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Dimensioning of Multi-Class Over-Provisioned IP Networks

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Abstract. The increasing traffic of data-centric applications has begun to dominate most of today's communication networks. Both network providers and their customers e.g. Internet Service Providers (ISPs) are faced with the issue, how they can effectively plan and adapt their networks and services for the future. In this paper we address the problem of dimensioning of IP/MPLS (Multi-Protocol Label Switching) networks to support differentiated services under per-class over-provisioning constraints with several different routing strategies. We present several (Mixed) Integer Linear Programming formulations for the problem, which can be applied to find optimal solutions for network instances of moderate sizes. For comparison purposes as well as for solving the problem for larger network instances a heuristic approach has been proposed. Several computational results using two sample networks are provided.
Keywords: network dimensioning, network design, IP/MPLS, differentiated services (DiffServ).

1 INTRODUCTION

The role of IP networks has become more and more important as the need for diverse communication services is growing rapidly. Both network providers (carriers) and their customers e.g. Internet Service Providers (ISPs) are confronted with increasing business competition. One of the important aspects is how they can provide better and new inovative services and keep investment and operational costs as low as possible while maximizing revenues and guaranteeing grades of service. From ISPs' point of view this means that they have to provision and adapt their networks efficiently subject to services offered to their customers. In other words, they are continuously faced with some strategic planning problems, that have to be solved each time the existing network infrastructure can not accommodate the new demand and service requirements. In this paper we address the problem of IP/MPLS (Multi-Protocol Label Switching) [7] network dimensioning to support differentiated services (DiffServ) [15] under per-class over-provisioning constraints with several different routing schemes. MPLS and DiffServ have been developed to support quality of service (QoS) in IP networks. In contrast to classical ones, IP networks deploying MPLS and DiffServ have two main benefits: (i) MPLS provides a basic means to better control IP traffic by allowing explicit path routing [3, 16]; and (ii) DiffServ gives the possibility to differentiate treatments for IP packets with respect to their class of service. Furthermore, we consider *Over-Provisioning* (OP) constraints since currently OP is a usual and practical way for ISPs to provide a certain level of QoS in their networks and it seems that it will still be an important aspect in providing QoS for IP networks in the future. OP basically means avoiding overload by ensuring that capacity of all links is greater than demand both in normal or in failure situations [10]. It is also useful for dealing with large variation in traffic demand or with delays required for link capacity upgrade due to current technology limitations. In the context of multi-class IP networks, OP requirements can be deployed both based on per-class or per-aggregate traffic. Here we use the term *aggregate* simply to point to the total traffic regardless of its class of service. In this paper we also focus on per-class OP constraints, since per-class OP is the more general situation and for most cases it is economically cheaper than OP applied to the total traffic [2]. The problem of IP network dimensioning using DiffServ architecture is relatively new and therefore, to the best of our knowledge, there are only a few publications in this area e.g. [11]. In this regard, our main contributions are in the following aspects: (i) we use a simple and practical per-class OP mechanism as a means for providing QoS; (ii) we present several (M)ILP ((Mixed) Integer Linear Programming) formulations for the problem, with several different routing schemes; and (iii) we propose a simple and flexible heuristic approach that can be extended by or combined with metaheuristic-based optimization frameworks. Furthermore, the problem and corresponding solving approach considered in this paper can be applied to both using the classical technology, where the necessary connections are leased from and established by carriers, or using the future technology, where the circuits can be established and released on demand by the ISPs. The first case is represented e.g. by the IP over SDH (Synchronous Digital Hierarchy) architecture, where the ISPs have to decide which and how many STM (Synchronous

