

## Fair Assignment of Efficient Network Admission Control Budgets

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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 objective 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 assignment 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.

### 1. Introduction

For the implementation of real-time services in packet-switched networks, admission control (AC) is required to limit the data volume of premium traffic. 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. *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 over a single link. In [1] 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. 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. However, the practical problem is vice versa. Therefore, our objective is the inversion of this 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 assignment and illustrate its effect on a single link. This leads to a definition of unfairness regarding flow blocking probabilities. We

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extend this mechanism to entire networks, such that it is adaptable to all presented NAC methods. These algorithms are most effective in real networking scenarios with heterogeneous traffic matrices.

The paper is structured as follows. Section 2 gives an overview of budget based NAC methods and Section 3 explains how budget and link capacities can be dimensioned. Section 4 proposes two methods for the partitioning of the capacity of a single link into several budgets and Section 5 extends this method from a single link to an entire network. Section 6 summarizes this work.

## 2. Methods for Network Admission Control (NAC)

We introduce four different budget based NAC concepts. An AC instance records the demand of admitted active flows  $\mathcal{F}_{admitted}$ . When a new flow arrives, AC 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. For the sake of a simple description, we take only peak rate allocation for flows into account. However, all NAC methods can be combined with more efficient LAC methods like effective bandwidths or measurement based AC [2–4].

### 2.1. Link Budget Based Network Admission Control (LB NAC)

The link-by-link NAC is probably most intuitive. The capacity<sup>1</sup>  $l.c$  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  $v$ <sup>2</sup>, egress router  $w$ , and bitrate  $f_{new}(v, w).c$  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 is successful if the following inequality holds

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

There are many systems and protocols working according to that principle. The connection AC in ATM and the Integrated Services 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. A bandwidth broker [5] administers the budgets in a central entity which represents a single point of failure but behaves in a similar way. The stateless-core approaches [6–8] are able to avoid states in the core at the expense of measurements or increased response time.

### 2.2. Ingress Budget 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 the requests to both

<sup>1</sup>We 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.

<sup>2</sup>A networking scenario  $\mathcal{N} = (\mathcal{V}, \mathcal{E}, u)$  is given by a set of border routers  $\mathcal{V}$  and set of links  $\mathcal{E}$ . The b2b traffic aggregate with ingress router  $v$  and egress router  $w$  is denoted by  $g(v, w)$ , the 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  $l$ .

budgets are successful (cf. Figure 2). Hence, the following inequalities must hold

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

Flows are admitted at the ingress and the egress irrespective of the path they are routed through the network. The mere IB NAC, which originates from the DiffServ context [9], admits traffic only at the ingress border router, i.e. only the first part of Equation (2) must be met for the AC procedure. 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 – traffic patterns that are admissible by the IBs and EBs with the required QoS. Hence, sufficient capacity must be allocated or the IBs and EBs must be set small enough.

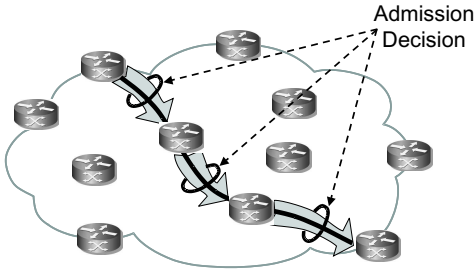


Figure 1. Network admission control based on link budgets.

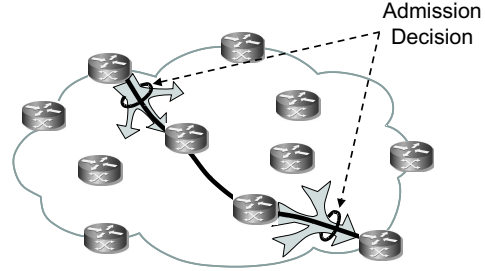


Figure 2. Network admission control based on ingress and egress budgets.

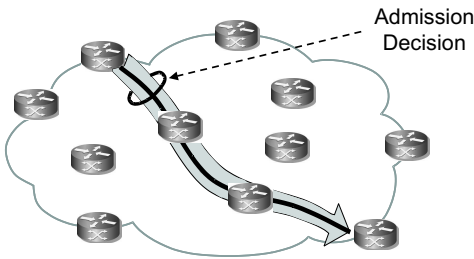


Figure 3. The BBB NAC corresponds to a virtual tunnel.

