandwidth to the NAC budgets. The first method is a naive approach just taking the expected offered load $g(v, w).a$ into account. The second approach is exact in the sense that the blocking probabilities of all flows are minimized, i.e. this approach takes the budget dimensioning step from the last section into account.

3.1.1 Naive Resource Assignment

A naive approach (NAIVELINKSTRATEGY) takes only the expected offered load $b.a$, $b \in \mathcal{B}$, for the assignment of budget capacities $b.c$ into account. If several budgets $b \in \mathcal{B}$ compete without any other constraints for the same resource $l.c$, that resource is partitioned among them such that the size of each budget is $b.c = b.a \cdot \frac{l.c}{l.a} = b.a \cdot b.\xi$ with $l.a = \sum_{b \in \mathcal{B}} b.a$. This is simple to compute since the budgets $b \in \mathcal{B}$ have the same relative size $b.\xi$ regardless of the associated offered load $b.a$. However, for a constant flow blocking probability $b.p$ the budget size $b.c$ is a non-linear function of the offered load $b.a$ since the ratio $\frac{b.c}{b.a}$ decreases for increasing $b.a$. This entails that the naive approach leads to different flow blocking probabilities if the $b.a$ are not equal and, therefore, this method is simple but not fair.

3.1.2 Fair Resource Assignment

Fair resource assignment (FAIRLINKSTRATEGY) takes primarily the resulting flow blocking probabilities into account. If several budgets $b \in \mathcal{B}$ compete for the same resource $l.c$, that resource is partitioned among them such that the resulting $b.p$ are equal.

We have implemented an efficient and numerically stable algorithm for the capacity dimensioning based on the recursive Kaufman-Roberts formula [4]. It computes $b.p$ for budget capacities $b.c$ that are integral multiple of bandwidth units and stops if a desired threshold is achieved ($b.p \leq p$). We take advantage of that fact in Algorithm 1 (FAIRLINKSTRATEGY). M resource units are incrementally partitioned among competing budgets $b \in \mathcal{B}$ by assigning one or more bandwidth units to the budget with the currently largest $b.p$ as long as $\sum_{b \in \mathcal{B}} b.c \leq M$ holds. If two budgets have the same $b.p$, the capacity of the budget with the larger offered load $b.a$ is incremented next.

Input: number of resource units M , competing budgets \mathcal{B}

```

while  $\sum_{b \in \mathcal{B}} b.c \leq M$  do
  choose  $b | b.p = \max_{b^* \in \mathcal{B}(l)} b^*.p$ 
   $b.c := b.c + 1$ 
   $M := M - 1$ 
end while

```

Output: $\{b.c | b \in \mathcal{B}\}$

Algorithm 1: Fair assignment of M resource units (FAIRLINKSTRATEGY).

3.2 Importance of Fair Resource Assignment

We illustrate the importance of the fair assignment of a single resource using a single link l and two competing budgets b_0 and b_1 .

3.2.1 Impact of Load Distribution

We consider this system with a link load $l.a = 100$ and study it depending on the load fraction $b_0.lf = \frac{b_0.a}{l.a}$ of b_0 . We dimension the budget capacities $b_i.c$ both for a desired blocking probability $p = 10^{-3}$ and set the link capacity to $l.c = b_0.c + b_1.c$. Figure 4 shows the budget sizes $b_i.c$ and the required link capacity $l.c$ for different load fractions of b_0 . The least capacity is required for $b_0.lf = 0$ or $b_0.lf = 1$ because then, b_1 or b_0 can be dimensioned most efficiently due to economy of scale. The increase of the required bandwidth per aggregate is especially large for small or large load fractions of b_0 because the small capacities $b_0.c$ or $b_1.c$ can not be used efficiently.

If we assign now the link capacity to the budgets $b_0.c$ and $b_1.c$ according to the fair assignment method, the flow blocking probabilities are due to the construction of this experiment exactly $b_i.p = 10^{-3}$. When we use the naive assignment method instead, we get $b_i.c = b_i.a \cdot \frac{l.c}{l.a} = b_i.a \cdot \xi$. The resulting flow blocking probabilities $b_i.p$ are illustrated in Figure 5. If the load fraction of a budget is smaller than 0.5, then its naively assigned capacity is smaller compared with the fair method, otherwise, it is larger. As a consequence, its blocking probability $b.p$ is significantly increased or slightly decreased. If the load fraction of b_0 is about $b_0.lf = 0.2$, the respective blocking probability is $b_0.p = 0.1$ while the blocking probability of b_1 is reduced to $b_1.p = 0.0001$. Hence, the naive resource assignment is clearly unfair.

