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Abstract

In this paper, we consider *adaptive bandwidth allocation* (ABA) for capacity tunnels as an effective means for multi-hour network design. Traffic engineering (TE) tunnels established in a network from border-to-border (b2b) can be used not only for route pinning between ingress/egress node pairs but also for efficient implementation of resilient network admission control. If *static bandwidth allocation* (SBA) based on peak-rate traffic assumptions is used to dimension the b2b tunnels, fluctuations of the network traffic can lead to under- or overprovisioning of network capacity in the tunnels. If ABA is used instead, the tunnel sizes are dynamically adapted to current traffic conditions. The efficient use of network capacity assigned to TE tunnels strongly depends on the structure of these tunnels. The contribution of this paper is an assessment of the bandwidth savings that are achievable with ABA in comparison to SBA for various tunnel structures with different path layouts and load balancing strategies. Our results show that the capacity savings due to ABA depend on the routing and load balancing schemes provisioned in the network and that these savings may be increased by appropriately chosen tunnel implementations.

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 control the congestion level in their networks. This can be achieved by means of traffic engineering (TE). Configurable capacity tunnels, also known as TE tunnels, are a popular means for TE within autonomous system (AS) networks of today's Internet because most emerging network technologies support them. In (generalized) multi-protocol label switching

(G)MPLS [1, 2], label switched paths (LSPs) associated with a guaranteed bandwidth are established through a network thereby pinning the traffic to predetermined routes [3]. Capacity tunnels might further be used to implement network admission control (NAC) which is used to limit the traffic transported from border-to-border (b2b) through a network [4]. If the tunneling concept and NAC are combined, the TE tunnels – we then call them border-to-border budgets (BBBs) – become load-controlled. In contrast to a single LSP, a BBB can consist of a load-balanced multi-path between border nodes. Per-flow AC is then performed only at the tunnel ingress routers based on the capacity of the BBBs. We call the corresponding NAC mechanism, the border-to-border budget based NAC (BBB NAC) [4]. In the following, we explain the problem considered in this work, give an overview of related work, and characterize the structure of this paper.

We imagine a network scenario where admission-controlled TE tunnels are established between each ingress/egress router pair. If the capacity of a tunnel does not suffice to accommodate another flow, further flows are blocked to ensure that the QoS of flows already admitted to that tunnel is maintained. With static bandwidth allocation (SBA), the tunnels have fixed sizes, i.e., they do not adapt to traffic fluctuations. Therefore, they must be dimensioned to cope with the busy-hour traffic which can lead to inefficient use of tunnel-bound network capacity at secondary times. This potential inefficiency can be avoided if adaptive bandwidth allocation (ABA) is applied to the tunnels, i.e. if the tunnels sizes are dynamically adapted to current traffic conditions.

The problem of efficient resource utilization is part of the general network design problem [5] which covers, next to bandwidth allocation [6, 7], many more issues such as traffic estimation [8], multi-hour network design [9–11], capacity dimensioning [12], routing [13], and combinations thereof [14, 15]. As a consequence, the network design problem has been studied in the literature from many varying perspectives and in the context of many different underlying network technologies.

The performance gain of ABA compared to SBA can be measured in different ways. Given a traffic model and a specified network topology with predetermined link capacities, the resulting b2b flow blocking probabilities can be calculated. This is the conventional approach which has been studied intensely in the context of call blocking analysis in multi-service ATM networks [12, 16, 17] and multi-layer architectures [18]. In contrast, our method tries to quantify the bandwidth savings that are achievable with ABA compared to SBA. Given a traffic model, a network topology, and a targeted b2b blocking probability, we determine the required capacitities for the TE tunnels and compute the corresponding link capacities and, finally, the resulting entire network capacity. In previous work, we investigated the bandwidth savings potential of ABA applied to simple single path capacity tunnels with regard to an opportunistic traffic model [19] and to different dynamic traffic models [20] which are more realistic for wide area networks. In this paper, we want to investigate the impact of routing and load balancing alternatives for TE tunnel strcutures on the bandwidth savings potential of ABA. To the best of our knowledge this is the first series of papers in the literature trying to quantify the performance gain of ABA compared to SBA by bandwidth savings. From our point of view this evaluation method yields more practical results with regard to a monetary savings 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 TE tunnels, also named BBBs. Section 3 describes possible implementations of ABA in existing networks. In Section 4, the bandwidth savings potential of ABA is investigated for a test network and various capacity tunnel implementations determined by different routing and load balancing options. Finally, Section 6 concludes this work.

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

We briefly review the BBB NAC architecture and explain how network capacity is assigned to the BBBs.

2.1 Network Architecture with BBB NAC

For our investigations, we consider a network architecture as shown in Fig. 1. This architecture uses a tunnel-based admission control scheme called the BBB NAC which, among several fundamentally different network admission control (NAC) approaches [4], has been elaborated in the project KING (Key components for the Internet of the Next Generation) [21,22]. In this project, the BBB NAC has been chosen for implementation in the testbed due to its technical simplicity and resource efficiency.