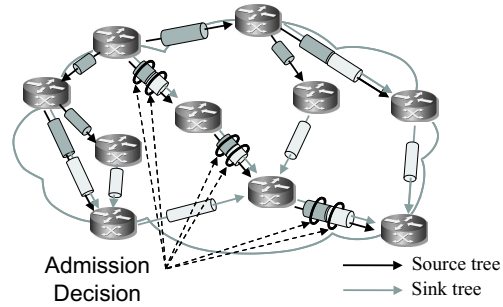


Figure 4. Network admission control based on ingress and egress link budgets.

### 2.3. B2B Budget Based Network Admission Control (BBB NAC)

The BBB NAC takes 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

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

The capacity  $BBB(v, w).c$  of a tunnel is dedicated to one specific b2b aggregate  $g(v, w)$  and can not be used for other traffic with different source or destination. Hence, there is no flexibility

but pathological traffic patterns are excluded. The BBB NAC is often realized in a more flexible manner, such that the size of the BBBs can be rearranged [10,11]. The same can be done for other NAC methods, too.

#### 2.4. 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  $\{l: ILB(l, v) > 0\}$  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  $ILB(\cdot, v)$  and  $ELB(\cdot, w)$  of all links that are traversed in the network by  $f_{new}$ . The NAC procedure will be successful if the following inequalities are fulfilled

$$\forall l \in \mathcal{E} : l.u(v, w) > 0 : f_{new}(v, w).c \cdot l.u(v, w) + \sum_{f(x,y) \in \mathcal{F}_{admitted}^{l,v,ingress}} f(x, y).c \cdot l.u(x, y) \leq ILB(l, v).c \quad (4)$$

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

There are several significant differences to BBB NAC. A BBB covers only an aggregate of flows with the same source and destination while the ILBs (ELBs) may cover flows with the same source (destination) but different destinations (sources). Therefore, the ILB/ELB NAC is more flexible than the BBB NAC. With BBB NAC, only one  $BBB(v, w)$  is checked while with ILB/ELB NAC, the number of budgets to be checked is twice the flow path lengths. Like with IB/EB NAC, there is the option to use only ILBs or ELBs by applying only Equation (4) or Equation (5). The concept of ILB/ELB or ILB NAC can be viewed as a set of 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.

### 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. We consider budget dimensioning in general and explain how NAC specific budget and link capacities are calculated.

#### 3.1. Capacity Dimensioning in General

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 [2] for the computation of the blocking probabilities  $r_i.p$  of request types  $r_i$  if a certain capacity  $c$  is provided. We relate the blocking probability  $p$  to the traffic volume instead to the number of flows and compute the overall blocking probability by  $p = 1 - \frac{\sum_{0 < i < n_r} (1 - r_i.p) \cdot r_i.c \cdot r_i.prob}{E[C]}$ . 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.

### 3.2. Resource Allocation for Budget Based NAC Methods

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

$$\forall v, w \in \mathcal{V} : g(v, w).c \geq 0 \quad \text{and} \quad \forall v \in \mathcal{V} : g(v, v).c = 0. \quad (6)$$

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  $l$ :

$$l.c \geq \max_{g.c \in \mathbb{R}_0^{+|\mathcal{V}|^2}} \sum_{v, w \in \mathcal{V}} g(v, w).c \cdot l.u(v, w). \quad (7)$$

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 in polynomial time. However, for most NACs there are more efficient solutions. We explain only the calculation for the BBB NAC since it is the candidate for the following experiments.

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  $BBB(v, w).a = g(v, w).a$ . Based on that value, the required capacity  $BBB(v, w).c$  is computed. Since Equation (3) is checked for admission

$$\forall v, w \in \mathcal{V} : g(v, w).c \leq BBB(v, w).c \quad (8)$$

must be fulfilled. Since this is a very simple side condition, the minimum capacity  $l.c$  of link  $l$  can be expressed by

$$l.c \geq \sum_{v, w \in \mathcal{V}} BBB(v, w).c \cdot l.u(v, w). \quad (9)$$

The budget and link capacity formulae for all NACs are given in detail in [1].