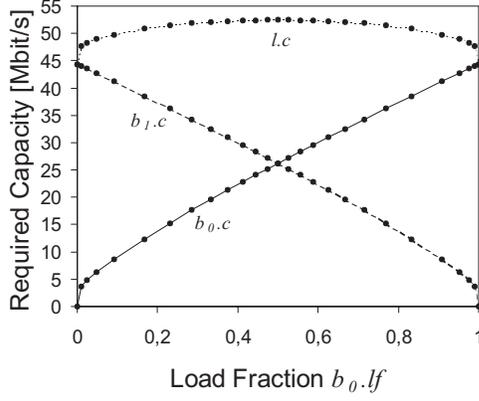


Figure 4: The impact of the load fraction on the required budget and link capacities.

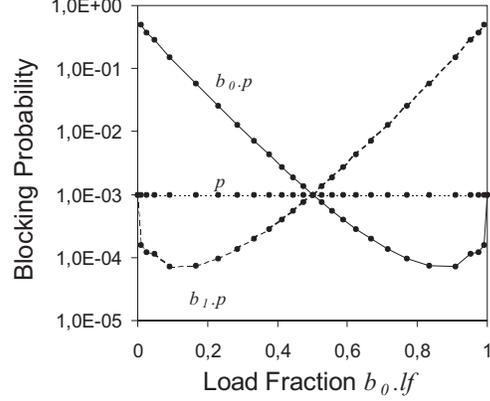


Figure 5: The impact of the load fraction on the blocking probability with naive resource assignment.

3.2.2 Impact of Offered Link Load

We conduct the same experiment for a fixed load fraction $b_0.lf = 0.1$ and a desired blocking probability $p = 10^{-3}$ depending on the offered link load. Figure 6 shows that for a very low load $l.a$, both b_0 and b_1 require the same capacity of about 2 Mbit/s. For large values of $l.a$, the required capacities for both budgets seem to rise about linearly with the offered link load. Figure 7 reveals that the blocking probability $b_0.p$ is about 10% even for large offered link load and the blocking probability $b_1.p$ does not exceed 10^{-4} . Hence, there is an unfairness of the simple assignment method for most load distributions and for all link loads.

3.2.3 Definition of the Unfairness

In our experiments we have already used the notion of unfairness for which we define a performance measure now. There is a positive (D^+) and a negative difference (D^-) to the fair assignment of resources regarding the logarithmic flow blocking probabilities in both cases

$$D^- = \sum_{b \in \mathcal{B}} \max(\log(b.p^{naive}) - \log(b.p^{fair}), 0) \quad (18)$$

$$D^+ = \sum_{b \in \mathcal{B}} \max(-(\log(b.p^{naive}) - \log(b.p^{fair})), 0). \quad (19)$$

However, we use only D^- as the general performance measure for unfairness. In the above experiments, it is the upward deviation of the blocking probability curve from the 10^{-3} line (cf. Figure 5 and Figure 7). This definition can be extended from a single link to an entire network just by adding the respective values of all links.

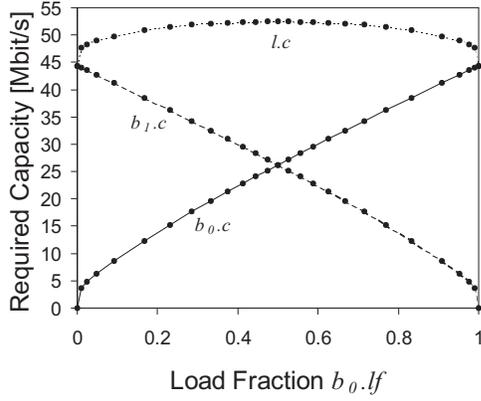


Figure 6: The impact of the offered link load on the required budget and link capacities.

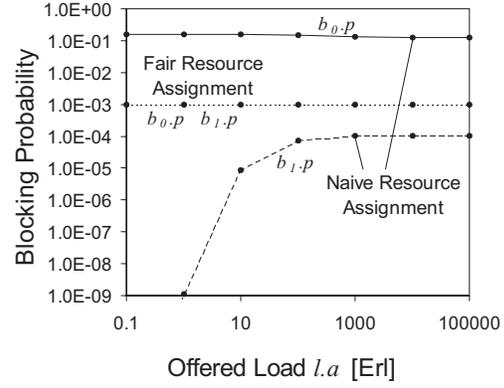


Figure 7: The impact of the offered link load on the blocking probabilities.