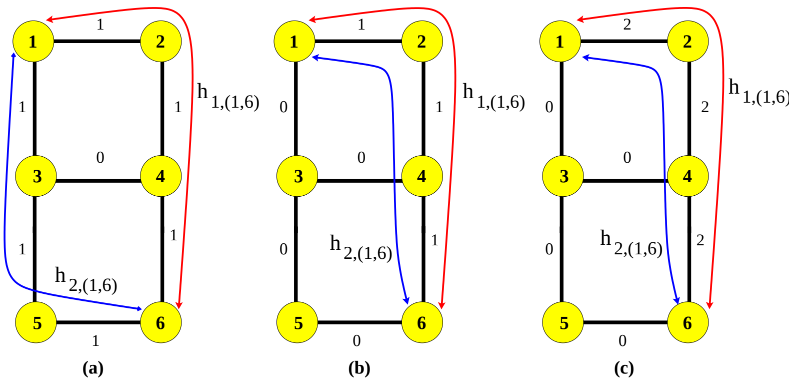

Figure 1. Some illustrations showing the number of transport modules to be installed for different routing strategies and over-provisioning constraints, see text.

Table 1
Some notations used in the formulation

sets:indices	
$\Theta : \theta$	traffic classes
$T : t, s$	types of transport modules
$D : d$	demands (node pairs)
$P_d : p$	candidate paths for flows realizing demand d
$E : e$	links
constants	
δ_{edp}	$= 1$, if link e belongs to path p realizing demand d; $= 0$, otherwise
$h_{\theta d}$	volume of demand d for class θ
c_θ^{OP}	given minimum OP factor for class θ
$c_{\mathrm{aggr}}^{\mathrm{OP}}$	given minimum OP factor for aggregate traffic
$\xi_t(\xi_s)$	cost for a transport module of type $t(s)$
$k_t(k_s)$	capacity of a transport module of type $t(s)$
variables	
$x_{\theta dp}$	flow fraction of demand d of class θ allocated to path p
$u_{\theta dp}$	flow fraction corresponding to $x_{\theta dp}$ (normalized); binary variable for the case single path (SP) routing scheme
x_{dp}	flow fraction of demand d (aggregate) allocated to path p
u_{dp}	flow fraction (normalized) corresponding to x_{dp} for problem P2; flow fraction (normalized) corresponding to $x_{\theta dp}, \forall\theta$ for problem P3; binary variable for the case single path (SP) routing scheme
$y_{et}(y_{es})$	number of transport modules of type $t(s)$ on link e

modules on each link $(1,2)$, $(2,4)$ and $(4,6)$. Now we will formulate the problem using mathematical notations. Given a possible network topology $G = (N, E)$, where N is the set of nodes and E is the set of links, on which transport modules can be installed. Let c_e be defined as total link capacity installed on link e, Θ as the set of all traffic classes, $\lambda_{\min}^{\theta}$ as the *actual* and c_θ^{OP} as the *given* minimum OP factor for traffic class θ, per-class OP constraint can be expressed by:

$$\lambda_{\min}^{\theta} \geq c_\theta^{\mathrm{OP}}, \quad \forall\theta \tag{1}$$

where $\lambda_{\min}^{\theta} = \min_e(c_e^{*\theta}/l_e^{\theta})$, l_e^{θ} is the load on link e contributed by θ, and $c_e^{*\theta} = c_e - \sum_{s=1}^{\theta-1} l_e^s$ the residual link capacity *available* for θ, assuming that the set Θ is ordered from high to low priority traffic (i.e. $\theta = 1$ more important than $\theta = 2 \cdots$). Thus, using so-called link-path notations [13] the problem of network dimensioning using per-class routing scheme under per-class OP constraints (denoted by **P1**) can be written as follows:

objective:

$$\text{minimize} \quad \psi = \sum_e \sum_t \xi_t \cdot y_{et} \tag{2}$$

constraints:

$$\sum_d \sum_p \delta_{edp} \left(c_\theta^{\mathrm{OP}} \cdot x_{\theta dp} + \sum_{i=1}^{\theta-1} x_{idp} \right) \leq \sum_t y_{et} \cdot k_t, \quad \forall\theta, \forall e \tag{3}$$