In a KING network, BBBs $b_{v,w}$ are defined between each two border routers v and w (cf. Fig. 1). BBB NAC entities are located at the network egde. They admit flows from v to w recording their requested rates and reject flows if their requested rates exceed the remaining free capacity of $b_{v,w}$. An advantage of the BBB NAC is that it does not induce states inside the core of the network. This feature is certainly desired with regard to scalability and resilience reasons. The network capacity assigned to $b_{v,w}$ is exclusively dedicated to the corresponding b2b traffic aggregate $g_{v,w}$ and cannot be used for traffic with a 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 $b_{v,w}$. Admitted traffic flows are then distributed over the partial paths of the illustrated virtual capacity tunnel from v to w.

The BBB NAC can be implemented in various forms, e.g. by label switched paths (LSPs) as single path TE tunnels associated with guaranteed bandwidths. Another implementation can be based on an IP network architecture where the traffic is carried on equal cost multi-paths. Basically, the BBB NAC can use any tunnel implementation in terms of path layout and corresponding load balancing. Therefore, we investigate in Section 4 different tunnel implementations and their impact on the bandwidth savings potential of ABA.

2.2 Tunnel Dimensioning with Static Bandwidth Allocation

The BBBs require enough capacity to carry the expected traffic with a sufficiently low flow blocking probability. The required capacity for BBB $b_{v,w}$ is calculated to carry the

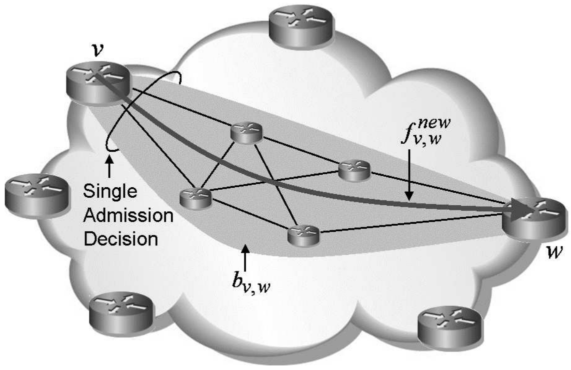


Figure 1: Network architecture with BBB NAC using multi-path capacity tunnels.

expected offered load $a_{v,w}$ with a sufficiently low flow blocking probability. We assume a Poisson model for the flow arrivals and a generally distributed holding time. Traffic flows make rate requests of different sizes which increases the variance in our traffic model. These are appropriate assumptions for a multi-rate real-time multimedia Internet [23,24]. The well-known Kaufman-Roberts algorithm [25] computes the flow blocking probability given the offered load and the link capacity. Our algorithm for tunnel dimensioning [26] inverts this formula in an efficient way such that we can determine the required capacities of all BBBs. The required capacity for a specific link is then calculated by summing up the capacities of all budgets whose aggregates are transported over that link, i.e., here, the routing and load balancing information comes into play.

In practice, the sum of all required link capacities is easier to compare than effective flow blocking probabilities for the b2b aggregates. Therefore, we use our network dimensioning approach to evaluate the performance gain of ABA vs. SBA in Section 4 for differently structured capacity tunnels implementing a certain routing and load balancing scheme.

3 Implementation of Adaptive Bandwidth Allocation (ABA)

We evaluate the performance of ABA within TE tunnels by a network dimensioning approach as described in Sec. 4. However, ABA also has to be implemented for existing networks for which the topology, link capacities, traffic matrix estimates, and information about the deployed routing and load balancing schemes are given. Hence, we first explain the architectural requirements for networks to use ABA for capacity tunnels, then we describe two concepts which implement the ABA concepts.

3.1 Network Requirements

Our goal is a fair assignment of network capacity to the TE tunnels such that each b2b traffic aggregate has almost the same blocking probability. If the loads of the aggregates change, an ABA mechanism has to reassign the network capacity to the tunnels in order to keep the blocking probabilities balanced. To trigger the capacity reassignment, we need a qualified feedback from the network about the current traffic aggregates and their blocking probabilities. Basically, both can be obtained through measurements. However, there are two reasons why we do not measure the blocking probabilities directly. Firstly, 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 in order to avoid them. Therefore, we rather observe the time-variant traffic matrix and calculate the blocking probabilities using the Kaufman-Roberts algorithm. The details on the calculation procedure which is explained in [4] are omitted due to the lack of space. Traffic matrix estimation is known as a difficult problem [8] but, e.g., LDP statistics can provide sufficient support to derive an appropriate estimate of the current traffic matrix [27].