4 Assignment of Efficient NAC Budgets

In this section, we consider the dimensioning of NAC budgets that manage the capacity of many resources instead of a single one and respect the constraints arising from the different budget types. Link budgets $LB(l)$ pertain only to a single link l . For those budgets, resources of network links can be assigned link-by-link to the corresponding NAC budgets according to the algorithm in the previous section. IBs, EBs, and BBBs are not link-specific and they impose side constraints on all links $\mathcal{L}(b)$ for which they can allow traffic

$$\mathcal{L}(b) = \begin{cases} \{l|l \in \mathcal{E} \wedge \sum_{w \in \mathcal{V}} b.a \cdot l.usage(v, w) > 0\} & \text{if } b = IB(v) \\ \{l|l \in \mathcal{E} \wedge \sum_{v \in \mathcal{V}} b.a \cdot l.usage(v, w) > 0\} & \text{if } b = EB(w) \\ \{l|l \in \mathcal{E} \wedge b.a \cdot l.usage(v, w) > 0\} & \text{if } b = BBB(v, w) \end{cases} \quad (20)$$

We propose a naive and an efficient algorithm for the dimensioning of these types of NAC budgets and illustrate the fairness aspect in entire networks. Both algorithms assign the budget sizes indirectly by setting the relative budget size $b.\xi$ or the respective b2b flow blocking probability $b.p_{b2b}$.

4.1 A Simple Dimensioning Method for NAC Budgets

The naive approach (SIMPLENETWORKSTRATEGY) determines the relative budget size $b.\xi(l)$ or the fair blocking probabilities $b.p_{b2b}(l)$ for all links $l \in \mathcal{L}(b)$. The budget size $b.c$ is then limited either by $b.\xi = \min_{l \in \mathcal{L}(b)} b.\xi(l)$ or by $b.p_{b2b} = \max_{l \in \mathcal{L}(b)} b.p_{b2b}(l)$. With this naive dimensioning method, some resources are used less than with our efficient algorithm. If $b.\xi$ is smaller than some $b.\xi(l)$ or if $b.p_{b2b}$ is larger than some $b.p_{b2b}(l)$, the resources associated with b on link l can neither be used by b nor by any other budget (cf. Figure 8).

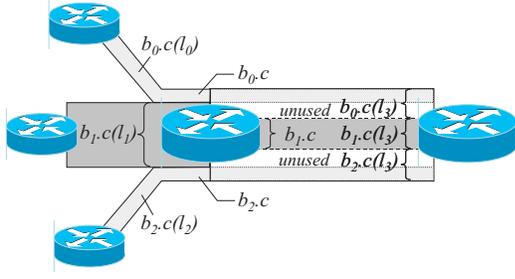


Figure 8: The simple network resource assignment strategy leaves capacity unused.

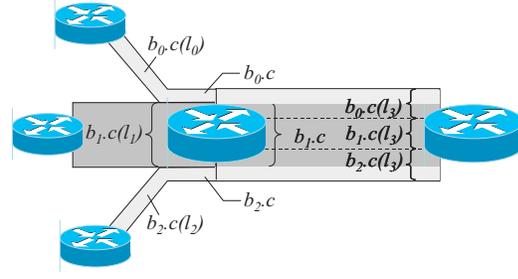


Figure 9: The efficient network resource assignment strategy distributes unused capacity to other budgets.

4.2 A Dimensioning Method for Efficient NAC Budgets

In Algorithm 2 (EFFICIENTNETWORKSTRATEGY) a dimensioning method for efficient NAC budgets is proposed. Initially, all budgets in the network have not been assigned, yet. Hence, the set of unassigned budgets is $\mathcal{B}_{free} = \mathcal{B}$. As long as \mathcal{B}_{free} is not empty, the following steps are performed. For each budget $b \in \mathcal{B}_{free}$, the relative size $b.\xi$ is increased (or the blocking probability $b.p_{b2b}$ is reduced) to such an extent that a bottleneck occurs on some link l . All budgets $\mathcal{B}(l)$ contributing to the bottleneck on link l are removed from the set of free budgets, i.e. their relative size $b.\xi$ (or their blocking probability $b.p_{b2b}$) is frozen for the further proceeding. Optionally, this procedure may stop if the blocking probability $b.p_{b2b}$ of the unassigned budgets $b \in \mathcal{B}_{free}$ falls below a predefined threshold p_{min} . As a result of this algorithm, the unused budget capacity $b_{0,2}.c(l_3) - \min_{l_i \in path(v,w)}(b_{1,2}.c(l_3))$ of link l_3 in Figure 9 may be used by budget b_1 .