Greedy Algorithm

```
$\psi \leftarrow 0$;
loop (L1) for each $d$ do
  loop (L2) for each $\theta$ do
    loop (L3) for each $p$ do
      calculate $\Delta\psi(p)$
    end (L3)
    choose the cheapest path $p$
    update the nework if necessary
    establish demand $d$ on path $p$
    $\psi \leftarrow \psi + \Delta\psi(p)$
  end (L2)
end (L1)
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Figure 2. A greedy heuristic for network dimensioning

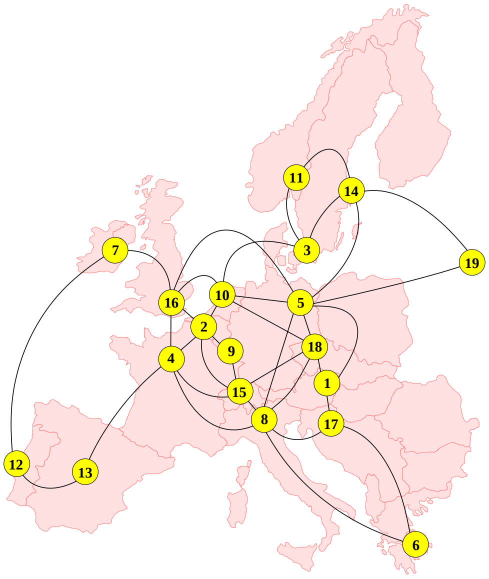

Figure 3. An example network topology (*eu35n19*) used for computational studies

cost ψ to zero. This can be thought of either as a *greenfield* approach i.e. without any existing resources or as a network expansion approach where no cost is charged for using the existing free resources. Then for each demand d in a certain sequence of the elements in D and for each class θ of the corresponding demand d, the algorithm calculates the incremental costs, which are possibly caused by the allocations of demand $h_{\theta d}$ to all considered path candidates. The demand $h_{\theta d}$ is then allocated to (one of) the cheapest path p, the necessary transport modules are installed, the overall cost ψ is updated and the algorithm processes the next θ or d. Using this approach we can transform the dimensioning problems to a *sequential ordering* problem of the demands in D. The incremental cost for establishing a demand $h_{\theta d}$ on a certain path p is the sum of the incremental costs of all links in that path, that is $\Delta\psi(p) = \sum_{e \in p} \Delta\psi(e)$. Before computing the incremental cost $\Delta\psi(e)$, we first define a condition that is required in order to give benefits for using transport modules with higher capacities. Assuming the set T is ordered from low to high capacity i.e. $k_{t=1} < k_{t=2} < \cdots$, a transport module $t+1$ will be used if the cost ξ_{t+1} is lower than the multiplication of the capacity gain k_{t+1}/k_t and the cost ξ_t, that is if the following condition is fulfilled.

$$\frac{k_{t+1}}{k_t} > \frac{\xi_{t+1}}{\xi_t}, \quad \forall t \in \{1, \cdots, |T|-1\} \tag{10}$$

The incremental cost $\Delta\psi(e)$ is computed as follows. Let $\psi_o(e) = \sum_t \xi_t \cdot y_{et}$ be defined as the total cost of transport modules currently installed on link e. Now, if by adding the load $h_{\theta d}$ on e, all capacity and OP requirements are still satisfied, then $\Delta\psi(e) = 0$ and further steps are not necessary. Otherwise a minimal number of transport modules of type $t = 1$ has to be additionally installed on e, such that all OP constraints are fulfilled. Then it has to be checked if it is necessary to replace some transport modules of lower capacity with one or more transport modules of higher capacity in order to reduce costs. Thus, for

Table 3
Results for network *eu35n19*

		CPLEX		greedy	cost saving
		cost	gap(%)	(best cost of 100 runs)	(%)
problem (SP only)	P1	165.5	6.18	190.5	15.11
	P2	166.5	4.19	188.0	12.91
	P3	423.5	3.48	453.5	7.08