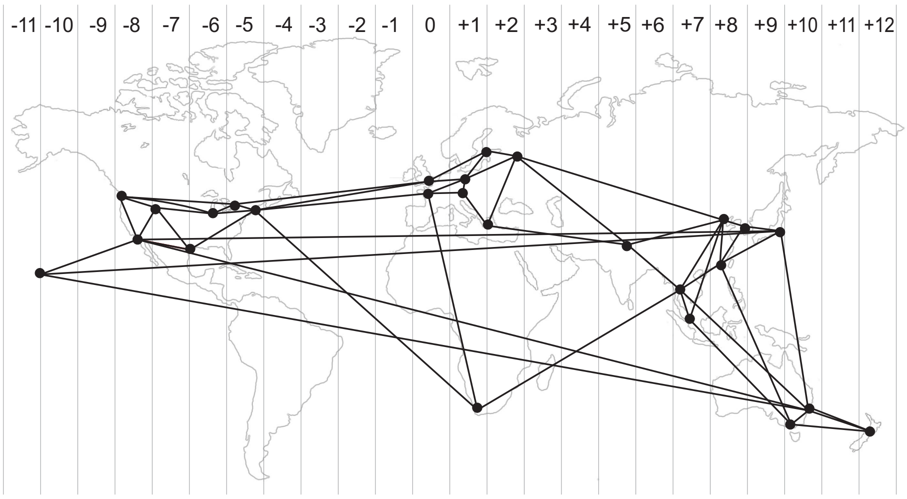
An intelligent entity is required to gather all the network monitoring information and to calculate thereon the necessary tunnel capacities. This entity might also be used to remotely (re-)configure the tunnels in the network. In contrast to a bandwidth broker, the entity might be implemented such that it is not vital to normal network operation. If so, it only optimizes the resource management of the network and the tunnel capacity assignment is performed offline.

3.2 Concepts for Adaptive Bandwidth Allocation

In the following, we suggest two ABA concepts for the assignment of network capacity to the TE tunnels. They both adapt the tunnel capacities to the current traffic demands but differ in their implementation, signaling, and processing complexity. We only describe them briefly since the details and the comparison of the concepts can be found in [19].

3.2.1 Complete Capacity Reassignment (CCR)

If triggered, this method recalculates and reconfigures all tunnels in the network. There are two options to define a trigger. The most intuitive is to iterate the CCR in regular time intervals and thus independent of the current network state. A small iteration interval requires much computation power and causes high signaling and configuration effort. A long interval may lead to large response times in case of traffic changes and to unbalanced blocking probabilities. Both extremes must be avoided. Another option is to explicitly trigger the CCR whenever the blocking probability of one or more tunnels leave a predefined tolerance interval. This interval provides an upper and lower bound for its corresponding blocking probability. CCR is triggered only if the current blocking probabilities of some b2b aggregates change significantly, i.e., if they leave their assigned tolerance intervals. The trigger for CCR can therefore be a capacity under- or overprovisioning in the TE tunnels.



Name	Population	Timezone
Honolulu	378.155	-11
Los Angeles *	3.798.981	-8
Vancouver *	545.671	-8
Denver *	560.415	-7
Chicago *	2.886.251	-6
Houston *	2.009.834	-6
New York *	8.084.316	-5
Toronto *	2.481.494	-5
London *	6.638.109	0
Berlin *	3.388.434	1
Cape Town	2.415.408	1
München *	1.227.958	1
Paris *	2.125.246	1
Athens *	745.514	2
Helsinki *	1.027.305	2
Moscow *	10.101.500	3
New Delhi	12.791.458	4
Bangkok	6.320.174	6
Beijing	13.820.000	7
Hong Kong	6.708.389	7
Singapore	4.017.733	7
Seoul	9.895.972	8
Tokyo	8.134.688	8
Melbourne	3.366.542	9
Sydney	3.997.321	9
Auckland	406.000	11

Figure 2: Topology, time zones, and population of our world-spanning test network.

3.2.2 Selective Capacity Reassignment (SCR)

This concept also requires tolerance intervals for the blocking probabilities of the b2b traffic aggregates. When the network capacity is assigned for the first time, all TE tunnels are dimensioned such that the corresponding blocking probabilities result to planned values, e.g. 10^{-3} for all aggregates. The network capacity not initially assigned to the tunnels is retained in a free resource pool. If some blocking probabilities leave their tolerance intervals, only the capacity of affected tunnels is adapted by acquiring more capacity from the free resource pool or by returning excessive capacity to it. This reduces the overall computation, signaling, and configuration effort. If the free resource pool is depleted, all tunnels are reinitialized.

4 Performance Evaluation of ABA

With SBA, the capacity of each TE tunnel must be dimensioned for its corresponding busy hour aggregate. The benefit of ABA consists of potential bandwidth savings that are due to temporal fluctuations of the traffic demands. In general, a link carries the traffic of various aggregates. If the busy hours of different aggregates occur at different times, less capacity may be required on a link if the TE tunnels adapt to their current demands. The bandwidth savings investigated in [19, 20] are restricted to simple single path tunnels. In the following, we quantify them for different tunnel implementations that use multi-path routings combined with different load balancing options.