4.3 Illustration of the Fairness Concept in a Network

4.3.1 Networking Scenario

We illustrate the effect of both network strategies in our test network, which is given in Figure 10. Its topology is based on the UUNET in 1994 [30] where nodes connected by only one or two links to the network were successively removed. Finally, the network has $|\mathcal{V}| = 20$ routers and $|\mathcal{E}| = 51$ links.

We set the overall traffic load in the network $a_{tot} = \sum_{\{v,w \in \mathcal{V} | v \neq w\}} g(v,w).a$ to $(|\mathcal{V}| - 1) \cdot a_{b2b}$ where a_{b2b} is the average offered load per b2b aggregate. We construct the traffic matrix $g.a$ proportionally to the city sizes π which are given in Figure 11

$$g(v,w).a = \begin{cases} a_{tot} \cdot \frac{\pi(v) \cdot \pi(w)}{\sum_{x,y \in \mathcal{V}, x \neq y} \pi(x) \cdot \pi(y)} & \text{for } v \neq w, \\ 0 & \text{for } v = w. \end{cases} \quad (21)$$

We limit our studies to the BBB NAC. We set $a_{b2b} = 10$ and dimension the network links for a b2b blocking probability of $p_{b2b} = 10^{-3}$.

Input: set of all budgets \mathcal{B} , set of all links \mathcal{E} , sets of budgets contributing to the capacity constraints $\mathcal{B}(l) = \{b | l \in \mathcal{L}(l)\}$ for each link $l \in \mathcal{E}$

$\mathcal{B}_{free} := \mathcal{B}$ {set of unassigned budgets}

while ($\mathcal{B}_{free} \neq \emptyset$) **do**

for all $b \in \mathcal{B}_{free}$ **do** {simultaneously until some b encounters bottleneck on some link $l \in \mathcal{E}$ }

increase(b, ξ) / *reduce*(b, p_{b2b})

if $b.p_{b2b} > p_{min}$ **then**

break

end if

end for

$\mathcal{B}_{free} := \mathcal{B}_{free} \setminus \mathcal{B}(l)$

end while

Output: b2b budget blocking probabilities $\{b.p_{b2b} | b \in \mathcal{B}\}$

Algorithm 2: Computation of efficient budgets for non-link-specific NAC types (EFFICIENT-NETWORKSTRATEGY).

A complete assignment method consists of a link and a network strategy. The first one is required for the fairness and the second one for the efficiency. Table 1 shows the possible combinations. AM0 is designed to be fair and efficient. Reduced efficiency also affects the blocking probabilities of the traffic, therefore, we can measure this by the suggested definition of unfairness by relating the respective data to the results of AM0.

4.3.2 Impact of Load Distribution

We want to investigate the impact of the load distribution on the unfairness resulted from different assignment strategies. To modify the load distribution, we modify the city sizes π by

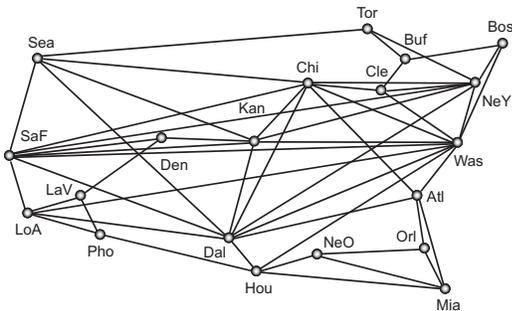


Figure 10: Our test network based on the UUNET (1994).

$Name(v)$	$(v) [10^3]$	$Name(v)$	$(v) [10^3]$
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 11: The population of the cities and their surroundings.

Table 1: Assignment strategies for NAC budgets.

Name	LINKSTRATEGY	NETWORKSTRATEGY
AM0	FAIR	EFFICIENT
AM1	FAIR	SIMPLE
AM2	NAIVE	EFFICIENT
AM3	NAIVE	SIMPLE

an exponential extrapolation using the following formula:

$$\pi(v, t) = |\mathcal{V}| \cdot \bar{\pi} \cdot \frac{\exp(\delta(v) \cdot t)}{\sum_{v \in \mathcal{V}} \exp(\delta(v) \cdot t)}, \quad (22)$$

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 for the original population π and $\pi(t=1)$ are the same.

Table 2: Impact of assignment method and load distribution on unfairness D^- .