### 4. Fair Assignment of a Single Resource to AC Budgets

In this section we consider several traffic aggregates  $g \in \mathcal{G}$  with a given load  $g.a$  being transported over a single link  $l$ . They are protected by private budgets  $g.b$  with the same load  $g.b.a$ , that compete for the capacity  $l.c$ . We suggest a naive and a fair strategy for resource assignment to the competing budgets and illustrate their impact by numerical results.

<sup>3</sup>We denote the offered load for a b2b aggregate  $g(v, w)$  by  $g(v, w).a$ . 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.

#### 4.1. Resource Assignment Strategies for a Single Link

A naive approach assigns the link capacity  $l.c$  to the budget capacities  $b.c$  proportionally to the offered load  $b.a$ , i.e.  $b.c = b.a \cdot l.\xi$  with  $l.\xi = \frac{l.c}{l.a}$  and  $l.a = \sum_{g \in \mathcal{G}} g.b.a$  (PROPORTIONALLINKSTRATEGY). This is simple to compute. All budgets  $b$  have the same relative size  $b.\xi = l.\xi$  related to the offered load  $g.a$  but traffic aggregates with more offered load encounter a lower flow blocking probability  $g.p$  due to economy of scale. This consideration leads to a vague notion of unfairness. Fairness is given if all traffic aggregates face the same blocking probabilities on that link.

We formulate an algorithmic approach to achieve fair resource assignment (FAIRLINKSTRATEGY). We choose a minimum capacity granularity  $u.c$  such that all capacities  $c_u$  are given as a multiple of  $u.c$ . The resource units  $l.c_u$  are assigned one after another to a budget that is associated with the maximum blocking probability ( $g^*.b : g^* \in \mathcal{G}, g^*.p = \max_{g \in \mathcal{G}}(g.p)$ ). If two traffic aggregates have the same blocking probability, the one with the largest offered load is chosen. The increase of the budget capacity  $g^*.b.c_u$  decreases the blocking probability  $g^*.p$  such that the next capacity unit is assigned to a different budget. The algorithm may also stop if a desired minimum blocking probability is reached.

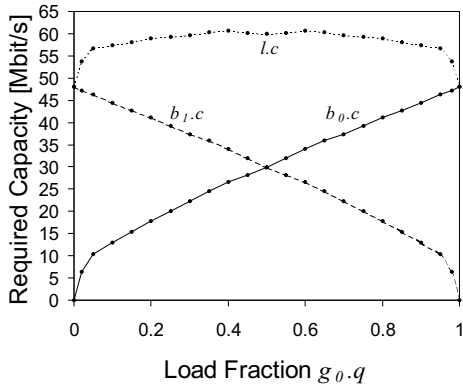


Figure 5. Impact of the load distribution on the required capacities.

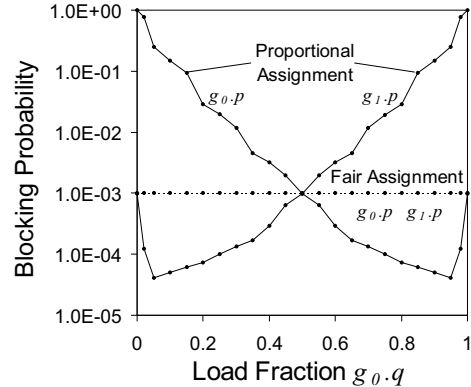


Figure 6. Impact of the load distribution on the blocking probabilities.

