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Abstract

In this paper, we propose mechanisms for an *adaptive bandwidth allocation* (ABA) based on border-to-border (b2b) bandwidth budgets. These budgets can be considered as virtual capacity tunnels binding a fraction of the network capacity and connecting different network border routers. Unlike MPLS label switched paths or ATM virtual path connections associated with a certain bandwidth, these tunnels support multi-path routing. Moreover, they can be used to implement resilient b2b budget-based network admission control. If *static bandwidth allocation* (SBA) based on peak-rate traffic assumptions is used to dimension the b2b budgets, fluctuations of the network traffic can lead to under- or overprovisioning of network capacity within these budgets. The contribution of this paper is twofold. Firstly, we address this problem by two new ABA mechanisms – *complete capacity reassignment* (CCR) and *selective capacity reassignment* (SCR) – which adapt the sizes of the b2b budgets with regard to their current bandwidth requirements. Secondly, we investigate the bandwidth savings potential of these meachanisms by the construction of synthetically shifted but constantly loaded traffic matrices. Though focused on the above two aspects, the study of ABA based on b2b budgets is not finished and further investigations are currently in progress.

1 Introduction

Internet service providers (ISPs) are facing two major challenges today, namely the permanent increase of traffic and the common request for Quality of Service (QoS). To master the first issue and to guarantee the second, ISPs must avoid congestion in their networks at any cost. This can be achieved by means of traffic engineering (TE). Configurable capacity tunnels are a popular means for TE in today's Internet. In MPLS, label switched paths (LSPs) are established through a network and associated with a

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guaranteed bandwidth [1]. Another means is network admission control (NAC) which is applied to limit the traffic transported through a network [2]. If the concepts of capacity tunnels and NAC are combined, the capacity tunnels – further called border-to-border (b2b) budgets (BBBs) – become load-controlled. In contrast to a single LSP, a BBB can consist of a multi-path between border nodes. Per-flow AC is then performed only at the ingress routers based on the capacity of the BBBs. We call the corresponding NAC mechanism, the border-to-border budget based NAC (BBB NAC) [2]. In the following, we explain the considered problem, give an overview of related work, and comment the structure of this work.

If the capacity of a BBB does not suffice to accomodate another flow, the flow is blocked to ensure that the QoS of flows already admitted to that budget is maintained. With static bandwidth allocation (SBA), the BBBs have fixed sizes, i.e., they do not adapt to traffic fluctuations. Therefore, the budgets must be dimensioned to cope with the busy-hour traffic which can lead to inefficient utilization of network capacity at secondary times. This potential inefficiency can be avoided if adaptive bandwidth allocation (ABA) is applied to the BBBs.

The resource efficiency problem is part of the general network design problem (NDP) [3] which covers, next to bandwidth allocation [4, 5], many more issues such as traffic estimation [6], network topology design [7, 8], capacity dimensioning [9] and routing [10]. As a consequence, the NDP has been studied in the literature from many varying perspectives and in context of many different underlying network technologies. The efficiency of AC methods combined with different bandwidth allocation strategies has been compared in many studies. Typically, the network topology, link capacities, and the traffic matrix are given. The resulting flow blocking probabilities are simulated or analyzed based on a common traffic model and serve for a performance comparison. This performance evaluation approach has often been applied in the context of call blocking analysis in multi-service ATM networks [9, 11, 12] and multi-layer architectures [13].

In the following, we suggest two ABA mechanisms for BBBs. The complete capacity reassignment (CCR) approach reoptimizes and reconfigures the sizes of all BBBs in regular time intervals and reassigns the entire network capacity to the budgets. The selective capacity reassignment (SCR) approach reoptimizes and reconfigures only those BBBs for which the blocking probabilities are too high or too low. Given these blocking probabilities, SCR assigns only the minimum required network capacity to the budgets and keeps the remaining capacity in a resource pool.

The performance gain of ABA vs. SBA can be measured in different ways. Given a traffic model and a specified network topology with predetermined link capacities, the resulting b2b blocking probabilities can be calculated. This is the conventional approach that has been studied intensely in the context of call blocking analysis in multi-service ATM networks. In contrast, our method tries to quantify the performance gain of ABA vs. SBA by means of bandwidth savings achievable with ABA. Given a traffic model, a network topology, and a targeted b2b blocking probability, we determine the required capacitities for the BBBs and compute the corresponding link capacities and the resulting entire network capacity, respectively. To the best of our knowledge this is the first paper in the literature trying to quantify the performance gain of ABA vs.