4.1 Evaluation Design

We use a network dimensioning approach and compare the overall network capacities required for ABA and SBA. Figure 2 shows our test network. The nodes are located in different time zones and the population of the associated cities and their surroundings are given. For the evaluation of bandwidth savings, we require static and dynamic traffic demand models. Therefore, we first describe the construction of a static demand matrix proportional to the city sizes in Fig. 2. Then we derive dynamic demand matrices by relating the offered load between each ingress/egress node pair according to their time-dependent user activity.

4.1.1 Static Demand Matrices

Based on the average b2b offered load a_{b2b} and the number of border nodes $|\mathcal{V}|$, we define the overall offered network load $a_{tot} = a_{b2b} \cdot |\mathcal{V}| \cdot (|\mathcal{V}| - 1)$. For each pair of ingress/egress nodes v and w, we define a static offered load

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

where $\pi(v)$ is the population of city $v \in \mathcal{V}$. We then declare the loads $a_{v,w}$ as busy hour loads and scale them simultaneously by the setting of a_{b2b}. The resulting static demand matrix $\mathcal{A} = [a_{v,w}]_{v,w \in \mathcal{V}}$ contains the offered loads measured in Erlang between each two TE tunnel endpoints.

4.1.2 Dynamic Demand Matrices

For the construction of dynamic demand matrices, we define for each node $v \in \mathcal{V}$ an activity function that depends on the coordinated universal time (UTC) t and the time zone of v:

$$\text{active}(v,t) = \begin{cases} 0.1 & \text{if } \mathcal{L}(v,t) \in [0{:}00;\, 6{:}00) \\ 1 - 0.9 \cdot \left(\cos\left(\frac{(\mathcal{L}(v,t) - 6h)\pi}{18h}\right)\right)^{10} & \text{else} \end{cases} \tag{2}$$

The function $\mathcal{L}(v,t) = (t + \tau(v) + 24) \bmod 24 \ \forall t \in [0{:}00;\, 24{:}00)$ calculates the local time at node $v \in \mathcal{V}$ at UTC t with $\tau(v)$ being the time zone offset for v. The activity function is illustrated in Fig. 3. The curve shows the percentage of active population of border router v depending on the local time t. Based on the activities at nodes v and w, we now define time-dependent aggregate loads $a_{v,w}(t)$. In [20], we identified three simple demand models to fluctuate these loads over time t. Hence, the offered load for each b2b relationship can be made proportional (1) to the active population at the ingress v, referred to as *linearity to provider activity* (LPA), (2) to the active population at the egress w, referred to as *linearity to consumer activity* (LCA), or (3) to the active population at both, ingress v and egress w, referred to as *linearity to provider and consumer activity* (LPCA). Detailed information about any of these models can be found in [20]. The first two models provide similar demand matrices since they are symmetric approaches. For the sake of simple comparison of the different tunnel implementations, we restrict our presented results to the LPCA model. With LPCA the offered load is proportional to the provider and the consumer activity, i.e.

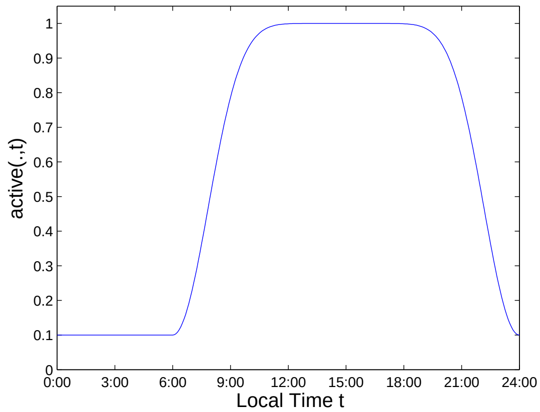


Figure 3: Node activity over 24 hours.

$a_{v,w}(t) = a_{v,w} \cdot active(v, t) \cdot active(w, t)$. The corresponding dynamic demand matrix is $\mathcal{A}(t) = [a_{v,w}(t)]_{v,w \in \mathcal{V}}$. LPCA traffic may be caused, e.g., by peer-to-peer applications where contents are exchanged among peers that are controlled by human beings. The peers may request and offer contents at the same time.

4.2 Tunnel, Link, and Network Capacity Dimensioning

We compare the required network capacity for ABA and SBA. In both cases, we first dimension the TE tunnel capacities with regard to a blocking probability of 10^{-3}, the respective static and dynamic demand matrices, and the routing and load balancing characteristics of the tunnel implementations. Then we assign capacities to the links as required by the previously determined tunnel capacities and, finally, we calculate the overall required network capacities for ABA and SBA.

4.2.1 Capacity Dimensioning for SBA

The demand matrix $\mathcal{A}_{max} = \left[max_{t \in [0:00;\ 24:00)}(a_{v,w}(t))\right]_{v,w \in \mathcal{V}}$ contains for each b2b aggregate its maximum offered load over all times t. Taking the mean flow rate into account, these values have to be supported by the TE tunnels with statically assigned capacity. The capacity c_l of link l is then calculated as the sum of capacities of those tunnels whose aggregates are carried on l. In our former experiments we used single-path routing. With multi-path routing, only the fractions of the aggregates transported on the links must be respected. Finally, we calculate the sum $\mathcal{C}_{tot}^{SBA}$ of the maximum link capacities c_l as the overall required network capacity for SBA.