#### 4.2. Impact of Resource Assignment Strategies

For simplicity reasons we conduct our experiments with only two traffic aggregates  $g_0$  and  $g_1$  (with budgets  $b_0$  and  $b_1$ ) competing for the capacity  $l.c$ . We assume a fixed link load  $b_0.a + b_1.a = l.a = 100$ . Since there are only two competing budgets, the load distribution among them is characterized by the load fraction  $g_i.q = \frac{b_i.a}{l.a}$ . We dimension the budget capacities  $b_i.c$  for a desired blocking probability  $g_i.p = 10^{-3}$  and set the link capacity to  $l.c = b_0.c + b_1.c$ . Figure 5 shows the budget sizes  $b_i.c$  and the required link capacity  $l.c$  for different load fractions  $g_0.q$ . The least capacity is required for  $g_0.q = 0$  or  $g_0.q = 1$  because then,  $b_1$  or  $b_0$  can be dimensioned most efficiently due to economy of scale. As a next step, we reassign the obtained link capacity  $l.c$  to the budget capacities  $b_0.c$  and  $b_1.c$  according to the proportional and to the fair resource assignment strategy. Figure 6 illustrates the resulting budget blocking probabilities. Due to the construction of the experiment, the blocking probabilities for the fair assignment method are exactly  $10^{-3}$ . For the proportional assignment method, the blocking probabilities depend on the load fraction. For  $g_i.q < 0.5$ ,  $g_i.p$  is larger than  $10^{-3}$  and for  $g_i.q > 0.5$ ,  $g_i.p$  is smaller. For  $g_0.q = 0.2$  we get a  $g_0.p \approx 10^{-4}$  and  $g_1.p \approx 10^{-1}$ . This is clearly unfair.

We conduct the same experiment for a fixed load fraction  $g_0.q = 0.2$  and vary the offered link load. Figure 7 reveals that for a very low load  $l.a$  both  $b_0$  and  $b_1$  require a capacity of about 2 Mbit/s which corresponds to the maximum request size  $r_{2.c}$ . For large values of  $l.a$ , the required capacities for both budgets rise about linearly with the offered link load. According to Figure 8 the blocking probability  $g_0.p$  is about  $10^{-2}$  even for large offered link load and the blocking probability  $g_1.p$  does not exceed  $10^{-4}$ . Hence, there is also a clear unfairness under all link loads.

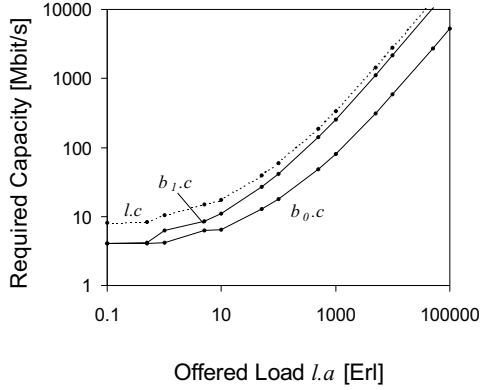


Figure 7. Impact of the offered link load on the required capacities.

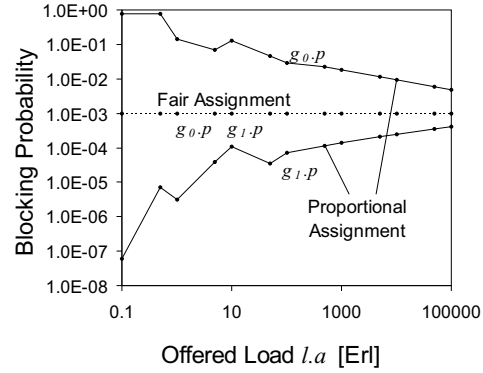


Figure 8. Impact of the offered link load on the blocking probabilities.

### 4.3. Definition of Unfairness

So far, we have only a definition for fair resource assignment but there is no measure for unfairness. In our experiments we observed positive and a negative deviations of the aggregate blocking probabilities for the proportional assignment strategy from the values  $g.p^{fair}$  of the fair assignment strategy. We use this distance as a metric for unfairness. This idea can also be applied to an entire network if the reference probabilities  $g.p^{fair}$  are defined. For the rest of the paper, we define unfairness by the negative deviations formally described by

$$\Delta^- = \frac{\sum_{g \in \mathcal{G}} \max(\log(g.p) - \log(g.p^{fair}), 0)}{|\mathcal{G}|}. \quad (10)$$

### 5. Assignment of Efficient NAC Budgets

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

$$\mathcal{L}(b) = \begin{cases} \{l : l \in \mathcal{E} \wedge \sum_{w \in \mathcal{V}} b.a \cdot l.u(v, w) > 0\} & \text{for } b = IB(v) \\ \{l : l \in \mathcal{E} \wedge \sum_{v \in \mathcal{V}} b.a \cdot l.u(v, w) > 0\} & \text{for } b = EB(w) \\ \{l : l \in \mathcal{E} \wedge b.a \cdot l.u(v, w) > 0\} & \text{for } b = BBB(v, w) \end{cases}. \quad (11)$$

We propose a simple algorithm for the capacity assignment to non-link-specific NAC budgets and suggest an improved method that leads to a more efficient use of the network capacity. Afterwards, we illustrate the increased performance under fairness aspects.

### 5.1. Resource Assignment Methods for Non-Link-Specific Budgets

A simple approach (SIMPLENETWORKSTRATEGY) for resource assignment to a non-link-specific budget  $b$  starts with a link specific assignment  $b.c(l)$  for all link-specific budgets for each link  $l \in \mathcal{L}(b)$ . This can be done, e.g., by the proportional or the fair resource assignment strategy (cf. Section 4). The budget capacity  $b.c$  is then determined by the minimum of the obtained results  $b.c = \min_{l \in \mathcal{L}(b)}(b.c(l))$ . This method leaves  $b.c(l) - b.c$  capacity on link  $l$  unused. If this capacity can be used to reduce the blocking probability for other budgets, we can apply our definition of unfairness to assess the assignment results.

Knowing about this inefficiency, we describe an algorithm (EFFICIENTNETWORKSTRATEGY) that avoids this problem. Initially, 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. We increase the budget capacities of all  $b \in \mathcal{B}_{free}$  simultaneously, such that they have all the same  $b.\xi$  or  $b.p$ , until 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  $\mathcal{B}_{free}$ , and their capacity is frozen. Then, the procedure continues until  $\mathcal{B}_{free}$  is empty. Optionally, this procedure may stop if the blocking probability  $b.p$  of the unassigned budgets  $b \in \mathcal{B}_{free}$  falls below a predefined threshold  $p_{min}$  or if their relative size  $b.\xi$  exceeds a given maximum value  $\xi_{max}$ . This would possibly leave some spare capacity in the network.

A complete assignment method (AM) consists of a link and a network assignment strategy. The first one is required for fairness and the second one for the efficiency. Table 1 shows the possible combinations. Since AM0 is fair and efficient, we use it as a fair reference to calculate the unfairness of the other AMs.

Table 1  
Assignment strategies for NAC budgets.

	EFFICIENT NETWORKSTRATEGY	SIMPLE NETWORKSTRATEGY
FAIRLINKSTRATEGY	AM0	AM1
PROPORTIONALLINKSTRATEGY	AM2	AM3

### 5.2. Impact of the Assignment Methods

We illustrate the effect of the AMs in our test network. The network has  $|\mathcal{V}| = 20$  routers and  $|\mathcal{E}| = 51$  links and the population of the city sizes is given by a function  $\pi$ . Further details can be found in [1]. We scale the overall traffic load in the network  $a_{tot} = (|\mathcal{V}| - 1) \cdot a_{b2b}$  using the average offered b2b load  $a_{b2b}$  and set the offered load of the traffic aggregates proportionally to the city population by  $g(v, w).a = \frac{a_{tot} \cdot \pi(v) \cdot \pi(w)}{\sum_{x, y \in \mathcal{V}, x \neq y} \pi(x) \cdot \pi(y)}$  for  $v \neq w$  and  $g(v, v).a = 0$ . To modify the variability of the traffic matrix, we change the city sizes  $\pi$  by an exponential extrapolation using the formula  $\pi(v, t) = \frac{|\mathcal{V}| \cdot \bar{\pi} \cdot \exp(\delta(v) \cdot t)}{\sum_{v \in \mathcal{V}} \exp(\delta(v) \cdot t)}$ , 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 for the original population  $\pi$  and  $\pi(t=1)$  are the same.

We limit our studies to the BBB NAC, set  $a_{b2b} = 10$ , and dimension the network links for a b2b blocking probability of  $p_{b2b} = 10^{-3}$ . We dimension our test network and reassign the capacity to the budgets. AM0 is essentially the inverse operation of the dimensioning method and yields the intended blocking probability  $p_{b2b}$  for all budgets after resource reassignment. In the following we study the impact of an unequal load distribution and the impact of the capacity granularity on the unfairness in the network for different AMs.