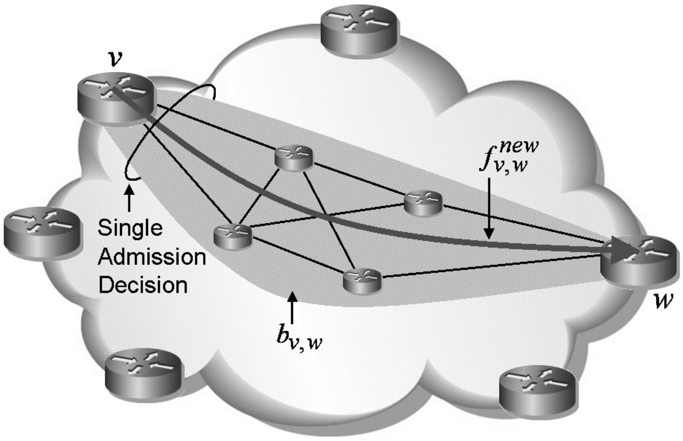

Figure 1: Network architecture with BBB NAC

SBA by bandwidth savings which yields more practical results than the comparison of blocking probabilities.

The remainder of this paper is structured as follows: In Section 2, we briefly review the BBB NAC and the SBA approach for the dimensioning of the BBBs. Section 3 introduces and compares the CCR and SCR mechanisms. In Section 4, the bandwidth savings potential of ABA is investigated for a core-level test network based and artificially oportunistic traffic matrices. Finally, Section 5 summarizes and concludes this work.

2 Border-to-Border Budget Based Network Admission Control (BBB NAC)

The BBB NAC is a new network-scoped admission control scheme and constitutes the fundament for our ABA mechanisms. Here, we briefly review the BBB NAC architecture and explain the static assignment of network capacity to the BBBs.

2.1 BBB NAC Architecture

In the following, we review the BBB NAC approach which was first introduced in [14]. There, the BBB NAC was presented as one of four alternative approaches towards a network-wide AC. These NAC approaches were profoundly studied and enhanced by resilience mechanisms in [2]. If resilience against network failures is required, the BBB NAC proved to be a resource-efficient method. Due to its economical superiority and technical simplicity, the BBB NAC was implemented in the testbed of the project KING (Key components for the Internet of the Next Generation) [15, 16].

In the KING network architecture (cf. Fig. 1), BBBs $b_{v,w}$ are defined between each two border routers v and w. A BBB NAC entity records the demands of flows, entering the network at node v and leaving it at node w, that are admitted to the budget $b_{v,w}$. When a new flow arrives, the entity checks whether the effective bandwidth of this flow together with the demand of already established flows $\mathcal{F}(b_{v,w})$ fits within the capacity of budget $b_{v,w}$. Therefore, the BBB NAC does not induce states inside the core of the network. This is basically desired with regard to scalability and resilience reasons. The network capacity assigned to a BBB $b_{v,w}$ is exclusively dedicated to the corresponding b2b flow aggregate $g_{v,w}$ and can thus not be used for other traffic with different ingress or egress router. Figure 1 illustrates that a new flow $f_{v,w}^{new}$ passes only a single AC procedure at the network edge for a specific BBB $b_{v,w}$.

2.2 Static Dimensioning of Border-to-Border Budgets (BBBs)

The BBBs can be dimensioned statically with SBA as described in [2]. There, we assume a Poisson model for the arrival of BBB NAC-controlled flows and a generally distributed holding time for these flows like in the telephone world. We furthermore assume a simplified, multi-rate real-time communication scenario with a request profile that includes different request types. We use an adaptation of the recursive Kaufman-Roberts algorithm [17] for the computation of the required BBB capacities such that a commonly desired blocking probability can be guaranteed for the flows of the respective b2b traffic aggregates.

For the capacity design of a resilient network, the minimum capacity of a link is the maximum traffic carried by that link during normal operation and in any respected failure scenario. Therefore, the calculated BBB capacities and the applied routing in any failure scenario are sufficient to figure out the required resources. According to this dimensioning rule, the network has enough capacity for the transportation of admitted traffic with the desired QoS in any respected operational mode. The sum of all link capacities, i.e., the overall required network capacity C_{tot}, can then be taken as a simple performance measure to assess the capital expenses.

Another aspect of SBA is the fair bandwidth assignment to BBBs when the link capacities are given. This is the inversion of the previous network dimensioning approach and is relevant for operational networks. Here, the bandwidths of the BBBs are increased iteratively, thereby decreasing the blocking probabilities, as long as there is capacity left on the links they use [18].

The ABA concepts developed in Section 3 support the bandwidth allocation in operational networks but their performance evaluation is based on the network dimensioning approach as we are interested in the capacity savings potential of ABA vs. SBA.

3 Concepts for Adaptive Bandwidth Allocation (ABA)

The bandwidth assignment algorithm in [18] calculates suitable BBB capacities for an assumed traffic matrix to achieve fair blocking probabilities for all b2b traffic aggregates. If this traffic matrix changes, the b2b blocking probabilities deviate from their planned values. To avoid large blocking probabilities for some aggregates and bandwidth underutilization for others, we propose two concepts for ABA: (1) complete capacity reassignment (CCR) which reoptimizes and reconfigures the entire network and (2) selective capacity reassignment (SCR) which adapts and reconfigures only those BBBs that deviate significantly from their planned blocking probabilities.

First, we explain the network monitoring that is necessary to perform ABA. We then present the relevant information about the KING network functions that enable the cooperation of distributed NAC entities and the adaptation of BBBs. Finally, we develop the two ABA concepts for BBBs. Note that these concepts are not limited to the KING network architecture but could equally fit into a (G)MPLS environment, as they apply for the adaptation of configurable capacity tunnels in general.

3.1 Network Monitoring

A prerequisite for ABA is a qualified feedback from the network about the current traffic load and the corresponding flow blocking probabilities which can both be acquired through measurements. However, there are two reasons why we do not measure the blocking probabilities directly to trigger the adaptation of BBBs. Firstly, the blocking probabilities are usually in the order of 10^{-3} or below and a relatively long time is required to get a good estimate. Secondly, we want to detect situations with high blocking probabilities before they actually occur because we want to avoid them.

Instead of observing the blocking probabilities directly, we rather observe the time-variant traffic matrix. Aware of the fact that traffic matrix estimation is a difficult problem itself (cf. e.g. [6]), we use an estimate for the traffic load in Erlang and a reasonable estimate for the flow request size distribution for each b2b aggregate to calculate its current flow blocking probability. This calculation is also based on the Kaufman-Roberts algorithm since the current BBB capacities are known. Hence, the blocking probabilities can be derived without measuring the blocking of flows. The load for a b2b aggregate and the corresponding flow request size distribution are gained from measurements by the NAC entities at the ingress routers.

3.2 KING Network Functions

The central intelligence that controls a KING network is the network control server (NCS). The NCS is responsible for the configuration and the optimization of the BBBs. However, the NCS is not required for a KING network to be operational since it does not perform any online computations like, e.g., a bandwidth broker. The tasks of the NCS therefore comprise the bandwidth assignment to the BBBs, the (re-)configuration of the NAC entities with adapted BBBs, and the centralized network monitoring. To implement the last task, the NCS regularly obtains information on aggregate loads and corresponding flow request size distributions from the NAC entities.

3.3 Complete Capacity Reassignment (CCR)

The CCR method is considered as a triggered iteration of the bandwidth assignment algorithm which recalculates and reconfigures all BBBs in the network. There are basically two options to define the trigger. (1) The most intuitive method is to trigger the CCR in regular time intervals and thus independent of the current network state. As a consequence, a small interval requires much computation power and causes high signaling and configuration costs whereas a long interval leads to delayed response times. Both extremes must therefore be avoided. (2) Another method is to explicitly trigger the CCR with one of the following two mechanisms.

(a) Using a tolerance interval (TI), we define for each b2b relationship an upper and lower bound for its corresponding blocking probability. The CCR is triggered only if a current blocking probability changes significantly, i.e. if it is not within its defined TI. A trigger for falling below the lower threshold is thus as important as a trigger for exceeding the upper threshold. As a consequence, less capacity requirements of some BBBs allow to reduce the blocking probabilities of others. There are different methods to determine the TI for a BBB with a planned blocking probability p where c is an arbitrary parameter. The TI can be defined linearly by $[p(1-c), p(1+c)]$ or logarithmic by $[p \cdot exp(-c), p \cdot exp(c)]$. Both methods allow for a regulation of the BBB update probability.

(b) Defining only a single lower reduction threshold (RT) for each b2b relationship, the CCR is triggered only if the blocking probability of a BBB decreases below its RT and if the applied bandwidth assignment algorithm sequentially leads to a reduced blocking probability for at least one BBB. Similar to the TI mechanism, the RT can be defined linearly by $p(1-c)$ or logarithmic by $p \cdot exp(-c)$. Setting up the RT regulates again the update probability of the BBBs.

3.4 Selective Capacity Reassignment (SCR)

The SCR is based on the following idea. When the bandwidth assignment algorithm is first applied to initialize all BBBs, a part of the link capacities is not assigned to the BBBs and retained in a free resource pool (FRP). The resulting blocking probabilities then represent planned values and the BBB capacities are adapted selectively, i.e., instead of recalculating all BBBs simultaneously, only those budgets are adapted for which the corresponding blocking probabilities deviate significantly from their planned values. The SCR therefore keeps some of the BBBs constant and adapts only the capacities of critical budgets with the help of the FRP. To increase the size of a BBB, resources are taken from the FRP if they are available. If, on the other hand, a budget is to be reduced due to capacity overprovisioning, resources are given back to the FRP such that the blocking probabilites match with the planned values. Therefore, an upper and a lower limit for the blocking probability have to be defined to indicate an under- or overprovisioning of capacity within a BBB. The TI mechanism as described in Sec. 3.3 is thus an appropriate mechanism to be used with SCR.

If there are too high blocking probabilities that cannot be lowered by assigning additional capacity to the respective BBBs due to a depletion of resources in the FRP, all BBBs are reinitialized and a part of the link capacities is again retained in the FRP. This also leads to new planned values for the blocking probabilities.

3.5 Comparison of CCR and SCR

The advantage of SCR over CCR is its fast reaction to local capacity shortages. On the other hand, SCR does not provide the lowest possible blocking probabilities since available link capacities are not assigned to the BBBs but retained in the FRP instead. While this is not a critical issue, a real handicap of SCR is its bad performance in network overload situations where the resources in the FRP are depleted. In this case, it is not possible to shift bandwidth between the BBBs and the blocking probabilities might therefore deviate very unequally from their planned values. Then, a global recalculation of all BBBs as with CCR and a reinitialization of the FRP with link capacities would improve the fairness between the BBBs even in the case of network overload. The above is merely a basic comparison between CCR and SCR. A more detailed performance investigation of both methods is considered as future work.

4 Performance Evaluation of Adaptive Bandwidth Allocation

The benefits of ABA are potential bandwidth savings that increase if the traffic matrix becomes more variable. With SBA, the capacity for every BBB must be dimensioned for its busy hour. At secondary times, this capacity is underutilized if the offered load is significantly lower. If the busy hours of different BBBs do not occur simultaneously, some of the bandwidth of underutilized budgets can be used to support other budgets in their busy hour. This change in current capacity requirements leads to bandwidth savings.

4.1 Experiment Design

Our objective is to find out to which degree potential capacity savings can be realized with ABA. Therefore, we construct traffic matrices with a high variability but constant overall load for the sake of simple comparison. First, we present the KING core-level test network and make assumptions for the construction of general traffic matrices for evaluation purposes. Then we make these traffic matrices time-dependent in such a way that maximum bandwidth savings can be achieved with ABA.

4.1.1 Calculation of Static Traffic Matrices

The method for generating a static traffic matrix $A[v,w]_{v,w\in\mathcal{V}}$ for the KING test network illustrated in Fig. 2 is based on the given city sizes. For each combination of ingress/egress routers v and w, the offered load $a_{v,w}$ in Erlang is defined as:

$$a_{v,w} = \begin{cases} \frac{a_{tot}\cdot\pi(v)\cdot\pi(w)}{\sum_{x,y\in\mathcal{V},x\neq y}\pi(x)\cdot\pi(y)} & \text{if } \; v\neq w \\ 0 & \text{if } \; v = w \end{cases} \tag{1}$$

where $\mathcal{V}$ is the set of network border routers, $\pi(v)$ is the population of border router v and $a_{tot} = a_{b2b}\cdot|\mathcal{V}|\cdot|\mathcal{V}-1|$ is the overall offered network load depending on the average offered b2b load a_{b2b}.

