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SOCIO-ECONOMICS OF THE FUTURE INTERNET: PROFIT-AWARE SOLUTIONS IN NETWORKING

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1 Introduction

A huge conceptional transition is started to happen in the networking industry in the recent decade. In the earlier years of telecommunication, technology related challenges were faced by the researchers and engineers. Namely, the ultimate goal was to design and build a system that is able to forward as many data as possible in the available highest quality for more and more people. Questions such as how can we increase the throughput of a link were asked and answered. However, because of the development of the telecommunication industry and the whole global economy the technology-related aspects of design processes are being overtaken by socio-economic aspects. In terms of the social aspects, more and more companies recognize the importance of getting to know the behavior of the users. They are not only using the services offered by the companies but also have a significant effect on the performance of the system. Contemplating the typical human behavior can help to scale the systems to match its future loads. IT services play a crucial and augmenting part in the environmental changes. Technology can help to reduce the power consumption in several industries; however, the power consumption and the carbon footprint of the telecommunication devices own a significant share of the aggregate global volumes. In terms of the economic aspects, each stakeholder focuses on its profits, i.e., they seek revenue maximizing and expenditure minimizing solutions to be more profitable. Numerous proposals failed to dominate the telecommunication market resulting from economic reasons; the most notorious example is the IPv6 protocol. Despite its fascinating technological features, it is still not used widely on the Internet 15 years after it has been proposed. The reason of this is that the Autonomous Systems of the Internet do not have incentives to migrate to the new version of the protocol. Therefore, more and more systems are built deliberating the profit-awareness of the stakeholders, e.g., by incorporating incentive-capable mechanisms into the services. The importance of socio-economic aspects was identified by the research initiatives as well; the NSF FIND (USA) [37], Euro-NF (EU) [23], AKARI (Japan) [5], FIF (Korea) [24], and CNGI (China) [20] also promote network design from a socio-economic viewpoint.

In this dissertation, I investigate three different topics of the telecommunication networks from a socio-economic point of view. Particularly, profit-aware solutions are proposed in case of network resilience, Internet access pricing, and data centers. The topics are located at different parts of the Internet: network resilience is an issue in the network layer, Internet access is sold to the end-users, while data centers are the facilities behind the cloud services. Next, I introduce the areas one-by-one and motivate the problems to be addressed.

While earlier the goal of networking was to connect the nodes of the systems, in case of the Future Internet the objective is to provide services to the customers. These

services, e.g. run by Google and Amazon, are innovative applications that are useful for the society; these services are also called as cloud services. The cloud services and the end-users are connected by the core networks whose operators apply profit-aware solutions, namely network resilience methods. Network resilience techniques try to route and protect the demands in the network using *as few resources as possible* while maintaining the require availability. Every method has its pros and cons; network operators have to choose an algorithm that fits their goals best. First, this can be the resource reservation because they want to reduce their operation costs as much as possible. Second, the main objective can be the high availability when they want to provide the most fault-tolerant service. Third, they can choose that they want to route every demand on-line without any pre-configured protection solutions. Finally, network delay can also be the most important aspect when operators deliver live, conversational traffic. Bhandari describes first the idea of routing demands over multiple disjoint paths [15]. Using multiple paths allows the reduction of expenditures related to resilience as only a branch of the demand have to be protected. A demand can be transmitted on multiple paths in case of several technologies. ATM (Asynchronous Transfer Mode) and MPLS (Multiprotocol Label Switching) support inverse multiplexing [34] where a traffic flow can be split into multiple streams, sent over parallel channels, and at the receiving end multiplexed into a single traffic flow again. Due to VCat (Virtual Concatenation) [2] and LCAS (Link Capacity Adjustment Scheme) [1], ngSDH/SONET (next generation SDH/SONET) and OTN (Optical Transport Network) [4][3] networks can apply resilience schemes using multiple paths. Several resilience methods have been proposed by the research community where the traffic is routed using multiple paths, including [9, 11, 30, 35, 32, 33, 31]. However, these proposals are either too complex, formulated by integer linear program, or provide non-optimal solutions based on heuristics. Accordingly, a resilience method that is able to exploit the opportunity of routing demand on multiple path and to guarantee minimal resource allocation may be a feasible resilience method in the abovementioned network architectures.