network *net6* the heuristic performs well in the sense that it can find the optimal solutions and the differences between the average to the optimal costs in all cases are below the value of 5%. Table 3 shows the results for network *eu35n19*. CPLEX was configured to terminate if either the gap is less than 1% or the computation time of 15 hours is reached. As indicated by the gap values in the CPLEX column, the last termination criterion is always used for all problems. The greedy heuristic was called 100 times for each problem which corresponds to a computation time of less than 2 minutes. The costs of the best solution resulting from the greedy heuristic and cost savings achieved by the ILP approach are shown in the last two columns in the table. The ILP approach can save up to 15% of the cost compared to the best result from the greedy heuristic. However, this happens at the price of significantly longer computing time.

Figure 4(a) shows the cost distribution resulting from the heuristic applied to *eu35n19* for 100 iterations for the case P1 (a-i), P2 (a-ii) and P3 (a-iii). As can be seen in the figures, the solutions for P3 in this case are also much more expensive compared to P1 and P2. Furthermore, it seems that the heuristic performs better if we deploy per-aggregate routing (P2) than per-class routing (P1): the best and mean cost for 4(a-ii) of 188 and 197.29 is better than that of 190.5 and 197.81 for 4(a-i). Figure 4(b) gives the number of transport modules to be installed in the network for the best solution found by the heuristic. The number of transport modules to be installed in P1 and P2 differ only in an additional *type-2* module, which is also indirectly expressed by the cost difference of 2.5. As the capacity requirements grow, e.g. in order to fulfill the aggregate OP constraints in P3 case, transport modules of higher capacity are more beneficial (cf. the cost and capacity parameters in Table 2a). This can be seen by comparing 4(b-iii) to 4(b-ii) and 4(b-i). Finally, Figure 5 displays link utilization and OP factors for all traffic classes for the best solution in P2 case i.e. the configuration with the number of installed transport modules as shown in Figure 4(b-ii). The minimum aggregate OP factor is about 1.7 which corresponds to maximum utilization of about 60%. The values of $\lambda^{\theta}_{\min}$ for each θ are $(5.04; 4.00; 2.92)$ and thus satisfy the requirements of the minimum values c^{OP}_{θ} of $(5.0; 4.0; 2.0)$. The minimum utilization for $\theta = 3$ is about 4%, which happens on link numbered by 22. This explains the high value of the OP factor for $\theta = 3$ in Figure 5(d) for the corresponding link.

5 CONCLUDING REMARKS

In this paper we have considered the dimensioning problem for multi-class IP networks under per-class over-provisioning constraints. We have presented several (M)ILP formulations and proposed a flexible greedy heuristic approach for solving the problem. Our

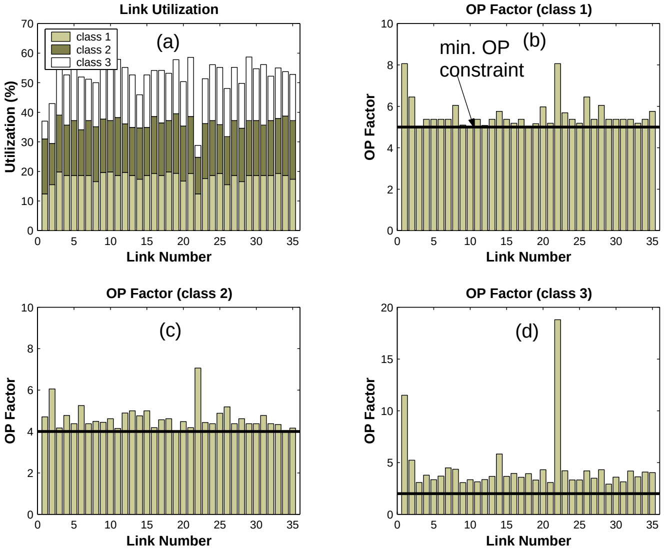

Figure 5. Link utilization and OP factors for all traffic classes for P2 case

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