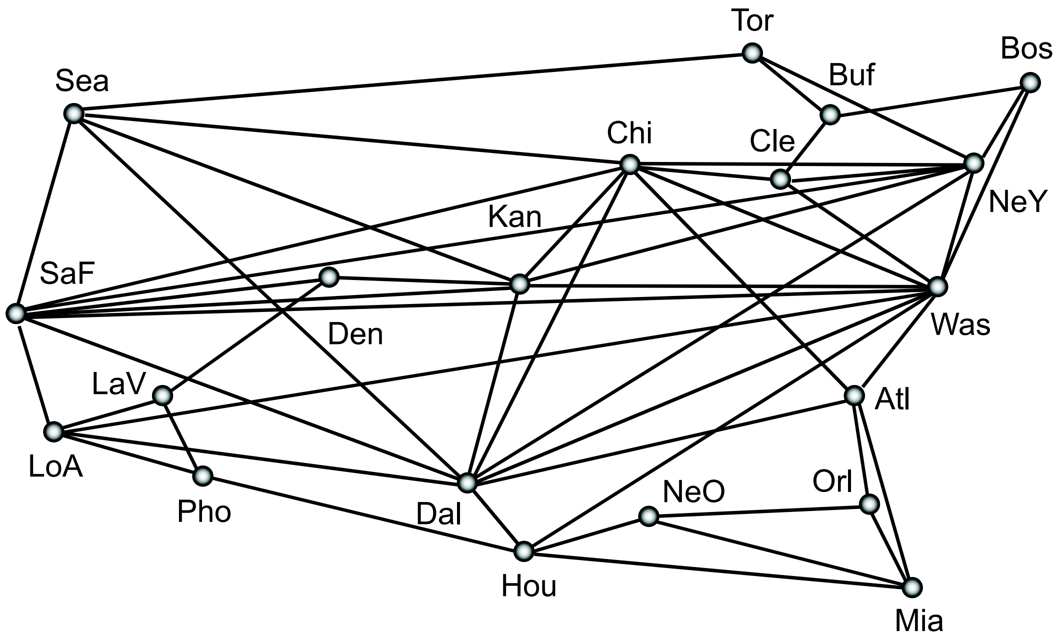

Figure 2: Network topology of the KING testbed

Table 1: City population of the KING testbed

$Name(v)$	$\pi(v)[10^3]$	$Name(v)$	$\pi(v)[10^3]$
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

4.1.2 Time-Variant Traffic Matrices with Maximum Potential for Bandwidth Savings

Time-variant traffic matrices are a prerequisite to effectively apply ABA. Based on the generation of static traffic matrices as described in Equ. 1, we use squared sine and cosine functions with a 24-hour period to model the temporal variability of the traffic taking advantage of the fact that $\forall t \in \mathbb{R} : \sin^2(t) + \cos^2(t) = 1$ holds. ABA can be most effective if busy and idle hours of various aggregates complement each other on any link.

Therefore, we set the offered load according to Eqn. 2. The required parameters are calculated by the algorithm in Fig. 3.

$$a_{v,w}(t) = \begin{cases} a'_{v,w} \cdot \sin^2(t) & \text{if } o_{v,w} = 0 \\ a'_{v,w} \cdot \cos^2(t) & \text{if } o_{v,w} = 1 \end{cases} \tag{2}$$

```
Input:    topology, routing, and static traffic matrix
          A[v, w]_{v,w∈V}

  G_hot := {g_{v,w} : (v, w) ∈ V × V}
  while G_hot ≠ ∅ do
    choose aggregate g*_{v,w} ∈ G_hot with longest path
    d_max := 0
    for all l used by g*_{v,w} do
      d := |S_sin(l) − S_cos(l)|
      if d > d_max then
        if S_cos(l) > S_sin(l) then
          o_tmp := 0
        else
          o_tmp := 1
        end if
        d_max := d
      end if
    end for
    o_{v,w} := o_tmp
    if g*_{v,w} uses only one link then
      a'_{v,w} := d_max
    else
      a'_{v,w} := a_{v,w}
    end if
    for all links l used by g*_{v,w} do
      if o_tmp = 0 then
        S_sin(l) := S_sin(l) + a'_{v,w}
      else
        S_cos(l) := S_cos(l) + a'_{v,w}
      end if
    end for
  end while

Output:   a'_{v,w} and o_{v,w}
```

Figure 3: Time series generation

We assign to any b2b aggregate $g_{v,w}$ an oscillation type $o_{v,w} \in \{sin, cos\}$ and record the sums $S_{sin}(l)$ and $S_{cos}(l)$ of the offered loads on any link $l \in \mathcal{E}$. We therefore choose the offered load $a'_{v,w}$ corresponding to the aggregate $g^*_{v,w}$ with the longest path from the set of undetermined aggregates $\mathcal{G}_{hot}$. Within this path we take the link l with the largest difference $d = |S_{sin}(l) - S_{cos}(l)|$. If the cosine sum $S_{cos}(l)$ is larger than the sine sum $S_{sin}(l)$, we set the oscillation type of the considered aggregate to 'sin' and to 'cos', otherwise. We do this for all aggregates $g_{v,w}$ that are routed over more than one link and set their offered loads $a'_{v,w} = a_{v,w}$. In general, the two sums $S_{sin}(l)$ and $S_{cos}(l)$ cannot be matched exactly when the oscillation types and traffic loads are set as previously described. We therefore set for every link l the oscillation type and the offered load of the aggregate routed directly on l according to the remaining difference $|S_{sin}(l) - S_{cos}(l)|$. Finally, the two sums match exactly with each other.

4.2 Capacity Dimensioning

In this section, we compare the required network capacity for SBA and ABA for BBBs. In both cases, we dimension the capacity of the BBBs for a flow blocking probability of 10^{-3}.

4.2.1 Capacity Dimensioning for SBA

The traffic matrix $A_{max} = [max_t(a_{v,w}(t))]_{v,w\in\mathcal{V}}$ contains the maximum offered load over all times t for all b2b traffic aggregates and these values have to be supported by the BBBs with static capacity. We calculate the sum $\mathcal{C}_{tot}^{SBA}$ of all required link capacities based on the traffic matrix A_{max} with static budget dimensioning as explained in Sec. 2.2.

4.2.2 Capacity Dimensioning for ABA

We reoptimize the network regularly in a 5 minutes period on a 24-hours day cycle, i.e., we dimension the network links based on the time-dependent traffic matrices $A(t = i \cdot 5 \text{ min})$, $0 \leq i < 12 \cdot 24 = 288, i \in \mathbb{N}$ which yields time-dependent link capacities $c_l(t)$. The actually required link capacity $c_l = max_t(c_l(t))$ is the maximum of all link capacities at any time t within a day. Finally, we calculate the sum $\mathcal{C}_{tot}^{ABM}$ of the maximum link capacities c_l.

4.3 Numerical Results

Figure 4 shows the numerical results of our experiments for different values a_{b2b}. The actually required overall network capacity increases with a rising offered load. As expected, more capacity is required for SBA (solid line) than for ABA (slashed line) which can be clearly observed by their fraction (dotted line).

Our experiments were designed such that we could expect bandwidth savings of 50% with ABA compared to SBA. However, the results show that this value strongly depends on the offered load a_{b2b}. The expected savings can be realized only for sufficiently high values $a_{b2b} \geq 10^4$ Erl while for low offered loads like $a_{b2b} = 10$ Erl, only half of the bandwidth savings potential can be exploited. The reason for this behavior is the economy of scale of the BBB capacities and is due to the fact that the required capacity for a given blocking probability can be on average less utilized for low offered load than for high offered load.

With SBA, the capacity of the BBBs is always dimensioned for the maximum offered load of the respective b2b aggregate. Hence, their capacity can be utilized to a relatively large degree. With ABA, the offered load $a_{v,w}(t)$ for the BBBs can become very small. The corresponding capacities are smaller but they are used on average to a minor degree, i.e., the required budget capacities do not scale down with reduced offered load. However, if a_{b2b} is sufficiently high, the tunnel capacities for reduced offered load are still large enough such that a good resource utilization is achieved. This explains the convergence of the required bandwidth ratio $\mathcal{C}_{tot}^{ABM}/\mathcal{C}_{tot}^{SBA}$ to 50% for high offered load.

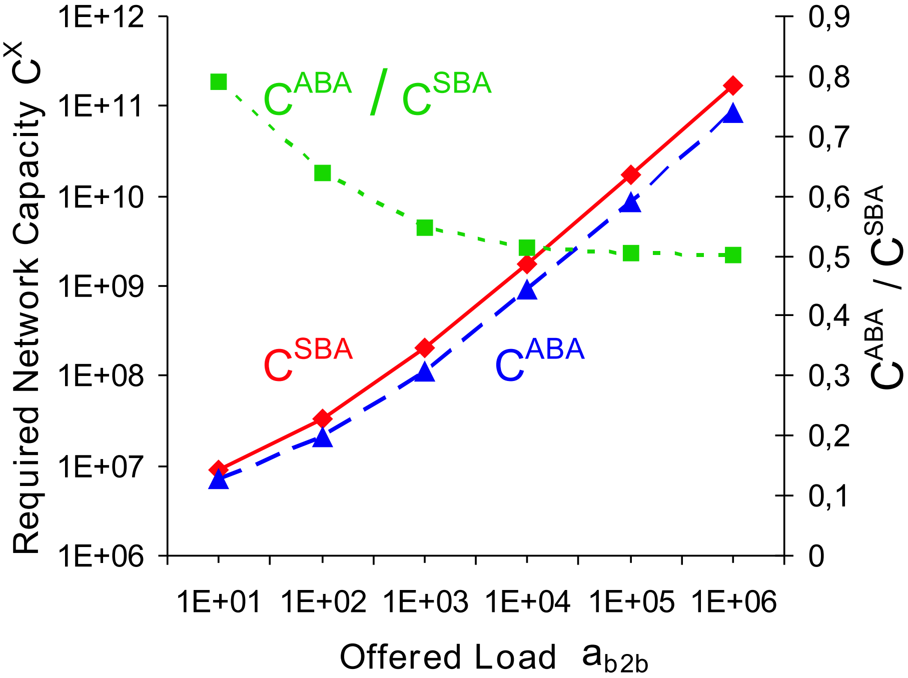

Figure 4: Performance of ABA vs. SBA

Off course, the amount of bandwidth saved with ABA (up to 50% of SBA) is due to the way we constructed our time-variant traffic matrices. In general, the bandwidth savings potential depends on the variability and the distribution of the network traffic over the time of day and it can be exploited best if the offered load in the network is high enough like, e.g., in wide area networks (WANs). Therefore, additional investigations are required (which are currently in progress) to figure out the efficiency of ABA under more reasonable demand distributions.

5 Conclusion

In this paper, we considered adaptive bandwidth allocation (ABA) concepts for capacity tunnels and investigated their efficiency compared to static bandwidth allocation (SBA). We described parts of the KING network architecture whose admission control method is based on virtual capacity tunnels called border-to-border (b2b) budgets (BBBs). We showed how to use SBA for the assignment of network capacity to the BBBs which works fine for static traffic matrices. With time-variant traffic matrices, however, the BBB capacities can be under- or overutilized. ABA is able to avoided this by adapting the BBB capacities according to the current traffic demands. We have presented two basically different approaches: complete capacity reassignment (CCR) and selective capacity reassignment (SCR). CCR adapts all BBBs simultaneously and tunes the network to the optimal point of operation. SCR changes only budgets with significantly deviating blocking probabilities and thereby reduces the reconfiguration overhead.

With ABA, network capacity can be allocated more efficiently in such a way that the same Quality of Service in terms of request blocking is observed by a customer. Blocking probabilities have thus often been the performance measure to evaluate ABA mechanisms from many different point of views. However, we tried to quantify the gain of ABA by determining its bandwidth savings potential, i.e. by calculating and comparing the overall required network capacity with SBA and ABA. For the evaluation, we constructed traffic matrices proportionally to city sizes and made them time-variant such that the overall traffic in the network remained constant and the capacity savings with ABA were maximized. Despite the artificiality of our experiment, we have an important finding. The bandwidth savings potential strongly depends on the b2b offered load which is the average number of simultaneously active flows per b2b aggregate. For low offered load, only half of the theoretical bandwidth savings potential can be realized while it can be fully exploited for high offered load.

We consider this paper as a first introduction to ABA for BBBs. Since this study is based on artificially opportunistic traffic matrices, the capacity savings with ABA are overestimated. Therefore, we currently investigate the effect of more realistic traffic patterns in global wide area networks where complementing busy hours occur according to the different time zones.

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