Profit-awareness is a crucial goal in case of the access networks of the Future Internet as well. In this perspective, the access providers try to augment their revenues resulting from the subscription fees. To retain the sustainability of the Internet Service Provider (ISP) ecosystem; the economic interactions among service providers of different levels and end-users have been in the focus of interest for several years. In these works, e.g. [29, 17, 39], the decisions of the stakeholders are investigated using game theoretic tools. In addition, user behavior, specifically the user loyalty, also has a significant imprint on the design of next-generation network architectures as well as creating profitable services running them. A vivid example of customer loyalty in practice is the loyalty contract between a service provider and a customer. The customers are charged with different price if they sign a contract, and this difference

depends on the length of the contract! Many empirical studies deal with user loyalty on the ISP markets [41, 19, 18, 38, 25, 10, 12, 13] reporting that significant fractions of the subscribers are loyal to their operators. The abovementioned works and recent works [40, 16] initiate the discussion on customer loyalty and its impact on *pricing strategies* of ISPs. However, many issues are still to be solved. First, these works use a simple user loyalty model; however, the price difference of the service plans may affect the churn of the customers. Second, these works deal with static market scenarios when fixed number of service providers exist on the market and they compete for the customer; the dynamics of the ISP market has not been examined yet.

To operate cloud services several issues have to be addressed including business model, routing, and infrastructure. I focus on the later one; the cores of the cloud service infrastructures are data centers. Data centers store enormous number of servers; designing a network inside a data center in order to connect thousands of servers is a challenging task. The available data center designs have two major issues that motivate our work: scalability and power consumption. The properties of data centers can be described based on capabilities like computation, storage, and Internet access. In addition, the network topology of the data center has a crucial impact on the performance as huge amounts of data have to be transmitted intra data center. Data center networking has attracted the attention of the research community recently. Data center networking has attracted the attention of the research community recently. Novel architectures are proposed with different network topologies, including BCube [27, 42], DCell [28], and fat-tree [6, 36, 26]—just to mention a few of them. Although these proposals present diverse structures, they also share two common basic properties: symmetric design and homogeneous equipments. Due to their symmetric structures the size of these data centers can be altered only in large quantities; accordingly, it is hard to scale the network with the flexibility of having heterogeneous deployments. Therefore, *scaling these structures is expensive* and *their power consumption is inefficient.* However, networks can also have asymmetric structures not only symmetric ones. The existence of biological networks, whose structures are mostly asymmetric, proves that these structures have preferable properties as they survived the evolutionary competition. Numerous biological networks share a common characteristic; i.e., the distribution of their node degrees follows power-law distribution [7]; these networks are called scale-free networks. Scale-free networks have two important aspects, namely, ultra-small diameter [21] and high error tolerance [8], which could be favorable in case of data center networks too. Accordingly, a data center network topology generation method, which is inspired by scale-free networks, could enhance the energy efficiencies of data centers.

2 Research Objectives

My research has three main objectives as follow:

(1) Design a network resilience scheme that is able to route and protect a demand in a communication network using multiple paths in order to reduce the expenditures of the protection. In addition, the method has to be solved in polynomial runtime to be applicable routing method in online systems.

(2) Analyze the impact of uncertainty, in terms of incomplete information and probabilistic strategies, the entrance of a new competitor, and long-term interaction on the price setting behavior of Internet Service Providers on a market considering the loyalty of the subscribers.

(3) Design and evaluate a scale-free network inspired data center architecture generation algorithm that, on the one hand, retains the preferable properties of scale-free network while, on the contrary, meets the physical properties, namely, the number of ports, of available network equipments.

3 Methodology

The resilience schemes proposed in Section 4.1 are formalized using linear programming. None of the proposed methods contain integer variables; therefore, the solutions of the formulas can be derived in polynomial runtime. To quantify the properties of the methods, the formulas were implemented based on the LEMON framework that uses GLPK and CPLEX LP solvers. Extensive simulations were run on real-world network topologies to evaluate the design. In order to model the routing problem, basic concepts of graph theory are applied.

As the Internet Service Providers have diverse interests, their interactions are modeled and analyzed with game theoretical tools (Section 4.2). Particularly, Nash equilibrium strategies are derived in case of non-cooperative games, