

Multi-Period Resource Allocation at System Edges – Capacity Management in a Multi-Provider Multi-Service Internet

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Abstract

Providing guaranteed QoS necessarily requires allocation of scarce resources. It is conceivable that at least at system edges scarcity of resources, exposed in the form of non-negligible (virtual) costs, will prevail to necessitate explicit allocation of resources as opposed to pure overdimensioning. An example of this logic is constituted by the Differentiated Services (DiffServ) architecture. Often such resource allocation decisions are done on a multi-period basis because resource allocation decisions at a certain point in time may depend on earlier decisions and thus it can turn out sub-optimal to look at decisions in an isolated fashion. Therefore, in this paper, we investigate a fairly large and diverse set of (network) QoS problems all of which deal with the problem of multi-period resource allocation at system edges. We devise a taxonomy for the classification of these problems and introduce a common mathematical framework under which these problems can be tackled. The ultimate goal of our work is to strive for solution techniques towards the generalized class of problems such that these are applicable in a number of scenarios which have so far not been regarded in an integrated fashion.

1. Introduction

Decentralized organization has always been at the heart of the Internet's philosophy. Actually, this is one of the key explanations for its success in a world of increasing deregulation. The decentralized organization is exhibited by the fact that the Internet consists of multiple independent providers that usually operate so-called autonomous systems which interwork with each other by peering agreements. It is interesting to note that both the number of ASes as well as the average number of ASes a given AS is peering with is increasing at a fairly high rate. The number of ASes rose from 909 in 9/95 to 4427 in 12/98 and 7563 in 10/00 [1,2]. Similarly, the average peering degree, i.e., the number of providers a certain provider has peering agreements with, rose from 2.99 in 9/95 to 4.12 in 12/98. It is also very notable that a single provider may peer with up to 1000 other providers [1].

From these observations it becomes obvious that for the efficient and dynamic provision of QoS in the Internet there is a good potential for optimization of resource allocations at provider edges. In particular, this optimization of resource allocations becomes a competitive factor for Internet providers. However, such an optimization can only be done on a multi-period basis, i.e., by making decisions based on earlier decisions about resource allocations at peering providers. In this paper, we want to deal with a general problem class called multi-period resource allocation at system edges (MPRASE) for which the peering providers have been the motivating scenario, although some other network QoS problems also fit into this problem class as we will discuss later on.

1.1 Motivating Example: Decoupling Different Time Scales of Network QoS Systems

Different time scales of providers' network QoS systems may arise due to different QoS architectures like RSVP/Int-Serv (Resource reSerVation Protocol/ Integrated Services) [3], DiffServ (Differentiated Services) [4], or ATM (Asynchronous transfer Mode) [5] being used. Choosing different QoS architectures results from serving different needs, e.g., for an access and backbone provider. An access provider that has a comparatively moderate load and directly connects to end-systems may favour a fast time scale system responding immediately to the end-systems requests. A backbone provider that connects access providers respectively offers transit services is generally faced with a drastically higher load of individual transmissions, so that reaction on the time scale of individual requests is usually not possible and a slower time scale system needs to be enforced. A realistic configuration for access and backbone providers may be, e.g., that access providers use RSVP/Int-Serv to suit their customers' needs while a backbone provider uses DiffServ with a Bandwidth Broker (DiffServ/BB) to allow for some dynamics but on a slower time scale. This scenario is shown in Figure 1.

Here it is also very obvious why a BB is generally not

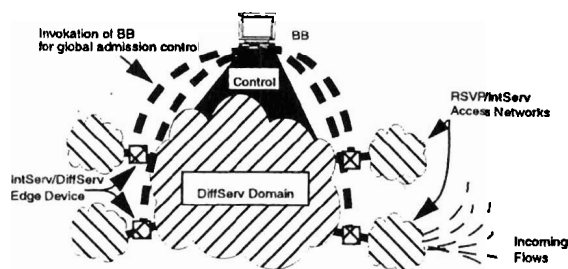


Figure 1: Combined local and global admission control.

able to react to individual RSVP requests that are arriving at edge devices between access and backbone provider. Because if it did, the BB would need to operate at a throughput of requests that is proportional to the square of the number of access providers it serves - that is not scalable. To see this, assume each of N edge devices would have M (new or modified) RESV messages for each other edge device in a given time period and would query the BB for each of these requests. Then the BB would have to deal with $N \times (N - 1) \times M$ requests in the same period. Note that the problem is not solved by spatial aggregation approaches like, e.g., [6] or [7] since for each of the M RESV messages the aggregate would have to be rearranged. Here a decoupling of the different time scales is necessary. The decoupling can be achieved by building "depots" of capacity which stabilize the fluctuations of the "nervous" demand curve for backbone capacity by individual requests. From another perspective, the decoupling technique can also be viewed as introducing a combined local and global admission control for the DiffServ/BB network. Global admission control is only invoked whenever local admission control at an edge device runs out of resources in its capacity depot. In such a case, local admission control on an edge device tries to obtain more resources from the global admission control represented by the BB. This scheme allows to trade off resource efficiency for a more stable and long-term capacity demand presented to the BB.

Note that the slow time scale of an underlying QoS system may not express itself in being unable to process requests for QoS at short time scales but by the fact that significant setup costs are incurred for QoS requests between different administrative domains. Such a scheme of QoS tariffing is an instance where a QoS strategy of a network provider restricts the capabilities of the employed QoS architecture. A possible reason for this may be, e.g., that the charging and accounting system is not able to deal with a large number of individual requests since this involves a lot of operational costs.

In conclusion, we have here a certain instance of the general problem class of multi-period resource allocation at system edges.

1.2 Outline

In the next section, we generalize the above presented example problem and extend it along several dimensions of a conceptual component model by which we try to capture all the different facets of the MPRASE problem structure. We show how the different characteristics of the components and their combinations lead to known network QoS problems. We thus establish the incentive to treat the generalized problem in a framework that has the potential to solve all MPRASE problems in an integrated fashion or at least establish relationships between different problem instances which may be helpful when approaching a certain problem, e.g., by making use of an existing algorithm for a certain problem as part of a solution strategy of another (more complicated) problem instance.

In Section 3, we then look at the most basic problem, the so-called single provider problem (SPP). We devise exact algorithms for its solution as well as some heuristics since it turns out to be fairly compute-intensive. Techniques for the SPP could be the basis for a solution strategy to the example problem described in Section 1.1 and in fact that is what has been proposed and evaluated in [8]. This constitutes an example where a relation between the different problem instances captured by our general model is used. In this paper, however, we try to exploit the SPP along a different dimension: the number of providers. Therefore, in Section 4, we turn to the so-called multi-provider problem (MPP). The MPP constitutes a really hard problem, however by using our techniques for the SPP we are at least able to devise heuristic approaches towards the MPP. To evaluate our techniques we carry out extensive simulations to compare the different alternatives.

In Section 5, we review related work and discuss how our approach differs from respectively extends former work. In Section 6, we summarize our findings and draw some conclusions.

2. MPRASE - Generalization & Taxonomy

In this section, we introduce a general structural model which tries to capture all the different facets of multi-period resource allocation at system edges (MPRASE) problems. This model then allows us to derive a taxonomy along its components which establishes the relations between the different problem incarnations.

2.1 Generalized Problem Structure Model

Figure 2 shows the overall structural model of the general class of MPRASE problems. Obviously, there are customers which generate requests towards several providers. These two groups are separated by a system edge on which an intermediary instance is located. The intermediary tries

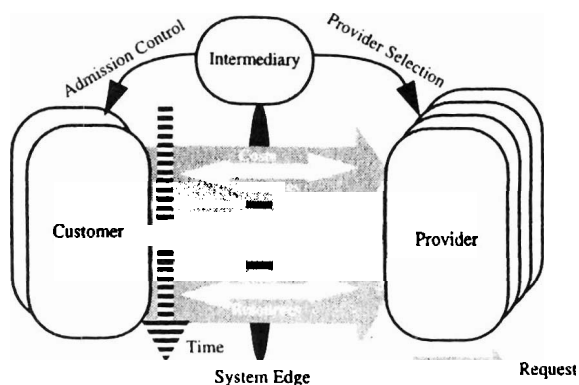


Figure 2: MPRASE problem structure.

to mediate between the two by selecting providers on the one hand and enforcing admission control of the customers on the other hand. Note that the logical separation of the intermediary instance from customer and provider does not necessarily imply that it may not belong to either customer or provider premises. The requests are originated by the customers which desire a certain amount of resources offered by the providers. Furthermore, requests incur certain costs at the providers which need to be accounted for by customers. Several requests are generated in the course of time, thereby, reacting upon the dynamics of customers' demand. Let us now look at the different components of the structural model for MPRASE.

2.1.1 Customer. The customer component of the MPRASE model captures the number of customers, i.e., if a single or multiple customers are considered, and the flexibility of the demand, i.e., whether demand may be dissatisfied or be served with a degraded quality.

2.1.2 Provider. The provider model encompasses the number of providers and whether they are modelled as having limited or unlimited capacity. While the latter is unrealistic it can be a simplifying, yet valid assumption for the case where supply exceeds demand with very high probability.

2.1.3 Resource. This component models the resources, i.e., whether they are one- or multidimensional or whether they are provided on a deterministic or statistical basis. In this paper, we focus on one-dimensional resource models, i.e., on capacity management, in order to keep the problem complexity manageable. However, in [9] we also extend our MPRASE models towards a two-dimensional resource model motivated by the token bucket mechanism. Furthermore, we make no particular assumption on the kind of guarantee with which resources are provided, i.e., whether they are statistically or deterministically available. Therefore, an allocation in our context does not necessarily mean an isolated, exclusive access to resources for a customer

that made it.

2.1.4 Cost. The cost model seizes the cost structure for allocation requests, i.e., whether these incur certain fixed or transactional costs or whether the number of requests is just bounded and how variable costs for resource allocations are modelled, e.g., linearly or non-linearly.

2.1.5 Edge. The edge model encompasses the nature of knowledge about capacity demands at the system edges, i.e., whether deterministic or statistical knowledge about future demands is available or if total uncertainty needs to be assumed. In our work here, we focus on deterministic knowledge at system edges because methods for this case may be used as basic methods for other edge models, as is demonstrated in [8]. Furthermore, the deterministic edge model is not totally unrealistic as it applies to advance reservation scenarios as described in [10, 11] and may play an important role in DiffServ-based scenarios as described in [12].

2.1.6 Intermediary. Note that the intermediary is the component where solution techniques towards MPRASE problems are conceptually located. Therefore, this component does not capture problem characteristics but characteristics of the solution techniques, e.g., whether these are striving for the exact solution or whether they are just heuristics which could again be classified in construction and improvement techniques.

2.2 MPRASE Problem Incarnations

The above dimensions, which are largely orthogonal to each other, span a large space of MPRASE problem incarnations. Some of these - the ones considered in this paper in varying detail - are given in Table 1. The darkly shaded rows of the table represent problems we treat in detail in this paper, whereas the lightly shaded are solely modelled in the next section and the white rows are not investigated here due to space restriction. However, the interested reader is referred to [8, 9] for the latter MPRASE problem incarnations. Nevertheless, the table shows MPRASE problem incarnations where each component is varied at least once (indicated by bold entries). This illustrates our basic goal of treating MPRASE problems in an integrated fashion by making their relations explicit and using that knowledge for solution approaches.

2.3 Mathematical Programming Models for MPRASE

As a common framework for the general MPRASE problem class we make use of mathematical programming (MP) techniques [13]. From our point of view, MP techniques provide a good tool to model this problem class as

Problem	Abbrev.	Cost	Resource	Customer	Provider	Edge
Single provider problem	SPP	linear fixed and variable costs	one-dimensional	single customer	single provider	deterministic
Multi-provider problem	MPP	linear fixed and variable costs	one-dimensional	single customer	multiple providers	deterministic
capacitated MPP	cMPP	linear fixed and variable costs	one-dimensional	single customer	multiple providers with finite capacity	deterministic
Flexible demand problem with admission control	SPP _{AC}	linear fixed and variable costs	one-dimensional	multiple rejectable customers	single provider	deterministic
Flexible demand problem with degraded quality	SPP _{DQ}	linear fixed and variable costs	one-dimensional	single degradable customer	single provider	deterministic
Limited number of allocations problem	SPP _{LAP}	limited number of allocations, linear var. costs	one-dimensional	single customer	single provider	deterministic
Buffered capacity allocation Problem	SPP _{BCP}	linear fixed and variable costs	Token Bucket	single customer	single provider	deterministic
Uncertain SPP	SPP _{UE}	linear fixed and variable costs	one-dimensional	single customer	single provider	uncertain

Table 1: MPRASE problem incarnations.

well as they allow for a common set of standard solution techniques for the different problem incarnations. In the following MP formulations of MPRASE problem incarnations we try to illustrate this point.

2.3.1 The Single Provider Problem (SPP). Let us first look at the single provider allocation problem (SPP). The customer has capacity demands b_t that must be fully satisfied at every discrete time interval $t = 1, \dots, T$. As the edge model is deterministic, the demand is known in advance for all periods. Capacity is requested from a single provider who is charging a fixed costs f_t for every allocation and variable allocation costs c_t per reserved capacity unit and period. A new allocation is constituted by a change in the allocated capacity. Using two types of variables and a number of parameters, this problem can be formulated as model M1.

The objective function (1) minimizes total costs. (2) ensures that demand is fully satisfied in each period. (3) and (4) force z_t to one whenever x_t and x_{t-1} differ, i.e., a new resource allocation takes place. Note that z_t will be set to 0 in all other cases automatically because of the non-negative entry f_t in the objective function.

2.3.2 Multi-Provider Allocation Problems. In this section, we present the multi-provider allocation problem in an uncapacitated and a capacitated version of it. Let us assume that there is more than one provider offering capacity to the customer. We assign index $j = 1, \dots, J$ to the different providers. Based on M1 we can model this problem with M2.

This model mainly differs from M1 in the additional index j . Furthermore, we now have to model the case that in a certain period no capacity is allocated at a certain provider. This is captured by the introduction of demand

M1 Single Provider Problem - SPP

Variables:

x_t Amount of reserved capacity in period $t = 1, \dots, T$.

z_t Binary variable, 1 if a allocation is made at beginning of period $t = 1, \dots, T$ and 0 otherwise.

Parameters:

b_t Demanded capacity in period $t = 1, \dots, T$. Demand is assumed to be greater than 0.

f_t Fixed allocation costs, costs per allocation. We assume positive costs ($f_t > 0$).

c_t Variable allocation costs, costs per reserved capacity unit per period.

x_0 Allocation level before the beginning of the first period.

M M is a sufficiently high number (e.g., $\max\{b_t\}$).

$$\text{Minimize } \sum_{t=1}^T f_t z_t + \sum_{t=1}^T p c_t x_t \quad (1)$$

subject to

$$x_t \geq b_t \quad \forall t = 1, \dots, T \quad (2)$$

$$x_t - x_{t-1} \leq M \cdot z_t \quad \forall t = 1, \dots, T \quad (3)$$

$$x_{t-1} - x_t \leq M \cdot z_t \quad \forall t = 1, \dots, T \quad (4)$$

$$z_t \in \{0, 1\} \quad \forall t = 1, \dots, T \quad (5)$$

defect variables, d_{jt} , and the constraints (10) and (11). Here, ε needs to be chosen small, e.g., $\varepsilon = 1/(\max\{b_t\})$, whereas M and L need to be chosen large, e.g., $M = \max\{b_t\}$ and $L = 1/(\min\{b_t | b_t > 0\})$.

In the next step we use additional parameters, k_{jt} , to model by (15) that each provider j can offer only a limited amount of resources k_{jt} in period t . This leads to model M3, the capacitated MPP (cMPP).

2.3.3 Single Provider Problems with Flexible Demand.

Above, we have assumed that the provider(s) had to sat-

M2 Multi-Provider Allocation Problem - MPP

Variables:

x_{jt} Amount of allocated capacity in interval t from provider j .
 z_{jt} 1 if an allocation for provider j is made at the beginning of period t and 0 otherwise.

d_{jt} 1 if allocation for provider j drops to 0 in interval t and 0 otherwise.

Parameters:

b_t Demanded capacity in interval $t = 1, \dots, T$. Demand must be fully satisfied in each period.

f_{jt} Fixed allocation costs, i.e., cost for an allocation in period t from provider j , we assume $f_{jt} > 0$.

c_{jt} Variable costs, i.e., costs per capacity unit per period (specific per provider and period).

x_{j0} Allocation level before the beginning of the first planning period.

$$\text{Minimize } \sum_{j=1}^J \sum_{t=1}^T f_{jt}(z_{jt} - d_{jt}) + \sum_{j=1}^J \sum_{t=1}^T c_{jt} x_{jt} \quad (6)$$

subject to

$$\sum_{j=1}^J x_{jt} \geq b_t \quad \forall t = 1, \dots, T \quad (7)$$

$$x_{jt} - x_{j(t-1)} \leq M \cdot z_{jt} \quad \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (8)$$

$$x_{j(t-1)} - x_{jt} \leq M \cdot z_{jt} \quad \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (9)$$

$$d_{jt} + \epsilon x_{jt} \leq 1 \quad \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (10)$$

$$L(x_{jt} + x_{j(t-1)}) \geq d_{jt} \quad \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (11)$$

$$d_{jt} \in \{0, 1\} \quad \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (12)$$

$$z_{jt} \in \{0, 1\} \quad \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (13)$$

$$x_{jt} \geq 0 \quad \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (14)$$

M3 Capacitated Multi-Provider Allocation Problem - cMPP

Minimize (6)

subject to (7)-(14) and

$$x_{jt} \leq k_{jt} \quad \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (15)$$

isfy customers' demand at all times. Now we describe a related SPP formulation where this is not the case, i.e., we have a different customer model. The demand can be dissatisfied (leading to degraded quality for the customer), yet for dissatisfying demand the intermediary has to take penalty costs into account. Those can be either real costs or opportunity costs because he risks to loose customers. This model as well as other models with flexible demand are discussed in [9].

3. Tackling the Single Provider Problem

After the presentation of the general MPRASE framework, we now want to investigate different solution techniques for the simplest possible problem incarnation: the

M4 Single Provider Problem with Degraded Quality - SPP_{DQ}

Variables:

s_t Unsatisfied demand in period t .

Parameters:

c_t^s Penalty costs per unit of dissatisfied demand in period t .

$$\text{Minimize } \sum_{t=1}^T f_t z_t + \sum_{t=1}^T c_t x_t + \sum_{t=1}^T c_t^s s_t \quad (16)$$

subject to (4), (5) and

$$x_t + s_t \geq b_t \quad \forall t = 1, \dots, T \quad (17)$$

uncapacitated single provider problem at a deterministic edge. From simulative experiments as well as theoretical observations it turns out that even this problem is not absolutely trivial although we are able to devise reasonably efficient exact solutions as well as computationally inexpensive, yet qualitatively satisfying heuristic techniques. Besides the value of having a solution for the SPP, these techniques are also the base components for devising techniques for more advanced problems. This will be demonstrated in Section 4 where we tackle the MPP by reusing solution techniques for the SPP.

3.1 Exact Algorithms

At first we want to look at techniques that guarantee to produce an optimal solution for the SPP.

3.1.1 Branch and Bound with Linear Programming

(LP) Relaxation. A standard approach to solve the single provider problem SPP is to use a mixed integer problem solver in order to solve model M1. A typical algorithm for solving a mixed integer LP model is a branch and bound algorithm that uses the LP relaxed problem M1' of M1:

M1' LP Relaxation of M1 (SPP)

The binary condition (5) is dropped from M1 and replaced by

$$0 \leq z_t \leq 1 \quad \forall t = 1, \dots, T \quad (18)$$

The resulting problem can be easily solved with the simplex algorithm. The solution of M1' is a lower bound to the optimal solution of M1. Branching can be done by fixing the highest not yet fixed z_t to 1 in the first and to 0 in the second subproblem.

An example problem with only 50 periods took already 33 minutes to be solved¹. Problems with more than 100 periods could not be solved within several days. The reason for this is that the structure of the problem does not make it very amenable to branch and bound algorithms since z_t are often set to very low values greater 0 resulting in a vast underestimation of fixed costs which leads to very loose bounds. Therefore, we strived for more efficient, yet still

¹ All experiments have been performed on a 400 MHz Pentium II processor.

exact algorithms for the SPP.

3.1.2 Dynamic Programming (DP).

Let (t_1, t_2) be the edge from vertex t_1 to vertex t_2 . The costs (or length) of edge (t_1, t_2) are defined as

$$C(t_1, t_2) = f_{t_1} + \sum_{\tau=t_1}^{t_2} c_{\tau} \cdot \max(b_i | i \in \{t_1, \dots, t_2\}).$$

With this, the problem can be solved efficiently with a dynamic programming algorithm which has a complexity of $O(T^2)$ (see Figure 3).

Preparation:
Prepare an empty array *cMin* and an empty array *pred*, each with *T* entries.

Start:
 $cMin(1) = C(t_1, t_1)$
 $pred(1) = 1$

Iteration $t = 2, \dots, T$:
 $cMin(t) = \min\{C(i, t) + cMin(i-1) | i = 1, \dots, t\}$
 $pred(t) = \operatorname{argmin}\{C(i, t) + cMin(i-1) | i = 1, \dots, t\}$

Result:
 $cMin(T+1)$ contains the minimal costs while array *pred* stores the hops towards that solution.

Figure 3: Dynamic programming algorithm for SPP.

3.1.3 Assessment of Execution Times. Table 2 shows the execution times for all of the exact algorithms for two differently sized problem instances.

Algorithm	B&B	DP
$T=50$	1920.7	0.0026
$T=1000$	n.a.	9.0

Table 2: Execution times for exact SPP algorithms (in sec).

3.2 Heuristics

While the last section introduced exact solutions for the SPP, which while they provided fairly good performance still required a certain computational effort that might be prohibitive in scenarios where there is either a large number of periods to be planned for or where there is only an extremely limited amount of time available for computation as, e.g., if the resource allocation is done in response to signalling messages and thus affects setup latencies. Therefore, we now want to investigate heuristic techniques which do not guarantee an optimal solution but allow very fast allocation decisions. A further reason for investigating heuristics becomes obvious when we extend the SPP techniques towards the MPP in Section 4 where we then need to solve a potentially large number of SPPs.

3.2.1 LP Heuristic (LH). The LP heuristic is solving the LP relaxation M1' of Section 3.1.1 to determine the amount of allocated capacity. After solving M1' (using the

simplex algorithm), any $z_i \neq 0$ is set to 1 wherever necessary (that is, where x_i and $x_{i,j}$ differ). This leads to a relative high number of allocations since fixed costs are systematically underestimated by allowing continuous z_i .

3.2.2 Merge Heuristic (MH).

The merge heuristic starts with a separate allocation for each period and then tries to merge two successive allocations into one if the saved fixed costs of the allocation are

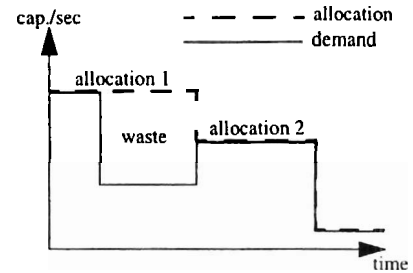


Figure 4: Waste of variable costs.

less than the waste of variable costs (see Figure 4 for an illustration of this).

3.2.3 Split Heuristic (SH). The split heuristic starts with a single allocation and then tries for all periods to split existing allocations if the fixed costs for the new allocation are less than the saved waste of variable costs.

3.2.4 Combined Heuristics (CH[x,y]). The merge and split heuristics can also be used to further improve the results of other heuristics. In our simulations we therefore iterated through merge and split in sequence until no further improvement could be achieved (CH[MH, SH]). Moreover, we also tried the combination of merge and split based on the result of the LP heuristic (CH[LP,MH,SH]).

3.3 Simulations for Qualitative Assessment of the Heuristics

In order to evaluate the performance of the heuristics we ran a simulation over 100 random problem instances, each with $T=1000$, fixed costs $f_i \in [200,800]$ drawn from a uniform random distribution once and then set equal for all *T* periods. Variable costs c_i are drawn from $[3,5]$ and remain equal for *p* periods; *p* is drawn from $[10,20]$.

The demand is calculated by superposing a number of requests (for example representing individual requests from several users) with their interarrival time modelled by a poisson distribution ($\lambda = 4$) and their duration

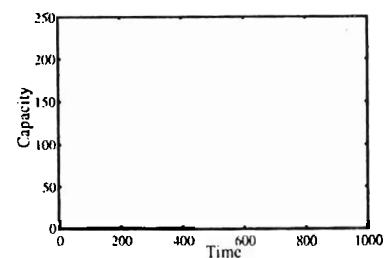


Figure 5: Sample capacity demand

($\lambda = 4$) and their duration

Algorithm	Costs	Relative deviation from optimum costs				Allocation length	Waste	Time (sec)
	<i>av</i>	<i>av</i>	<i>stddev</i>	<i>min</i>	<i>max</i>	<i>av</i>	<i>av</i>	<i>av</i>
Optimum (DP)	452304	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	9.43	36515	9.000
PH	1010199	123.81%	32.96%	58.97%	221.73%	1000.00	645804	< 0.001
MH	474027	4.79%	1.07%	2.05%	7.15%	10.65	64257	0.002
SH	568759	25.93%	10.43%	12.96%	73.65%	3.72	63295	0.010
LP	554317	22.34%	8.37%	6.12%	39.07%	2.62	424	0.452
CH[MH, SH]	469723	3.85%	0.74%	1.80%	5.34%	9.81	56064	0.005
CH[LP, MH, SH]	460404	1.77%	0.70%	0.39%	3.75%	8.93	41918	0.452

Table 3: SPP simulation results.

modelled by an exponential distribution ($\mu = 20$)². For calculating the requests' capacity demand we draw from a uniform random distribution from one out of three possible intervals [2,8], [10,20] and [35,50] representing small, medium and high capacity requests. The interval itself is selected for each request with a probability of 40%, 30% and 30%. Figure 5 shows a sample problem generated in this way.

Table 3 shows the results generated by the simulations. Here, allocation length denotes the average duration of a allocation and waste is the total waste of variable costs for a single SPP instance (as illustrated in Figure 4).

As a very simple alternative heuristic and to have a reference value we also used what we called the peak heuristic (PH) which makes a single allocation with the highest capacity demand over all periods. Expectedly, PH performed very poorly compared to the other techniques. A much better performance at very low execution time is achieved by the merge heuristic (MH): on average it imposes less than 5% additional costs relative to the optimum and reduces execution time by a factor of 4500. The conceptually very similar split heuristic (SH) is considerably less effective. Looking at the allocation length shows the reason: it overdoes its job by splitting too often, resulting in too short allocation lengths and thus incurring fixed costs more often although waste of variable costs is roughly equal to MH.

The LP heuristic performs only marginally better than SH, although it consumes considerably more time. This is due to its characteristic of underestimating fixed costs which is also expressed in a very low waste and small allocation lengths.

Next, let us see how these results may be improved by the combination of heuristics as described in Section 3.2.4. The combination of MH and SH leads expectedly to better results than the techniques in isolation. Yet, even better

results can be achieved by integrating LP with MH and SH.

In conclusion, the best results are achieved by CH[LP,MH,SH], yet the most attractive trade-off between cost performance and execution time is probably achieved by MH or CH[MH,SH].

4. Extension to the Multi-Provider Problem

After the rather extensive treatment of the SPP, we now want to extend our investigations along the provider model by assuming more than one provider, i.e., we move to the MPP. Note that the MPP can also model a single provider that offers multiple tariffs among which can be chosen, e.g., tariffs comprising different fixed and variable costs which do not dominate each other. In line with our argument for taking an integrated view on MPRASE problems we approach the MPP by trying to take advantage from the techniques developed for the

In Section 2.3.2, we have modelled two different versions of the MPP, an uncapacitated and a capacitated one. Here, we want to take a look at both of them. The uncapacitated MPP represents a situation where a customer's demand is relatively small compared to the provider's supply such that the resulting problem consists mainly in the selection of the cheapest provider. The capacitated MPP (cMPP), on the other hand, rather deals with a good mixing of providers to achieve low total costs.

Note that the problem complexity of MPP is much higher than that of SPP. First, the demand of each period can be satisfied by 2^{J-1} different combinations of providers and second, if two or more providers are selected to satisfy the demand of one period there is a high number of sensible shares between these. This higher complexity is also illustrated by the execution times of applying the standard branch and bound solver to model M2. A small MPP with $T=20$ and $J=4$ already took 1920.8 seconds to solve while the corresponding SPP with $T=20$ only took 1.2 seconds. For any larger MPPs execution times were no longer reasonable. With this complexity in mind we go directly for heuristics and try to use our knowledge about the SPP.

² We have to admit that parameter choice is rather arbitrary (albeit sensible) due to lack of empirical data. However, we have experimented with other values without changing the results in a significant manner.

4.1 SPP-Based Heuristics for the Uncapacitated MPP

4.1.1 Static Cheapest Provider Heuristic (SCPH). A straightforward approach to tackle the uncapacitated MPP is to transform it into J SPPs, one for each provider and each with the full demand. The SPPs can then be solved by any of the algorithms discussed in Section 3. After solving the J SPPs we select the provider of the SPP with the least costs. That means we obtain a solution where one provider is used for all periods.

In our simulations, we use DP to solve the SPPs because it yields the optimal results for the SPP at affordable execution time. Alternatively, we use the peak heuristic to see how non-optimal solutions for the SPP will affect the result for the MPP.

4.1.2 Dynamic Cheapest Provider Heuristic (DCPH).

One drawback of SCPH is that it does not allow provider changes. Using a technique similar to the dynamic programming algorithm from Section 3.1.2 we can eliminate this characteristic of the SCPH. The resulting algorithm is called dynamic cheapest provider heuristic (DCPH). This is also illustrated in Figure 6.

We use the same algorithm as in Section 3.1.2, but the minimal costs $C(t_1, t_2)$ for satisfying the demand between two periods t_1 and t_2 are obtained by solving J independent SPPs for the interval $[t_1, t_2]$ and choosing the cheapest provider. Unlike the DP algorithm from

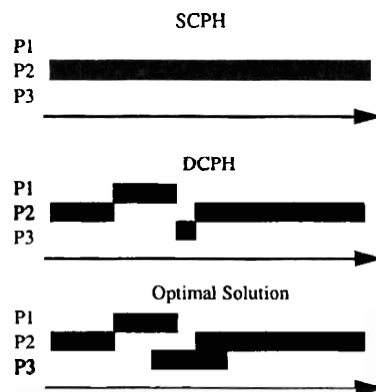


Figure 6: Provider usage of the different algorithms for the MPP.

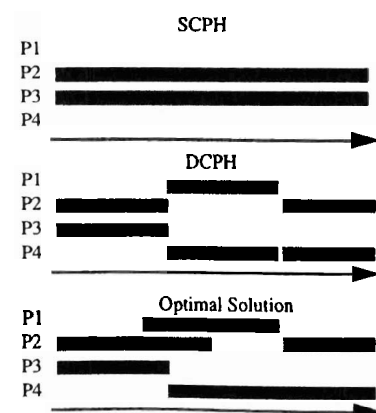


Figure 7: Provider usage of the different algorithms for the cMPP.

Section 3.1.2, this algorithm does not necessarily lead to the optimal result as it does not allow for a constellation as depicted for the optimal solution in Figure 6. Again, we have the freedom of selecting any of the SPP algorithms for solving the sub-SPPs. In our simulations, we choose again DP and PH.

4.2 Adaptation of the Heuristics for the Capacitated MPP

If the capacity of one provider is not enough to satisfy the whole demand we can no longer simply select a single provider in SCPH and DCPH but have to combine several providers. We do this by first cropping the demands in each SPP to the capacity of the according provider. We then solve the SPPs for all J providers and select the provider that has the minimum costs per satisfied demand. The overall demand is then reduced by the capacity served by the selected provider and the procedure is repeated until no more demand remains unsatisfied. Example allocations are shown in Figure 7.

Please note that the non-zero demand assumption in section 2.3.1 can now no longer be held and model M1 as well as the heuristics of Section 3.2 had to be adapted to cope with periods of no demand.

4.3 Other Heuristics for the MPP

4.3.1 LP Heuristic (LP). Of course, we can again use the results of the LP relaxation for M2 and M3 to obtain a solution for MPP/cMPP.

4.3.2 Merge Heuristic (MH). We adapted the merge heuristic to the multi-provider case and to the capacity constraints and combined it with DCPH and LP in order to investigate whether it can improve their solutions.

4.4 Simulations for Qualitative Assessment of the Heuristics

In order to evaluate the MPP heuristics described above we ran a simulation over 50 MPP instances similar to the simulations in Section 3. Because of the much higher computational complexity we reduced the number of periods T from 1000 to 100. We used 10 providers and three different levels of capacity: first the uncapacitated MPP, second a cMPP with the capacity of each provider drawn from [30%, 50%] of the maximum demand over all periods, and third a cMPP with provider capacity drawn from [15%, 35%].

Algorithm	Costs	Alloc. Len.	Waste	Total Num. of Prov.	Av. Num. of Prov.
SCPH (PH)	59563	100.00	350954	1.00	1.00
SCPH (DP)	36428	8.23	31271	1.00	1.00
DCPH (PH)	31999	7.62	29751	5.10	1.00
DCPH (DP)	31999	7.62	29751	5.10	1.00
CH[DCPH (PH), MH]	31999	7.62	29751	5.10	1.00
LP	39165	2.52	35	3.28	1.27
CH[LP, MH]	35246	5.55	27269	3.28	1.27

Table 4: Results for the uncapacitated MPP.

The results for the uncapacitated MPP simulations are displayed in Table 4. Here, the total number of providers denotes how many of the providers were selected at least once by a heuristic whereas average number of providers expresses how many providers were on average simultaneously active.

Algorithm	Costs	Alloc. Length	Waste	Total Num. of Prov.	Av. Num. of Prov.
SCPH (PH)	65548	32.17	320415	3.14	3.14
SCPH (DP)	38890	7.64	31421	3.04	1.90
DCPH (PH)	38048	5.63	45981	6.68	1.88
DCPH (DP)	35650	6.72	29182	5.52	1.79
CH[DCPH (PH), MH]	36990	7.21	49292	6.64	1.88
LP	44334	2.21	10	4.96	2.05
CH[LP, MH]	38910	5.04	27344	4.96	2.05

Table 5: Results for the capacitated MPP (high capacity providers).

Algorithm	Costs	Alloc. Length	Waste	Total Num. of Prov.	Av. Num. of Prov.
SCPH (PH)	62219	19.60	348896	5.18	5.18
SCPH (DP)	37084	7.42	34826	4.68	2.77
DCPH (PH)	39105	5.22	58985	7.08	2.75
DCPH (DP)	34976	6.52	29759	6.26	2.58
CH[DCPH (PH), MH]	37165	7.61	63301	7.00	2.75
LP	45167	2.04	78	5.72	2.75
CH[LP, MH]	37860	5.25	32848	5.72	2.75

Table 6: Results for the capacitated MPP (low capacity providers).

DCPH is obviously and expectedly significantly better than SCPH, however all DCPH-based heuristics perform

identically, although the SPP heuristics are very different. Even if using the simple PH as SPP solver the results are very good (in contrast to SCPH(PH)). The explanation for this behaviour is that the use of the dynamic programming paradigm as provider selection strategy makes the use of dynamic programming as SPP strategy unnecessary.³ Note that MH is ineffective for DCPH because within its range (i.e., only one provider at a time) the solution is already optimal. The LP heuristic shows the same behaviour as in the SPP case and can again be further improved by MH.

In Table 5 and 6 the results for the cMPP with high respectively low capacity providers are given. Now DCPH with DP is significantly better than with PH. Since more providers are involved at the same time there is now

Algorithm	Execution Time (sec)
SCPH (PH)	0.010
SCPH (DP)	0.397
DCPH (PH)	0.689
DCPH (DP)	243.073
CH[DCPH (PH), MH]	0.689
LP	2.323
CH[LP, MH]	2.323

Table 7: Execution times.

potential for more intelligent SPP strategies such as DP. Not surprisingly, the number of providers in the low capacity provider case is higher.

To make recommendations for the MPP heuristics we also have to take into account the execution times of the different alternatives as given in Table 7. While DCPH(DP) exhibits the best cost performance it needs considerably more time than the other heuristics. If execution time plays a crucial role then SCPH(DP) is a good choice.

5. Related Work

It is difficult to find directly related work since our MPRASE approach is very general and other work mainly treated individual MPRASE problem incarnations in isolation. Yet, interestingly, work done in the field of renegotiable services, e.g. [15,16], arrives at very similar algorithms to calculate renegotiation schedules for stored video transmissions which further emphasizes the general structure of the MPRASE framework for problems found in the domain of providing network QoS. However, the emphasis of [15,16] is on the definition of renegotiable services and not so much on algorithms and their evaluation whereas this is the main focus of our paper.

Relating to the analysis of dynamic provisioning in a multi-provider environment (in particular a DiffServ environment), the work described in [17] gives very interesting insights into the global behaviour of such a system by

³ This is due to the fact that under the further constraint of using only one provider at a time DCPH is an exact algorithm.

game-theoretic observations. Yet, our perspective is more local from a single system's point of view and how to optimize resource allocations for its purposes. It would certainly be interesting to investigate how providers using optimized resource allocation strategies as proposed in our work would interoperate from a global point of view.

In [8], we dealt with the SPP under uncertainty and made use of the deterministic edge SPP in an adaptive heuristic scheme which is based on past optimal resource allocations. This constitutes another example of utilization of the MPRASE framework in that it links different problem incarnations together. In general, MPRASE problems with an uncertain edge model show similarities to capacity management problems from other domains like air-line reservations or hotel booking in which usually yield management techniques are applicable, e.g. [18]. In contrast to yield management, however, we view the MPRASE problems from the perspective of an intermediary acting on behalf of the customer (in most models) and not so much from the provider's perspective as is the case with yield management.

6. Conclusion & Outlook

This paper has dealt with a so far largely neglected class of network QoS problems related to resource allocation at system edges over multiple time periods. We developed the MPRASE model to classify and describe this class of problems and to analyse their mutual dependencies and relationships. Next, we have established a solution framework for MPRASE based on mathematical programming models. The most basic MPRASE problem (SPP) has been dealt with extensively by developing and evaluating a variety of exact as well as heuristic techniques. The algorithms perform fast and well. We have then shown how to extend the SPP along one dimension of MPRASE (the provider model) towards the MPP and how to apply the SPP techniques to this extension. Since the MPP is a very complex problem we concentrated on the development and evaluation of heuristics. With these it has been possible to solve the MPP in an efficient way.

Many interesting issues for future work arise from our MPRASE framework. For example, it will be very interesting to investigate solution techniques for other problem incarnations with resource models that incorporate more than one dimension of capacity and to extend our models towards a stochastic edge. Also, a parameter sensitivity analysis for the problems discussed in this paper is planned as future work.

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