4.2.2 Capacity Dimensioning for ABA

We reoptimize the network every 5 minutes during a 24 hours day cycle. More precisely, we redimension the TE tunnels based on the dynamic demand matrices $\mathcal{A}(t =$

$i \cdot 5$ min) which yields time-dependent link capacities $c_l(t)$. Hence, the required capacity for the link is the maximum of the required link capacities at any time t, i.e. $c_l = max_{t\in[0{:}00;\ 24{:}00)}(c_l(t))$. Finally, we calculate the sum $\mathcal{C}_{tot}^{ABA}$ of the maximum link capacities c_l as the overall required network capacity for ABA.

5 Numerical Results for Different Tunnel Implementations

The performance measures in our study are the overall required network capacity $\mathcal{C}_X^Y$ and the bandwidth savings $\mathcal{B}_X$ for ABA compared to SBA. We calculate them, given the traffic demand model presented in Sec. 4.1.2, for a blocking probability of 10^{-3} and different capacity tunnel implementations $X \in \{SPF, ECMP, xECMP, kSPMe, kSPMr\}$ and bandwidth allocation methods $Y \in \{SBA, ABA\}$. In the following, we describe the different tunnel implementations investigated in our experiments and give numerical evidence of their bandwidth savings potentials for ABA.

A tunnel is most simply implemented by mapping it on a single path between an ingress and an egress node according to, e.g. the shortest path first (SPF) principle. An ECMP-based tunnel consists of an equal cost multi-path (ECMP) as defined in [28]. xECMP tunnels represent a kind of relaxed ECMP tunnels, i.e., all partial paths no longer than x times the shortest possible path are joined in the xECMP tunnel structure. This tunnel implementation can be deployed by appropriately set link weights and may be reasonable for networks where only few equal cost paths between routers exist. Since parameter x is critical to the packet packet delay experienced in the network, we restrict its values to $x \in [1.0, 2.0]$ and use a hop-count metric. kSPMe and kSPMr tunnels are based on the concept of the self-protecting multi-path (SPM) introduced in [29]. According to parameter k, a kSPM tunnel consists of the k link- and node-disjoint shortest paths [30, 31] between tunnel in- and egress nodes. These k shortest paths might certainly have different lengths. For a kSPMe tunnel, its traffic load is distributed equally among all k partial paths. For a kSPMr tunnel, the traffic load is distributed reciprocally to the partial path lengths, i.e., shorter partial paths carry larger traffic load shares than longer partial paths.

5.1 SPF vs. ECMP Tunnel Implementation

Tables 1 and 2 show the overall required network capacities $\mathcal{C}_X^Y$ and the bandwidth savings $\mathcal{B}_X$ of ABA vs. SBA for SPF and ECMP tunnel implemenations, respectively. The results are calculated for different b2b offered loads a_{b2b}. Both, the required network capacities and the bandwidth savings, increase with increasing offered load. For values $a_{b2b} \leq 10^4$, $\mathcal{C}_X^Y$ scales sub-proportionally with a_{b2b} which is due to the superior economy of scale of larger links. For values $a_{b2b} \geq 10^4$ the achievable multiplexing gain diminishes and $\mathcal{C}_X^Y$ scales almost linearly with a_{b2b}. This holds for SPF as well as for ECMP tunnels. Likewise, the bandwidth savings $\mathcal{B}_X$ first increase over-proportionally with the offered load and then converge slowly to a maximum of about 17.8% for SPF tunnels and 20.1%

Table 1: Network capacity requirements and bandwidth savings for SPF tunnels

a_{b2b}	$\mathcal{B}_{SPF}$	$\mathcal{C}_{SPF}^{SBA}$	$\mathcal{C}_{SPF}^{ABA}$
1E+01	9.69%	1.85E+07	1.67E+07
1E+02	14.47%	6.78E+07	5.80E+07
1E+03	16.82%	4.44E+08	3.69E+08
1E+04	17.54%	3.88E+09	3.20E+09
1E+05	17.73%	3.74E+10	3.08E+10
1E+06	17.79%	3.71E+11	3.05E+11

Table 2: Network capacity requirements and bandwidth savings for ECMP tunnels

a_{b2b}	$\mathcal{B}_{ECMP}$	$\mathcal{C}_{ECMP}^{SBA}$	$\mathcal{C}_{ECMP}^{ABA}$
1E+01	11.00%	1.85E+07	1.64E+07
1E+02	16.39%	6.78E+07	5.67E+07
1E+03	19.00%	4.44E+08	3.60E+08
1E+04	19.77%	3.88E+09	3.12E+09
1E+05	19.97%	3.74E+10	2.99E+10
1E+06	20.03%	3.71E+11	2.96E+11

for ECMP tunnels as ECMP tunnels are slightly more effective in connection with ABA than SPF tunnels. Please note that the values for $\mathcal{C}_{SPF}^{SBA}$ and $\mathcal{C}_{ECMP}^{SBA}$ are identical per definition. In contrast, less overall network capacity is required for ECMP compared to SPF tunnels if ABA is used instead of SBA, i.e. $\forall a_{b2b} : \mathcal{C}_{ECMP}^{ABA} < \mathcal{C}_{SPF}^{ABA}$. If the tunnels are implemented according to ECMP, the network links need on average less capacity than for SPF which is explained by the composition of the traffic carried on these links. For SPF tunnels, we have on average 15 integral aggregates carried on a link, whereas for ECMP tunnels, we have on average 28 partial aggregates. A larger number of flows on a link increases the potential of capacity sharing for aggregates which have their busy hours at different times. This savings potential can only be exploited by ABA and not by SBA.

5.2 xECMP Tunnel Implementation

Figure 4 shows the required network capacities $\mathcal{C}_{xECMP}^{Y}$ and the bandwidth savings $\mathcal{B}_{xECMP}$ achievable with xECMP tunnels for different values of the relaxation parameter x. Here, we set the offered b2b load $a_{b2b} = 10^4$ Erlang. From previous investigations (cf. Sec. 5.1) we know that the multiplexing gain for $a_{b2b} \geq 10^4$ is widely exploited and therefore does not influence the illustrated results. Increasing the parameter x from 1.0 to 1.2 and from 1.8 to 2.0 has no impact on $\mathcal{C}_{xECMP}^{Y}$ and $\mathcal{B}_{xECMP}$ because the structures of the xECMP tunnels do not change for these transitions of x. In contrast, the bandwidth savings and

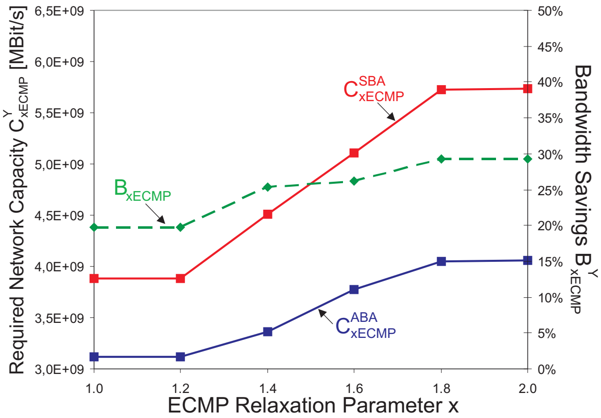


Figure 4: Network capacity requirements and bandwidth savings for xECMP tunnels.

capacity requirements rise continuously for values x between 1.2 to 1.8. The reason for the growing capacity requirements is the increased average path length in the xECMP tunnels. From $x = 1.2$ to $x = 1.8$ the average number of links per xECMP tunnel rises from 4 to 30 and, simultaneously, the average number of aggregate shares per link rises from 28 to 183. Intensifying the load distribution causes that the network capacity requirements for ABA increase on average less with rising x than those for SBA. The increase of $\mathcal{C}^{SBA}_{xECMP}$ is stronger than that of $\mathcal{C}^{ABA}_{xECMP}$ and therefore, $\mathcal{B}_{xECMP}$ enlarges from about 20% for $x \leq 1.2$ to 30% for $x \geq 1.8$.

5.3 kSPM Tunnel Implementation

Figure 5 shows the required network capacities $\mathcal{C}^{Y}_{kSPMe}$ and shows the bandwidth savings $\mathcal{B}_{kSPMe}$ for different numbers of partial paths k per SPM tunnel with equal load distribution. Figure 6 shows the respective results $\mathcal{C}^{Y}_{kSPMr}$ and $\mathcal{B}_{kSPMr}$ for kSPM tunnels with a load distribution reciprocal to the partial path length. All values are again calculated for a b2b offered load $a_{b2b} = 10^4$ Erlang. The network capacities $\mathcal{C}^{Y}_{kSPMe}$ and $\mathcal{C}^{Y}_{kSPMr}$ grow strongly for a maximum of $k \leq 4$ partial paths per SPM tunnel and independently of the load distribution option and the bandwidth allocation method. For $k > 4$, the network capacity requirements grow less. The reason is that only few ingress/egress node pairs exist for which more than 4 link and node disjoint paths can be provided in our test network. Although kSPMr tunnels require less overall network capacity than kSPMe tunnels, i.e. $\forall k : \mathcal{C}^{Y}_{kSPMr} \leq \mathcal{C}^{Y}_{kSPMe}$, the bandwidth savings for both implementations are almost identical and range from about 18% for $k = 1$ to 29% for $k = 6$.

6 Conclusion

In this paper we considered adaptive bandwidth allocation (ABA) for traffic engineering tunnels. We investigated the impact of different tunnel implementations on the band-

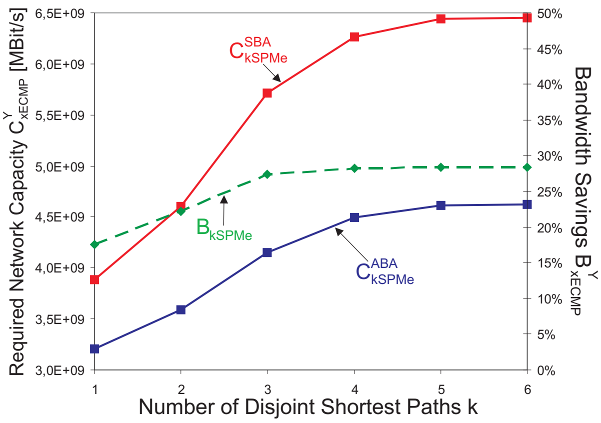


Figure 5: Network capacity requirements and bandwidth savings for kSPMe tunnels.

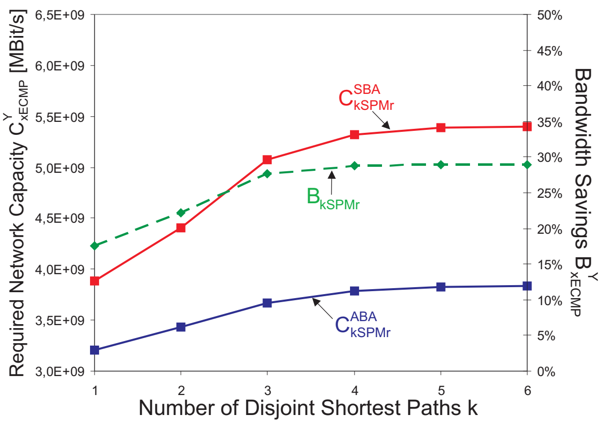


Figure 6: Network capacity requirements and bandwidth savings for kSPMr tunnels.

width savings potential of ABA. Static bandwidth allocation (SBA) assigns the network capacity to the tunnels according to the busy hours of their corresponding traffic aggregates. If the traffic demand is highly variable, this leads to underutilization of some tunnels and increased blocking probabilities at others. Adaptive bandwidth allocation avoids this problem by adapting the capacity assigned to the tunnels according to the current traffic demand.

We quantified the advantage of ABA over SBA by calculating the overall required network capacity for a wide area test network. We constructed traffic demand matrices proportionally to the user activity at the network nodes and considered five different tunnel implementations: single path tunnels according to the shortest path first (SPF) principle, equal cost multi-path (ECMP) tunnels, relaxed ECMP (xECMP) tunnels, and self-protecting multi-path (SPM) tunnels with equal (kSPMe) or reciprocal (kSPMr) load distribution among the k partial paths. Our evaluation results show that the bandwidth savings potential of ABA depends on the tunnel implementation. Hence, about 17.5% capacity savings were achievable with SPF tunnels, 20% with ECMP tunnels, 25.5% for xECMP with $x = 1.4$, and about 28.5% for kSPMe and kSPMr tunnels with $k = 4$.

Our numerical results are of course specific to our test network and the traffic model assumptions. However, these assumptions apply for all investigated tunnel implementations and, therefore, the results advocate multi-path tunnels which are also favoured if we take network resilience aspects into account. The resilience requirements surely influence the bandwidth savings of adaptive bandwidth allocation and give room for future work.

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References

[1] E. Rosen, A. Viswanathan, and R. Callon, "RFC3031: Multiprotocol Label Switching Architecture," January 2001.

[2] E. Mannie, "RFC3945: Generalized Multi-Protocol Label Switching (GMPLS) Architecture," October 2004.

[3] D. O. Awduche, L. Berger, D. Gan, T. Li, V. Srinivasan, and G. Swallow, "RFC3209: RSVP-TE: Extensions to RSVP for LSP Tunnels," Dec. 2001.

[4] M. Menth, *Efficient Admission Control and Routing for Resilient Communication Networks*, Ph.D. thesis, University of Würzburg, July 2004.

[5] J. Moy, *Routing, Flow, and Capacity Design in Communication and Computer Networks*, Morgan Kaufmann Publishers (Elsevier), San Francisco, USA, June 2004.

[6] Peerapon Siripongwutikorn, Sujata Banerjee, and David Tipper, "A Survey of Adaptive Bandwidth Control Algorithms," *IEEE Communications Surveys and Tutorials*, vol. 5, no. 1, June 2003.

[7] H.T. Tran and T. Ziegler, "On Adaptive Bandwidth Provisioning Schemes," in *IEEE International Conference on Communications (ICC 2004)*, Paris, France, June 2004.

[8] A. Medina, N. Taft, K. Salamatian, S. Bhattacharyya, and C. Diot, "Traffic Matrix Estimation: Existing Techniques and New Directions," in *ACM SIGCOMM*, Pittsburgh, USA, August 2002.

