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Routing and resource optimization in service overlay networks

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ABSTRACT

Service Overlay Networks (SONs) create a virtual topology on top of the Internet and provide end-to-end quality of service guarantees without requiring support by the underlying network.

The optimization of the resources utilized by an SON is a fundamental issue for an overlay operator owing to the costs involved and the need to satisfy user requirements. Careful decisions are necessary to provide enough capacity to overlay links, to route traffic, to assign users to access nodes and to deploy overlay nodes.

In this paper, we propose two mathematical programming models for the user assignment problem, the traffic routing optimization and the dimensioning of the capacity reserved on overlay links in SONs. The first model minimizes the SON installation cost while providing full access to all users. The second model maximizes the SON profit by selecting which users to serve, based on the expected gain, and taking into consideration budget constraints of the SON operator. Moreover, we extend these models to include the optimization of the number and position of overlay nodes.

We provide the optimal solutions of the proposed SON design formulations on a set of realistic-size instances and discuss the effect of different parameters on the characteristics of the planned networks. Numerical results show that the proposed approach is able to solve the problem to the optimum even for large-scale networks.

1. Introduction

The Internet is fast becoming the unifying platform for providing worldwide not only classical data service but also Quality of Service (QoS) sensitive applications such as VoIP, video communication and surveillance, streaming services, etc. It now connects thousands of autonomous systems operated by different Internet Service Providers (ISPs), companies and universities.

The Internet was originally designed to provide a best-effort delivery service, but the new multimedia applications require end-to-end QoS guarantees over multiple domains. Although several approaches have been proposed in the literature to support QoS in the Internet, like integrated services [1] and differentiated services [2], they are far from being widely implemented and have been mainly adopted for intra-domain quality support. Indeed, achieving a large-scale QoS support is challenging, as cooperation among multiple network operators is difficult to arrange in practice since it involves business and legal issues in addition to technical problems.

Service Overlay Networks (SONs) have recently emerged as one of the most promising architectures envisioned to provide end-to-end Quality of Service guarantees in the internet, while leaving the underlying Internet infrastructure unchanged [3–7].

An SON is an application-layer network built on top of the traditional IP-layer networks. In general, the SON is operated by a third-party ISP that owns a set of overlay nodes hosted in the underlying ISP domains. These overlay nodes perform service-specific data forwarding and control functions, and are interconnected by virtual overlay links

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which are mapped into a path of one or more IP-layer links [3].

The service overlay architecture is based on business relationships between the SON operator, the ISPs and the users. The SON establishes bilateral service level agreements with the individual underlying ISPs for hosting overlay nodes and purchasing the bandwidth needed for serving its users. On the other hand, the users pay the SON for using its overlay services via a service contract [3,7]. In order for an SON to operate efficiently, the user-generated traffic must be routed on overlay links so as to guarantee application-specific quality requirements and to minimize the overall network cost. To provide the bandwidth to the SON, the underlying ISPs have several technical options. They can lease a transmission line to the SON, use bandwidth reservation mechanisms or create a separate label switched path if MPLS [8] is available in their networks.

Obviously, the deployment of service overlay networks can be an expensive investment. It is therefore imperative to develop efficient tools that optimize the assignment of users to access overlay nodes, the traffic routing and the SON topology, while considering the cost and the expected revenue. The main costs of SON deployment include the cost of the bandwidth that the SON must purchase from the underlying network domains and the installation cost of overlay nodes to support its services.

Only a very few works consider the joint user assignment and overlay routing problem, or the general topology design problem in Service Overlay Networks [7,9–15].

All these works, however, assume that a full coverage of all traffic demands must be provided, while the main goal of an SON provider is that of maximizing its profit by selecting which users to serve based on the expected revenue. Furthermore, they often impose no bounds on overlay links capacities, assuming that the underlying ISPs are always able to provide bandwidth to the SON. Finally, several works assume that the number and location of overlay nodes are pre-determined, while the overlay node placement is a critical issue in the deployment of an efficient network topology.

In this paper, we first tackle the joint user assignment and traffic routing problem, proposing two novel optimization models that determine the optimal assignment of users to access overlay nodes, as well as the capacity reserved for each overlay link, while taking accurate account of traffic routing. The first model minimizes the network installation cost while providing full coverage to all the network's users. The second model maximizes the SON profit by further selecting which users to serve in order to make its operation profitable, and also includes a budget constraint that the SON operator can specify to limit its economic risks in the deployment of the overlay network.

We then extend such models to consider the more complex SON design problem, where the number and positions of overlay nodes to be deployed are optimized. To this end we present two SON design models that jointly optimize the number and location of overlay nodes, the user assignment to access overlay nodes, the traffic routing and the capacity dimensioning of overlay links.

Even if the problems are NP-hard, the proposed mixed integer linear programming (MILP) formulations can be solved to the optimum for realistic-size instances in reasonable time. Moreover, the formulation that considers only the user assignment and routing problem can be solved to the optimum even for large-scale instances in a short computing time.

We provide numerical results for a set of randomly-generated instances and investigate the impact of different parameters on the SON design problem, such as number and installation cost of overlay nodes, bandwidth costs, traffic demands and SON provider's budget.

In summary, the main contributions of this paper are:

- Two network optimization models that determine the optimal assignment of users to access overlay nodes, as well as the capacity reserved for each overlay link, while taking accurate account of traffic routing.
- Two overlay network design models that also select the optimal number and location of the overlay nodes to be deployed, as well as the optimal coverage of network users to maximize the SON operator's profit.
- An extensive performance evaluation of the proposed optimization framework in several realistic network scenarios.

The paper is structured as follows: Section 2 discusses related work. Section 3 describes the proposed user assignment and traffic routing models, while Section 4 introduces the overlay network design formulations. Section 5 discusses numerical results that show the effect of different parameters on the characteristics of the planned networks. Section 6 concludes this paper.

2. Related work

Several works have appeared in the literature with the purpose of providing optimal routing and topology design in different contexts, such as wired backbone networks [16–19], wireless networks [20,21], and recently Service Overlay Networks [7,9–15].