Figure 9 shows the unfairness  $\Delta^-$  of the different AMs and the coefficient of variation of the traffic aggregate sizes  $g(v, w).a$  depending on the extrapolation parameter  $t$  that is used for the construction of the traffic matrix. Since the network capacity has been dimensioned for a blocking probability  $p_{b2b}$  for all budgets, fair resource assignment of the link capacities to the budgets  $b \in \mathcal{B}(l)$  yields the same blocking probabilities  $b.p = p_{b2b}$  on all links  $l \in \mathcal{E}$ . Therefore, all  $b(l) \in \mathcal{L}(b)$  have the same capacity and no resources are wasted due to a simple resource assignment strategy in the network. Hence, AM1 returns the same budgets as AM0 and its unfairness is always zero in this experiment. For  $t = 0$  AM3 and AM2 give also fair results because all aggregates have the same offered load  $g(v, w).a = a_{b2b}$  and this is why the proportional and the fair link assignment yield the same budget capacities. For increasing  $t$ , the load distribution becomes more heterogeneous such that the unfairness increases with the variation of the traffic matrix. AM3 is more unfair than AM2 because in addition to unfair assignment of link budget capacities  $b.c(l)$ , some capacity is wasted due to the simple resource assignment in the network.

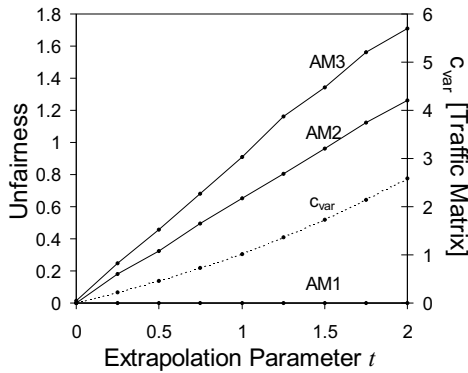


Figure 9. Impact of the load distribution on the unfairness.

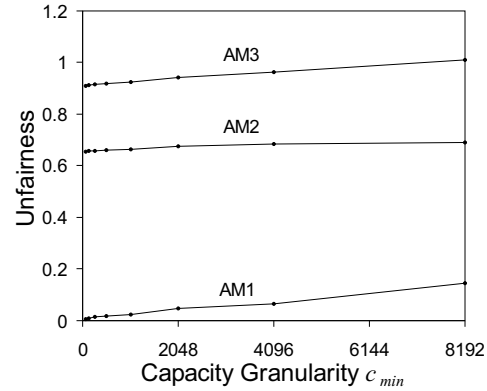


Figure 10. Impact of the capacity granularity on the unfairness.

In the previous experiments we have seen that the efficient resource assignment strategy for networks has no impact if the link assignment strategy is fair. Now, we assume that the network is dimensioned for  $p_{b2b} = 10^{-3}$  but only multiples of a finest granularity  $c_{min}$  can be provided as bandwidth portions, i.e. the correctly dimensioned link capacities are rounded up. Figure 10 shows the impact of  $c_{min}$  on the unfairness. Again, AM0 is fair by definition and AM1 is fair for a granularity of  $c_{min} = 64$  Kbit/s since all request sizes in our model are a multiple of that quantity. So, this is not a restriction. For increasing  $c_{min}$ , the unfairness slightly increases. Both AM3 and AM2 suffer from the proportional link strategy. The increasing capacity granularity enlarges the unfairness only slightly whereby the increase is less for the efficient network strategy AM2.

Hence, the strategy for assignment of link resources (PROPORTIONAL/FAIRLINKSTRATEGY) is most crucial for the minimization of the network wide blocking probabilities. When the link capacities in the network were properly dimensioned, the bandwidth assignment strategy for networks (SIMPLE/EFFICIENTNETWORKSTRATEGY) plays a minor role.

## 6. Summary

In this paper 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 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, which is a new concept. 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 NAC budgets have to be set 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 must be as low as possible. We suggested a simple and a fair strategy for the bandwidth partitioning of a single link into budgets and gave a formal definition of unfairness with respect to blocking probabilities. Our experiments showed that the fair assignment of link resource has a large impact on the unfairness. In addition, we presented an algorithm for the assignment of network-wide resources to non-link-specific budgets (BBB, IB, EB). This is an efficient method because it avoids the waste of resources which is commonly observed for simpler approaches. A performance comparison with BBBs showed that the fair assignment of efficient NAC budgets achieves lower flow blocking probabilities than simpler approaches. In particular, this has a significant impact for skewed traffic matrices and coarse bandwidth granularities.

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