[9] O. Heckmann, J. Schmitt, and R. Steinmetz, "Multi-Period Resource Allocation at System Edges," in *10th International Conference on Telecommunication Systems Modelling and Analysis (ICTSM)*, Monterey, USA, October 2002, pp. 1–25.

[10] B. G. Józsa, D. Orincsay, and L. Tamási, "Multi-Hour Design of Dynamically Reconfigurable MPLS networks," in 3^{rd} *IFIP Networking Conference (Networking)*, Athens, Greece, May 2004, vol. 3042 of *LNCS*, pp. 502–513, Springer.

[11] E. Mannie, "Multi-Hour, Multi-Traffic Class Network Design for Virtual Path-based Dynamically Reconfigurable Wide-Area ATM Networks," *IEEE/ACM Transactions on Networking*, vol. 3, no. 6, pp. 809–818, 1995.

[12] T. Bauschert, *Optimale Dimensionierung von ATM-Weitverkehrsnetzen mit mehrstufiger Durchschaltung*, Herbert Utz Verlag, Herausgegeben von Eberspächer, Jörg, München, Deutschland, 1997.

[13] B. Fortz and M. Thorup, "Internet Traffic Engineering by Optimizing OSPF Weights," in *Proceedings of IEEE INFOCOM 2000*, Tel-Aviv, Israel, 2000.

[14] D. Medhi and D. Tipper, "Some Approaches to Solving a Multi-hour Broadband Network Capacity Design Problem with Single-Path Routing," *ToN*, vol. 13, no. 2, pp. 269–291, 2000.

[15] O. Schelen, A. Nilsson, J. Norrgard, and S. Pink, "Performance of QoS Agents for Provisioning Network Resources," in 7^{th} *IWQoS*, London, UK, June 1999.

[16] N. Anerousis and A. A. Lazar, "Virtual Path Control for ATM Networks with Call Level Quality of Service Guarantees," *IEEE/ACM Trans. Netw.*, vol. 6, no. 2, pp. 222–236, 1998.

[17] S. O. Larsson, "Comparisons of different approaches for capacity management in atm networks," in *25th Conference on Local Computer Networks, LCN 2000*, Tampa, Florida, USA, November 2000, pp. 462 – 471.

[18] A. Arvidsson, "Real Time Management of Virtual Paths," in *Global Telecommunications Conference, 1994, GLOBECOM '94*, San Francisco, CA, USA, Dec 1994, pp. 1399 – 1403.

[19] J. Milbrandt, M. Menth, and S. Kopf, "Adaptive Bandwidth Allocation: Concepts and Efficiency for Admission-Controlled Capacity Tunnels," in *3rd International Conference on Computing, Communications and Control Technologies (CCCT '05)*, Austin, Texas, USA, July 2005.

[20] Jens Milbrandt, Michael Menth, and Stefan Kopf, "Adaptive Bandwidth Allocation: Impact of Traffic Demand Models for Wide Area Networks," in *19th International Teletraffic Congress (ITC 19)*, Beijing, China, August 2005.

[21] C. Hoogendoorn, K.J. Schrodi, M.N. Huber, C. Winkler, and J. Charzinski, "Towards Carrier-Grade Next Generation Networks," in *Proc. ICCT 2003*, Beijing, China, April 2003.

[22] J. Moy, "Re-engineering the internet gently," *I&C WORLD, www.siemens.com/icworld*, December 2002.

[23] V. Paxson and S. Floyd, "Wide-Area Traffic: The Failure of Poisson Modeling," *IEEE/ACM Transactions on Networking*, vol. 3, no. 3, pp. 226–244, June 1995.

[24] J. W. Roberts, "Traffic Theory and the Internet," *IEEE Communications Magazine*, vol. 1, no. 3, pp. 94 – 99, January 2001.

[25] J. Roberts, U. Mocci, and J. Virtamo, *Broadband Network Teletraffic - Final Report of Action COST 242*, Springer, Berlin, Heidelberg, 1996.

[26] M. Menth, J. Milbrandt, and S. Kopf, "Capacity assignment for NAC budgets in resilient networks," in *11th Int. Telecommunication Network Strategy and Planning Symposium*, Vienna, Austria, June 2004.

[27] S. Schnitter and M. Horneffer, "Traffic Matrices for MPLS Networks with LDP Traffic Statistics," in *11th International Telecomunications Network Strategy and Planning Symposium, Networks 2004*, Vienna, Austria, June 2004, pp. 231 – 236.

[28] J. Moy, "RFC2328: OSPF Version 2," April 1998.

[29] M. Menth, A. Reifert, and J. Milbrandt, "Self-protecting multipaths - a simple and resource-efficient protection switching mechanism for MPLS networks," in *The* 3^{rd} *IFIP Networking Conference (Networking)*, Athens, Greece, May 2004.

[30] D. Eppstein, "Finding the k Shortest Paths," in *Proc. 35th Symp. Foundations of Computer Science*. November 1994, pp. 154–165, IEEE.

[31] J. W. Suurballe, "Disjoint paths in a network," *Networks*, vol. 4, pp. 125–145, 1974.