An adaptive topology design framework for SONs is presented in [7] to ensure inter-domain QoS, and a set of heuristics is proposed to solve the least-cost topology design problem. The problem is, however, formulated considering full coverage of all traffic demands and assuming that overlay node locations are given. Moreover, no bounds on link capacities are included and the user assignment is not optimized.

The joint end-system assignment and routing problem is investigated in [9] to determine the minimum-cost overlay network. Two sub-problems are considered separately: the first assigns each end-system to an overlay node and the second selects transport links between overlay nodes to relay traffic between the end-systems. A meta-heuristic based on simulated annealing is used to provide solutions for large-sized networks. Unlike our work, in this paper, routing is not optimized and traffic flows are routed considering the cost as metric when the shortest paths are computed. Moreover, the overlay topology design problem is addressed in a simplified network scenario, where the number and locations of overlay nodes are pre-determined.

Another set of heuristics for SON design is proposed in [10]; these algorithms aim to construct an overlay topology maintaining the connectivity between overlay nodes under various IP-layer path failure scenarios.

The dynamic topology construction problem is considered in [11] to adapt to the underlying network topology changes. An architecture for topology-aware overlay networks is proposed to enhance the availability and performance of end-to-end applications by exploring the dependency between overlay paths. Several clustering-based heuristics for overlay node placement and a routing mechanism are also introduced.

The problem of dynamic overlay network reconfiguration is addressed in [12], where the main goal is to find the optimal reconfiguration policies that can both accommodate time-varying communication requirements and minimize the total overlay network cost.

The problem of overlay node placement is addressed in [13–15]. In [13] the authors consider how to place service nodes optimally in a network, balancing the need to minimize the number of nodes and to limit the distance between users and service nodes. This work, however, only proposes optimization algorithms for the version of the problem without capacity constraints. The work in [14] focuses on designing an overlay network that maximizes the number of unicast and multicast connections with deterministic delay requirements, without considering link costs. Finally, the overlay node placement problem is investigated in [15] to improve routing reliability and TCP performance. This paper, however, assumes that overlay nodes and links have infinite capacities, and does not take into account the costs involved in the deployment of the overlay network.

In summary, unlike our models for joint user assignment and traffic routing, some previous works optimize separately either the overlay routing [7] or the assignment [9] problem. Moreover, the overlay topology design techniques previously proposed [10–15] are less general than our SON design models since they consider at least one of the following special cases: (1) the number and location of overlay nodes are pre-determined, (2) the routing is fixed and known, (3) there are no capacity constraints on overlay links, and (4) full coverage of all network users is provided without consideration of the SON profit maximization issue. In our work we tackle the SON design problem taking into account all these issues within a general optimization framework that in addition considers the expected profit of the SON operator and a budget constraint that can limit the economic risk.

3. Service Overlay Networks: user assignment and routing models

A common approach to the user assignment and routing problem is to consider feasible positions of traffic concentration points in the service area test points (TPs), which generate traffic towards one or more destination nodes (DNs) [16]; the placement of TPs and DNs depends on the expected traffic distribution. Although the concept of *test point* is distinguished from *end-user* (formally, the end-user is the traffic generation agent that is placed in a TP), we will use the two terms as synonyms throughout the paper. *Destination nodes* can represent either terminal nodes or access points to other networks.

Let $I = 1, \ldots, n$ denote the set of TPs, $D = 1, \ldots, p$ the set of destinations and $R = 1, \ldots, r$ the set of overlay nodes installed in the SON.

The cost for the SON operator to buy one bandwidth unit between overlay nodes j and l from the underlying ISPs is denoted by c^B_{jl}, while c^A_{ij} is the access cost per bandwidth unit required between TP i and node j. Finally, c^E_{jk} represents the cost per bandwidth unit for the traffic transmitted on the egress link between node j and destination node $k \in D$.

The traffic generated by TP i towards destination node k is given by the parameter d_{ik}, $i \in I, k \in D$. The maximum capacity that can be reserved by the SON operator between nodes j and l on the overlay link (j, l) is denoted by u_{jl}, $j, l \in R$, while the maximum capacity of the access link of node j is denoted by v_j, $j \in R$.

According to TPs, DNs and overlay nodes' geographic location and the underlying physical topology, the following connectivity parameters can be calculated.

Let a_{ij}, $i \in I, j \in R$ be the test point coverage parameters:

$$a_{ij} = \begin{cases} 1 & \text{if TP } i \text{ can access the SON through} \\ & \text{overlay node } j, \\ 0 & \text{otherwise.} \end{cases}$$

Similarly, let e_{jk}, $j \in R, k \in D$ denote destination nodes coverage parameters:

$$e_{jk} = \begin{cases} 1 & \text{if overlay node } j \text{ can be connected} \\ & \text{with destination node } k, \\ 0 & \text{otherwise.} \end{cases}$$

Obviously, a_{ij} depends on the proximity of TP i to node j, that is on the access coverage provided by the SON operator with node j through agreements with local network operators. Similarly, e_{jk} is related to the distance between DN k and node j.

Let b_{jl}, $j, l \in R$ denote the connectivity parameters between two different overlay nodes, which may depend on the proximity of the overlay nodes j and l in the underlay network, as well as on the agreements between the SON and the different ISPs.

$$b_{jl} = \begin{cases} 1 & \text{if nodes } j \text{ and } l \text{ can be connected} \\ & \text{with an overlay link,} \\ 0 & \text{otherwise.} \end{cases}$$

Decision variables of the problem include TP assignment variables x_{ij}, $i \in I, j \in R$:

$$x_{ij} = \begin{cases} 1 & \text{if TP } i \text{ is assigned to overlay node } j, \\ 0 & \text{otherwise,} \end{cases}$$

destination assignment variables w_{jk}, $j \in R, k \in D$:

$$w_{jk} = \begin{cases} 1 & \text{if node } j \text{ is connected to destination node } k, \\ 0 & \text{otherwise,} \end{cases}$$

connection variables y_{jl}, $j, l \in R$:

$$y_{jl} = \begin{cases} 1 & \text{if there is an overlay link between nodes } j \text{ and } l, \\ 0 & \text{otherwise,} \end{cases}$$

and finally flow variables f_{jl}^k which denote the traffic flow routed on link (j, l) destined for destination node $k \in D$. The special variables f_{jk} denote the traffic flow on the egress link between node j and destination node k.

Given the above parameters and variables, we propose two different user assignment and routing formulations. The first, called Full Coverage User Assignment and Routing model (FC-UAR), optimizes the user assignment and traffic routing minimizing the total network cost while ensuring full coverage of all end-users. The second formulation, called Profit Maximization User Assignment and Routing model (PM-UAR), maximizes the total network profit, choosing which users to serve based on the revenue generated by their subscription to the SON services and the cost necessary to cover them.

3.1. Full Coverage User Assignment and Routing model

The Full Coverage User Assignment and Routing model (FC-UAR) optimizes the users' assignment and traffic routing minimizing the total network cost while ensuring full coverage of all end-users.

$$\text{Minimize} \quad \left\{ \sum_{j,l \in R} \sum_{k \in D} c_{jl}^B f_{jl}^k + \sum_{i \in I, j \in R, k \in D} c_{ij}^A d_{ik} x_{ij} + \sum_{j \in R, k \in D} c_{jk}^E f_{jk} \right\} \tag{1}$$

$$\text{s.t.} \quad \sum_{j \in R} x_{ij} = 1, \quad \forall i \in I, \tag{2}$$

$$x_{ij} \leqslant a_{ij}, \quad \forall i \in I, \; j \in R, \tag{3}$$

$$\sum_{i \in I} d_{ik} x_{ij} + \sum_{l \in R} (f_{lj}^k - f_{jl}^k) - f_{jk} = 0, \quad \forall j \in R, \; k \in D, \tag{4}$$

$$\sum_{k \in D} f_{jl}^k \leqslant u_{jl} y_{jl}, \quad \forall j, \; l \in R, \tag{5}$$

$$\sum_{i \in I, k \in D} d_{ik} x_{ij} \leqslant v_j, \quad \forall j \in R, \tag{6}$$

$$f_{jk} \leqslant h_{jk} w_{jk}, \quad \forall j \in R, \; k \in D, \tag{7}$$

$$y_{jl} \leqslant b_{jl}, \quad \forall j, \; l \in R, \tag{8}$$

$$w_{jk} \leqslant e_{jk}, \quad \forall j \in R, \; k \in D, \tag{9}$$

$$x_{ij}, w_{jk}, y_{jl} \in \{0, 1\}, \quad \forall i \in I, \; j, l \in R, \; k \in D. \tag{10}$$

The objective function (1) accounts for the Service Overlay Network cost, including the costs related to the connection of overlay nodes, users' access and egress costs.

Constraints (2) provide full coverage of all TPs, while constraints (3) are coherence constraints ensuring that TP i can be assigned to overlay node j only if i can be connected to j.

Constraints (4) define the flow balance in node j for all the traffic destined for node k. These constraints are the same as those adopted for classical multicommodity flow problems. The term $\sum_{i \in I} d_{ik} x_{ij}$ is the total traffic generated by the assigned TPs destined for destination node k, $\sum_{l \in R} f_{lj}^k$ is the total traffic received by j from neighboring nodes, $\sum_{l \in R} f_{jl}^k$ is the total traffic transmitted by j to neighboring nodes, and f_{jk} is the traffic transmitted towards the destination node k.

Constraints (5) impose that the total flow on the link between overlay nodes j and l does not exceed the capacity of the link itself (u_{jl}). Constraints (6) impose for each overlay node that the ingress traffic serviced by such network device does not exceed the capacity of the link used for the access, whilst constraints (7) force the flow between node j and the destination node k to zero if node j is not connected to k, and impose that such flow does not exceed the maximum capacity (h_{jk}) of the egress link between overlay node j and destination node k.

Constraints (8) define the existence of an overlay link between nodes j and l, depending on the connectivity parameters b_{jl}. Constraints (9) are coherence constraints ensuring that a node j can be connected to a destination node k only if k is located in the proximity of node j. Finally, constraints (10) are the integrality constraints for the binary decision variables.

It is easy to see that this problem is equivalent to the integer multi-commodity flow problem and therefore is NP-hard. We show in Section 5, however, that this problem can be solved to the optimum even for large-size instances with a short computing time.

Note that we can consider alternative formulations to the FC-UAR model. For example, we might want end-users to be connected to more than one overlay node, for redundancy. This is easily accomplished by modifying constraints (2) as

$$\sum_{j \in R} x_{ij} = \eta, \quad \forall i \in I, \tag{11}$$

where η is the number of overlay nodes per end-user.

3.2. Profit Maximization User Assignment and Routing model

The Profit Maximization User Assignment and Routing model (PM-UAR) maximizes the SON operator's profit, choosing which users to serve based on the revenue generated by their subscription to the SON services and the required cost to the SON provider for covering them.

The objective function (1) is therefore changed as follows:

$$\text{Maximize} \sum_{i \in I, j \in R, k \in D} g_i d_{ik} x_{ij} - \left\{ \sum_{j,l \in R} \sum_{k \in D} c_{jl}^B f_{jl}^k + \sum_{i \in I, j \in R, k \in D} c_{ij}^A d_{ik} x_{ij} + \sum_{j \in R, k \in D} c_{jk}^E f_{jk} \right\}, \tag{12}$$

where $g_i, \forall i \in I$, represents the revenue per bandwidth unit that the SON operator obtains covering test point i. Here, we assume for simplicity that the price paid by the ith user is proportional to the amount of traffic the user introduces in the SON, $\sum_{k \in D} d_{ik}$, with g_i being the proportionality coefficient, but some general pricing models can be easily accounted for.

Constraints (2) are changed as follows, while all the other constraints are the same as in the FC-UAR model:

$$\sum_{j \in R} x_{ij} \leqslant 1, \quad \forall i \in I. \tag{13}$$

With such formulation, the SON operator maximizes the network profit, obtained by subtracting the total revenue, achieved by covering a subset of the test points, to the cost necessary to deploy an overlay network satisfying the users' requirements. Note that, differently from constraints (2) in the FC-UAR model, in this formulation constraints (13) do not impose full coverage of all TPs.

The Service Overlay Network designer may be required to stay within a given cost budget (B) to limit the economic risks in the deployment of the network. The PM-UAR formulation can be modified to account for budget limitation simply by the addition of the following constraint:

$$\sum_{j,l \in R} \sum_{k \in D} c^B_{jl} f^k_{jl} + \sum_{i \in I, j \in R, k \in D} c^A_{ij} d_{ik} x_{ij} + \sum_{j \in R, k \in D} c^E_{jk} f_{jk} \leqslant B. \tag{14}$$

4. Service Overlay Network Design models

In this Section we extend the models presented in Section 3, proposing two novel Service Overlay Network design formulations, namely Full Coverage SON Design and Profit Maximization SON Design models, which also optimize the number and location of overlay nodes to be deployed.

To this end, in addition to test points and destination nodes, we consider feasible positions, called candidate sites (CSs), where overlay nodes can be installed [16]. The placement of CSs depends on the underlying network topology and the agreements of the SON operator with ISPs. Let $S = 1, \ldots, m$ denote the set of CSs, and c^I_j the cost associated with installing an overlay node at CS j.

Decision variables now include overlay node installation variables $z_j, j \in S$:

$$z_j = \begin{cases} 1 & \text{if an overlay node is installed in CS } j, \\ 0 & \text{otherwise.} \end{cases}$$

All the other variables and parameters are the same as defined in Section 3, where the overlay nodes set R is now replaced by the set of candidate sites, S.

4.1. Full Coverage SON Design model

The Full Coverage SON Design model (FCSD), whose formulation is reported below, optimizes the number and location of overlay nodes minimizing at the same time the total network cost and ensuring full coverage of all SON users.

The objective function can be obtained from (1) including the overlay nodes installation costs:

$$\text{Minimize} \quad \left\{ \sum_{j \in S} c^I_j z_j + \sum_{j,l \in S} \sum_{k \in D} c^B_{jl} f^k_{jl} + \sum_{i \in I, j \in S, k \in D} c^A_{ij} d_{ik} x_{ij} + \sum_{j \in S, k \in D} c^E_{jk} f_{jk} \right\}. \tag{15}$$

The problem variables are subject to constraints (2), (4)–(8) and to the following constraints.

TP i can be assigned to CS j only if an overlay node is installed in j and if i can be connected to j:

$$x_{ij} \leqslant z_j a_{ij}, \quad \forall i \in I, \; j \in S. \tag{16}$$

The existence of an overlay link between CSs j and l depends on the installation of nodes in j and l, and is defined by:

$$y_{jl} \leqslant z_j, y_{jl} \leqslant z_l, \quad \forall j, \; l \in S. \tag{17}$$

Coherence constraints ensure that a CS j can be connected to a destination node k only if an overlay node is installed in j and if k can be connected to j:

$$w_{jk} \leqslant e_{jk} z_j, \quad \forall j \in S, \; k \in D. \tag{18}$$

Finally, the integrality constraints for the binary decision variables are:

$$x_{ij}, z_j, w_{jk}, y_{jl} \in \{0, 1\}, \quad \forall i \in I, j, \; l \in S, \; k \in D. \tag{19}$$

The FCSD problem is therefore defined by the objective function (15) subject to constraints (2), (4)–(8) and (16)–(19).

4.2. Profit Maximization SON Design model

The Profit Maximization SON Design model (PMSD) maximizes the SON operator's profit, selecting the optimal number and location of overlay nodes to be deployed, and choosing which users to serve based on the expected gain and the cost necessary to satisfy their traffic demands.

The PMSD formulation is obtained by modifying the objective function (15) as follows:

$$\text{Maximize} \quad \sum_{i \in I, j \in S, k \in D} g_i d_{ik} x_{ij} - \left\{ \sum_{j \in S} c^I_j z_j + \sum_{j,l \in S} \sum_{k \in D} c^B_{jl} f^k_{jl} + \sum_{i \in I, j \in S, k \in D} c^A_{ij} d_{ik} x_{ij} + \sum_{j \in S, k \in D} c^E_{jk} f_{jk} \right\}, \tag{20}$$

and by introducing constraints (21), as for the PM-UAR model:

$$\sum_{j \in S} x_{ij} \leqslant 1, \quad \forall i \in I. \tag{21}$$

All other constraints are the same as in the FCSD model.

Finally, a cost budget can be introduced in PMSD simply by adding the following constraint:

$$\sum_{j \in S} c^I_j z_j + \sum_{j,l \in S} \sum_{k \in D} c^B_{jl} f^k_{jl} + \sum_{i \in I, j \in S, k \in D} c^A_{ij} d_{ik} x_{ij} + \sum_{j \in S, k \in D} c^E_{jk} f_{jk} \leqslant B. \tag{22}$$

5. Numerical results

In this section we test the sensitivity of the proposed models to different parameters like the number of overlay nodes, candidate sites and test points, the traffic demands, the installation costs, as well as the revenue obtained by covering end-users and the SON operator's budget.

We consider both randomly-generated network instances as well as hierarchical (transit-stub) models, typical of the Internet topology, generated by the GT-ITM topology generator [22,23].

To generate random network instances, we have implemented a topology generator which considers a square area with edge equal to 1000 and randomly extracts the position of m candidate sites (CSs), n test points (TPs) and p destination nodes (DNs). The area is divided into N Internet Service Providers (ISPs); for simplicity, in this paper we consider $N = 25$ ISPs obtained by dividing the whole area into $L \times L$ squares, with $L = 200$. The same procedure is used to generate network instances with r overlay nodes for the model where their position is given.

Unless stated otherwise, we assume that each TP and DN can be connected to a CS only if the CS is at a distance not greater than 100 from the TP or DN. As for the connectivity parameters between different CSs, we assume that each CS can be directly connected with an overlay link to any other CS (i.e., $b_{jl} = 1, \forall j, l \in S$); this allows our models to investigate all possible link configurations in order to find the optimal overlay topology.

The cost matrix for bandwidth (c^B_{jl}) is then generated. If CSs j and l belong to the same ISP, we assume that c^B_{jl} is fixed and equal to 1 monetary unit per Mb/s. On the other hand, if CSs j and l belong to different ISPs, c^B_{jl} depends on the peering agreements between such ISPs. For the sake of simplicity, we assume that in this case c^B_{jl} is a random variable uniformly distributed between $C/2$ and $3C/2$, with C being equal to $\frac{L_{jl}}{L}$, that is the distance between j and l (L_{jl}) divided by the width of an ISP domain (L), i.e. 200 with the above settings.

The installation cost of an overlay node is equal to 10 monetary units, unless otherwise specified. As for the access and egress cost, we assume they are fixed and equal to 1 monetary unit per Mb/s.

The maximum capacity that can be reserved between CSs j and l on the overlay link (j, l) u_{jl}, $j, l \in S$ is set equal to 50 Mb/s, as well as the maximum capacity of the access link of CS j,v_j,$j \in S$. The capacity of the egress links connecting overlay nodes to destination nodes is u_{jk} =100 Mb/s, for all $j \in S$ and $k \in D$.

Obviously, none of the above assumptions affects the proposed models, which are general and can be applied to any problem instance and network topology.

All the results reported hereafter are the optimal solutions of the considered instances obtained by formalizing the proposed models in AMPL [24] and solving them with CPLEX [25] using workstations equipped with an Intel Pentium 4 (TM) processor with CPUs operating at 3 GHz, and with 1024 Mbyte of RAM. For each network scenario, the results reported are the average values on 10 random instances.

5.1. User assignment and routing models

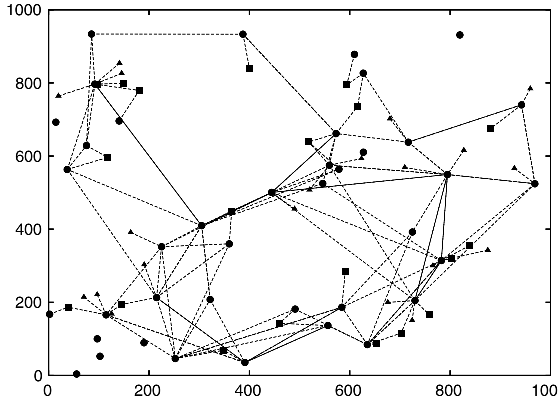
We first tackle the user assignment and routing problem, considering different network scenarios and varying several parameters such as the number of overlay nodes, the traffic demands, the gain the SON operator obtains serving end-users and the cost budget.

5.2. Effect of the traffic demands: random network instances

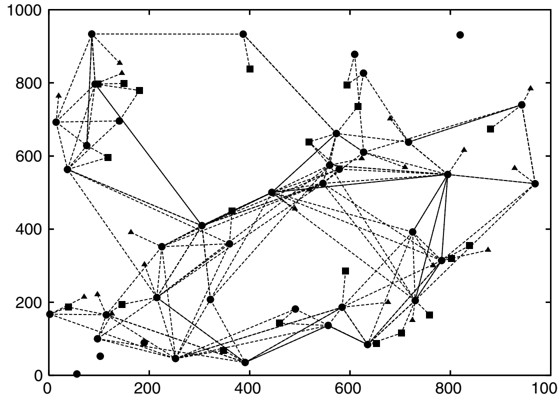
We first consider the Full Coverage User Assignment and Routing model (FC-UAR) in a random network scenario with $n = 20$ TPs and $p = 20$ DNs. Each test point offers the same amount of traffic d_{ik} to all destination nodes.

Fig. 1 reports an example of the planned networks when applying the FC-UAR model to the same instance with $r = 40$ overlay nodes and with two different requirements on the end-user traffic, $d_{ik} = 500$ kb/s and $d_{ik} = 2$ Mb/s for all TPs and DNs. Overlay nodes, TPs and DNs are represented respectively by circles, triangles and squares. We observe that increasing the traffic demands forces the model to use a higher number of overlay nodes and to install more links to convey the traffic towards the destination nodes.

Table 1 analyzes the characteristics of the solutions in the same scenario when varying the number of overlay nodes r. For each couple (r, d_{ik}) we report the number of installed overlay links (N_L), the network cost (i.e. the value of the objective function (1)) and the processing time to get the optimal solution.



(a) 500 kb/s



(b) 2 Mb/s

Fig. 1. Sample SONs planned by the FC-UAR model with increasing traffic demands (500 kb/s and 2 Mb/s). The number of TPs and DNs is 20, while the number of overlay nodes is 40. Overlay nodes, TPs and DNs are represented respectively by circles, triangles and squares.

Table 1
Solutions provided by the FC-UAR model with 20 TPs and DNs

r	N_L	Cost	Time (s)
$d_{ik} = 500$ kb/s			
30	184.6	783.1	0.5
40	217.3	765.6	1.2
50	239.8	746.8	2.2
100	305.7	698.0	23.6
200	414.6	661.6	220.9
300	452.3	643.3	718.3
$d_{ik} = 1000$ kb/s			
30	195.8	1568.9	0.6
40	231.4	1532.7	1.2
50	249.4	1494.6	2.3
100	320.4	1395.6	22.8
200	431.9	1323.5	223.4
300	470.8	1285.9	765.7

Table 1 suggests three main comments. First, the very same effect of traffic increase observed in Fig. 1 is evident also in averaged results. In fact, owing to capacity constraints, just increasing the link bandwidth is not sufficient and it is necessary to use more overlay nodes and links. Second, for a given traffic value, increasing the number of overlay nodes (r) in the FC-UAR model increases the solution space; as a consequence, the model favors the solutions providing connectivity at a lower cost, which in turn decreases with r. Finally, it can be noted that the FC-UAR model solves the user assignment and routing problem even for large-scale network instances with a short computing time.

We then simulated a scenario with a higher number of traffic flows, considering 100 TPs and 10 DNs, where DNs can be seen as acting like concentrator nodes or access points to other networks. The results obtained with the FC-UAR model are shown in Table 2 with r ranging from 30 to 300 and for different d_{ik} values, and they are in line with the observations reported above.

5.3. Effect of the traffic demands: transit-stub topologies

To investigate the behavior of the FC-UAR model with a large number of traffic flows, we generated large-scale transit-stub topologies using GT-ITM [22].

Table 2
Solutions provided by the FC-UAR model with 100 TPs and 10 DNs

r	N_L	Cost	Time (s)
$d_{ik} = 20$ kb/s			
30	260.5	77.3	0.2
40	290.8	74.7	0.3
50	323.7	73.2	0.6
100	425.1	69.0	5.9
200	547.0	65.8	68.0
300	631.7	64.2	239.8
$d_{ik} = 40$ kb/s			
30	260.5	154.7	0.2
40	290.9	149.4	0.3
50	324.0	146.4	0.6
100	425.2	138.1	5.8
200	547.1	131.5	68.2
300	631.9	128.3	242.8

In such scenarios, the Internet is modeled as a collection of interconnected routing domains, which can be classified as either Transit domains (that contain backbone nodes) or Stub domains (which have one or more gateway nodes that are connected to transit domains).

We considered 10 random transit-stub topologies with $r = 50$, 100, 200 overlay nodes and an average number of links equal to 400, 550 and 1200, respectively, including access and egress links; each link can be selected as an overlay link. For each topology we generated 10 random distributions of $n = 100$ TPs and $p = 100$ DNs, where each TP offers the same amount of traffic $d_{ik} = 10$ kb/s to all destination nodes. All other parameters are the same as in the previous network scenarios.

The numerical results obtained with the FC-UAR model, averaged over all network topologies and random TPs/DNs distributions, are shown in Table 3. We observe that owing to the hierarchical structure of Transit-Stub topologies, a large number of overlay links is selected in the planned SON; furthermore, the time necessary to compute the optimal solution is very short.

5.4. Effect of the gain parameter on profit maximization

We evaluate the effect of the gain parameter on the Profit Maximization User Assignment and Routing model (PM-UAR) considering a scenario with 50 TPs, 50 DNs and $r = 100$ overlay nodes. We assume that the gain per

Table 3
Transit-stub topologies: solutions provided by the FC-UAR model with 100 TPs, 100 DNs and $d_{ik} = 10$ kb/s

r	N_L	Cost	Time (s)
50	341.9	700.0	0.5
100	418.6	873.8	5.7
200	449.6	1040.4	10.5

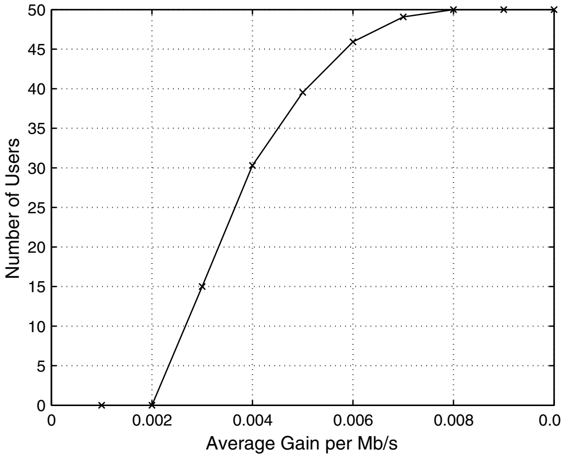


Fig. 2. Number of end-users covered by the SON as a function of the average gain per bandwidth unit (PM-UAR model), with 50 TPs, 50 DNs, 100 overlay nodes and $d_{ik} = 100$ kb/s.

Table 4
Solutions provided by the PM-UAR model with 50 TPs and DNs, 100 overlay nodes and $d_{ik} = 100$ kb/s

G	N_L	Profit	Cost	Time (s)
0.005	703.3	383.7	682.1	42.2
0.006	755.7	608.7	792.6	42.1
0.007	771.4	847.7	847.6	42.0
0.008	780.7	1091.6	865.2	41.9
0.009	780.8	1336.2	865.2	42.0
0.010	780.9	1580.8	865.2	41.8

Table 5
Solutions provided by the PM-UAR model with 20 TPs and DNs, 40 overlay nodes, $G = 0.01$ monetary units per Mb/s and $d_{ik} = 500$ kb/s

B	Users	N_L	Profit	Cost	Time (s)
500	13.0	175.1	1015.3	492.8	40.2
600	15.4	192.7	1118.3	583.8	37.4
700	18.0	209.0	1203.2	686.9	33.7
800	20.0	217.4	1241.6	765.6	2.8
900	20.0	217.4	1241.6	765.6	2.7
1000	20.0	217.4	1241.6	765.6	2.7

bandwidth unit that the SON operator obtains for serving an end-user (the parameter g_i in the objective function (12)) is a random variable with average equal to G and a uniform distribution between $G/2$ and $3G/2$, with G ranging between *0* and 0.01 monetary units per Mb/s.

Fig. 2 shows the number of end-users covered by the SON as a function of G. Obviously, for small G values, the SON is not profitable enough to cover any of the end-users; as G increases, the SON covers more end-users, and eventually all of them. Similar results have been observed with different values of r.

Table 4 reports, for the same scenario, the number of installed links, the SON operator's profit (i.e. the value of the objective function (12)), the network cost and processing time, as a function of G. Note that when G increases, the planned network covers more end-users, and as a consequence it uses more overlay links.

5.5. Effect of the budget parameter

Finally, to evaluate the effect that a budget constraint has on the planning of an SON, we consider several budget (B) values in the 500–1000 range, solving the PM-UAR model in a random network scenario with 20 TPs and DNs, 40 overlay nodes and $d_{ik} = 500$ kb/s.

Fig. 3 illustrates the number of end-users covered by the SON as a function of the operator's budget, for different G values. For each value of G, as the budget increases, the number of end-users accepted in the network increases until it reaches its maximum.

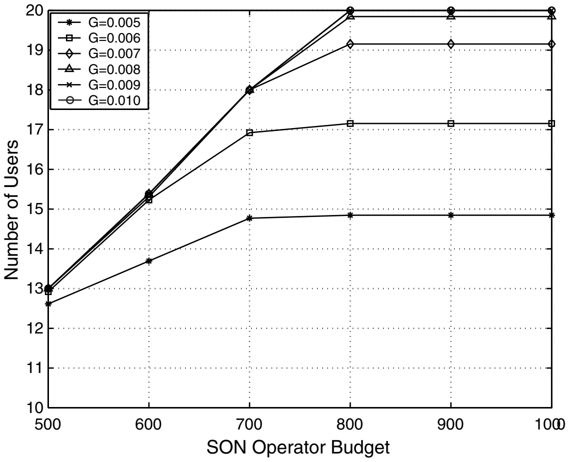


Fig. 3. Number of end-users covered by the SON as a function of the budget for different values of the average gain per bandwidth unit G (PM-UAR model), with 20 TPs, 20 DNs and 40 overlay nodes.

Table 5 reports in detail the characteristics of the solutions provided by the PM-UAR model in such a scenario, for $G = 0.01$ monetary units per Mb/s and for different budget values. The results show that deploying higher-cost networks allows the SON operator to achieve higher network profits. This, however, also increases the economic risk faced by the SON operator in the deployment of the overlay network.

5.6. Network design models

We now present the results of the SON design models, providing also a comparison with the user assignment and routing problem.

5.7. Effect of the traffic demands: random network instances

To gauge the effect of the traffic demands on the Full Coverage SON Design model (FCSD), let us consider a random network scenario with $n = 20$ TPs, $p = 20$ DNs and a variable number of candidate sites, m. Each TP offers the same amount of traffic d_{ik} to all DNs.

Table 6 reports the number of installed overlay nodes (N_R), overlay links (N_L), the total network cost and the processing time to get the optimal solution.

To compare the results obtained with FCSD with those of the FC-UAR model, we assume that the set S of candidate sites considered in FCSD is the same as the set R of overlay nodes used in FC-UAR (as a consequence, $m = r$). In this way, the solution of the FCSD model measures the advantage obtained by optimizing the number and position of the installed overlay nodes, in addition to the user assign-

Table 6
Solutions provided by the FCSD model with 20 TPs and 20 DNs

FCSD					FC-UAR	
m	N_R	N_L	Cost	Time (s)	Cost	gap_c(%)
$d_{ik} = 500$ kb/s						
30	18.9	146.6	997.9	49.7	1083.1	8.5
40	19.3	148.5	987.0	203.4	1165.6	18.1
50	19.5	148.3	981.9	4665.8	1246.8	27.0
$d_{ik} = 1000$ kb/s						
30	21.1	167.7	1803.5	11.6	1868.9	3.6
40	20.5	155.7	1636.7	80.8	1932.7	18.1
50	19.9	148.2	1621.0	2616.3	1994.6	23.0

ment and traffic routing optimization performed by the FC-UAR model. For the sake of comparison we also added two columns in Table 6 that show the network cost achieved with the FC-UAR model and the percentage gap (gap_c) between the cost provided by the FCSD model and that obtained solving FC-UAR. To make a fair comparison between the two models, in the Table we reported for FC-UAR the objective function value (1) increased by the cost necessary to install r overlay nodes ($r \cdot 10$ monetary units, with the settings used in this scenario).

We note that the gap between the costs obtained with FC-UAR and FCSD is remarkable and it increases with increasing m values. The results also confirm the behavior already observed for FC-UAR, where the number of installed overlay nodes and links increases with increasing traffic demands.

We also simulated a network scenario with $n = 100$ TPs and 10 DNs which act as concentrator nodes or access points to other networks. The results, summarized in Table 7, are obtained for different m and d_{ik} values, and they are in line with the observations reported above. Note that in this case the processing time to obtain the optimal solutions is almost negligible.

5.8. Effect of the traffic demands: transit-stub topologies

To evaluate the behavior of the FCSD model with transit-stub topologies, we considered the same scenario illustrated previously for FC-UAR. The numerical results, averaged over all network instances, are reported in Table 8. If we compare these results with those obtained with FC-UAR (see Table 3), we can observe that the FCSD model installs, on average, considerably fewer overlay nodes and links than FC-UAR, thus reducing consistently the cost of the planned network.

Table 7
Solutions provided by the FCSD model with 100 TPs and 10 DNs

FCSD					FC-UAR	
m	N_R	N_L	Cost	Time (s)	Cost	gap_c(%)
$d_{ik} = 20$ kb/s						
30	24.1	235.2	320.5	0.5	377.3	17.7
40	24.0	232.1	317.8	4.9	474.7	49.4
50	24.0	231.1	317.4	34.0	573.2	80.6
$d_{ik} = 40$ kb/s						
30	24.1	235.2	399.5	0.6	454.7	13.8
40	24.0	232.1	395.7	5.5	549.4	38.8
50	24.0	230.9	394.8	29.1	646.4	63.7

Table 8
Transit-Stub topologies: solutions provided by the FCSD model with 100 TPs, 100 DNs and $d_{ik} = 10$ kb/s

FCSD					FC-UAR	
m	N_R	N_L	Cost	Time (s)	Cost	gap_c(%)
50	25.3	310.9	954.6	1.6	1200.0	25.7
100	38.0	338.1	1272.4	484.1	1873.8	47.3
200	72.3	386.9	1768.7	2436.0	3040.4	71.9

Table 9
Variable cost ratio β: solutions provided by the FCSD model with 20 TPs, 20 DNs, 40 CSs and $d_{ik} = 500$ kb/s

β	N_R	N_L	Cost	Time (s)
10	19.3	148.5	987.0	203.4
1	28.7	197.2	795.3	12.0
1/10	40.0	215.9	767.9	0.7
FC-UAR	40.0	217.3	765.6	1.2

5.9. Effect of the installation and bandwidth reservation costs

The number of installed overlay nodes and links clearly depends on the ratio β between the overlay nodes' installation cost and the bandwidth reservation cost.

Table 9 illustrates this effect in a network scenario with 20 TPs, 20 DNs and 40 CSs; the offered traffic d_{ik} is equal to 500 kb/s. If the cost of installing an overlay node decreases with respect to the bandwidth reservation cost, the FCSD model tends to install more overlay nodes.

For comparison, the results obtained with FC-UAR are also reported in the last row of the Table since they represent a bound for FCSD corresponding to a negligible cost of the overlay nodes.

5.10. Effect of the gain parameter

To evaluate the Profit Maximization SON Design model (PMSD), we consider a scenario with 20 TPs and DNs, 40 CSs and $d_{ik} = 500$ kb/s. We assume, as for PM-UAR, that the gain per bandwidth unit g_i is a random variable with average equal to G and a uniform distribution between $G/2$ and $3G/2$, where G ranges between 0 and 0.01 monetary units per Mb/s.

Fig. 4 compares the number of end-users covered by the SON for the PMSD and PM-UAR models ($r = m$) as a function of G. Since the cost of installing overlay nodes is not considered in PM-UAR, such a model tends to cover more end-users than PMSD for all G values.

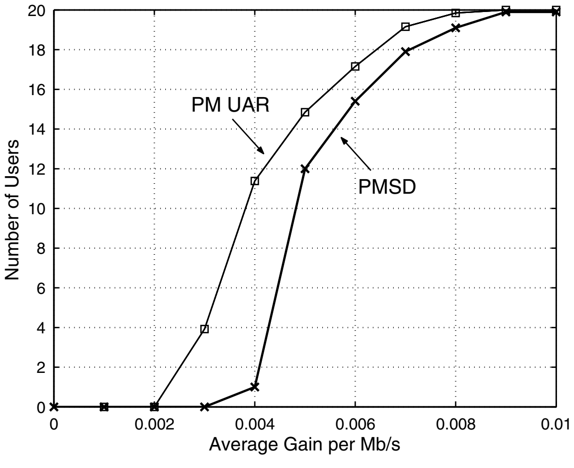


Fig. 4. Number of end-users covered by the SON as a function of the average gain per bandwidth unit, with 20 TPs, 20 DNs and 40 CSs.

Table 10
Solutions provided by the PMSD model with 20 TPs and DNs, 40 CSs and $d_{ik} = 500$ kb/s

G	N_R	N_L	Profit	Cost	Time (s)
0.005	15.0	103.0	71.9	644.6	560.8
0.006	17.2	125.7	241.8	785.1	359.5
0.007	18.2	138.0	422.7	900.4	326.1
0.008	18.9	142.8	616.3	954.0	263.3
0.009	19.2	146.5	814.8	984.0	190.5
0.010	19.2	146.5	1015.0	988.0	195.0

For the same scenario, Table 10 shows the number of installed nodes and links, the SON operator's profit, the total network cost and processing time, as a function of G. These results confirm the trend observed in the PM-UAR model.

5.11. Effect of the budget parameter

Finally, to capture the effect of a budget constraint on the PMSD model, we consider the same scenario varying the budget value (B) between 500 and 1000 monetary units.

Fig. 5 shows the number of end-users covered by the SON as a function of the operator's budget, for different G values. For a given value of G, the number of end-users accepted in the SON increases with B up to its maximum which can be obtained from Fig. 4.

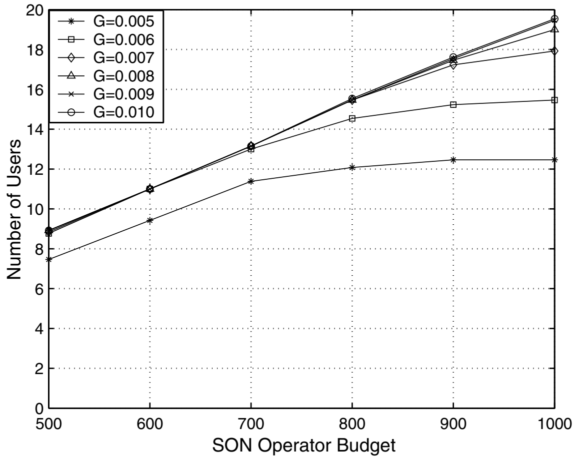


Fig. 5. Number of end-users covered by the SON as a function of the budget for different values of the average gain per bandwidth unit G, with 20 TPs, 20 DNs and 40 CSs.

Table 11
Solutions provided by the PMSD model with 20 TPs and DNs, 40 CSs, $G = 0.01$ monetary units per Mb/s and $d_{ik} = 500$ kb/s

B	N_R	N_L	Profit	Cost	Time (s)
500	14.3	87.2	588.1	495.1	3956.6
600	15.6	101.8	723.1	591.8	1394.5
700	16.4	111.9	827.4	687.0	1420.8
800	17.4	126.8	913.5	790.0	920.8
900	18.2	136.0	973.2	882.5	674.9
1000	19.2	145.6	1008.2	969.9	339.9

Table 11 details the characteristics of the solutions provided by the PMSD model in such a scenario, for $G = 0.01$ monetary units per Mb/s and for different budget values. The results are in line with those obtained with the PM-UAR model and confirm that higher profits can be achieved with higher budget values, at the cost of increasing the economic risk of the SON operator.

6. Conclusion

In this paper, we first addressed the user assignment and routing problem for Service Overlay Networks in terms of deciding the assignment of SON users to access overlay nodes, the traffic routing, the capacity reserved on each overlay link and the optimal subset of end-users to be covered in order to maximize the SON operator's profit.

To this end, we proposed two novel optimization models based on mathematical programming that take into account the individual requirements of the end-users, the connectivity between overlay nodes and the management of the traffic flows. The objective of the first model is the minimization of the overall network installation cost while ensuring full coverage of all end-users. The second model maximizes the SON profit by choosing which users to serve based on the expected gain and budget constraints specified by the SON operator.

We then addressed the topology design problem for Service Overlay Networks, optimizing the number and positions of the overlay nodes to be deployed in addition to all the variables considered in the user assignment and routing problem.

To test the quality of the solutions provided by our models, we generated synthetic instances of SONs and solved them to the optimum varying several network parameters. The numerical results we gathered show that our models are able to capture the effect on the network topology configuration of all these parameters, providing a promising framework for the design of SONs.

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