Assignment Method	$t = 0$	$t = 1$	$t = 2$
AM0	0	0	0
AM1	0	0	0
AM2	0	232.6	491.9
AM3	0	328.5	584.0
$c_{var}[city\ sizes]$	0	0.69	2.02

Table 2 shows the unfairness of the different assignment strategies depending on the extrapolation parameter t . AM0 is fair by definition. For $t = 0$ all aggregates have the same offered load $g(v, w).a$, so both the fair and the naive resource assignment yield the same values per link. Since the network was designed for p_{b2b} , the budget sizes $b.\xi(l)$ or $b.p_{b2b}(l)$ are the same for all $l \in \mathcal{L}(b)$, and therefore, all resources are used. Hence, under these (hardly realistic) circumstances, none of the proposed methods is unfair. We observe that for increasing the extrapolation parameter t , the coefficient of variation $c_{var}[g(v, w).a]$ of the entries in the traffic matrix increases, too. For FAIRLINKSTRATEGY methods (AM0, AM1), this has no impact because all budgets get $b.p_{b2b}(l) = p_{b2b}$ for all $l \in \mathcal{L}(b)$ according to the dimensioning of the link capacities. Therefore, there are no extra link capacities that can be assigned to other budgets.

The NAIVELINKSTRATEGY methods (AM2, AM3) lead to unfair budget assignments on individual links and, in addition, $b.\xi(l)$ differs more, the larger the variation of the traffic matrix is. Only the minimum $b.\xi = \min_{l \in path(v, w)} b.\xi(l)$ can be taken for the dimensioning of the b2b budget. With AM2, the rest capacity can be used to increase the shares of other b2b aggregates while with AM3 it remains unused. Therefore, AM3 is more unfair than AM2.

4.3.3 Impact of Link Granularity

In the previous section we have seen that the efficiency aspect hardly influences the unfairness unless the link resource assignment has already been unfair. Now we consider the case that the network is dimensioned for $p_{b2b} = 10^{-3}$ but only multiples of a finest granularity c can be provided as bandwidth portions, i.e. the correctly dimensioned link capacities are rounded up. The impact of this granularity problem on the unfairness is given in Table 3. Again, AM0 is fair by definition and AM1 is fair for a granularity of $u_c = 64$ Kbit/s since this is the minimum bandwidth request in our model, so it does not represent any restriction. For the same reason, AM2 and AM3 are only affected by the unfairness of the link resource assignment.

If the link granularity is larger, the reference method AM0 can take advantage of rounded up link sizes to lower the blocking of the BBBs. Compared to AM0, the unfairness of the other methods rises only slightly with the link granularity. Hence, the fair assignment of link resources (LINKSTRATEGY) is most crucial for the minimization of the network wide blocking probabilities. The assignment of unused bandwidth to other BBBs (NETWORKSTRATEGY) plays a minor role when the network resource were properly dimensioned.

Table 3: Impact of assignment method and capacity granularity u_c on unfairness D^- ($t = 1$).

Assignment Method	$u_c = 64$ Kbit/s	$u_c = 512$ Kbit/s	$u_c = 4096$ Kbit/s
AM0	0	0	0
AM1	0	6.8	44.7
AM2	232.6	232.8	244.4
AM3	328.5	329.9	354.1

5 Conclusion

We distinguished between *link* admission control (LAC) and *network* admission control (NAC). LAC limits the number of flows on a link to assure their QoS requirements while NAC limits the number of flows in a network. We presented three basic NAC methods: the link budget (LB) based NAC, the border-to-border (b2b) budget (BBB) based NAC, which consists of virtual tunnels, and the ingress and egress budget (IB/EB) based NAC, known from the Differentiated Services context. Many research projects implement admission control (AC) schemes that can be classified by these categories. We explained the capacity dimensioning for the budgets using an efficient implementation of the Kaufman-Robert's formula. Based on these budgets, the required capacities of all links in the network are computed.

In practice, there is a different challenge. The link capacities are given and the budgets should be assigned such that no congestion can occur inside the network. In addition, the budgets should be assigned in a fair way, i.e. all flow blocking probabilities should be as low as possible. First, we explained how this can be achieved in a fair way on a single link. Then, we defined the notion of unfairness regarding blocking probabilities. We showed in

a numerical comparison that the advantage of this approach is evident on a single link for low or high offered load, as well as for skewed load distributions. Finally, we presented a network resource assignment algorithm for non-link-specific budget types (BBB, IB/EB). A performance comparison with b2b budgets showed in our test network that the fair assignment of efficient NAC budgets achieves lower flow blocking probabilities than simpler approaches, in particular for skewed traffic matrices and coarse bandwidth granularities.

Hence, our method allows for fair and resource efficient configuration of budget-based NACs such that no network congestion occurs. The flow blocking probabilities are as low as possible and the link bandwidth can be used to a large extent. A challenge remains the computation of NAC budgets for networks with resilience requirements.

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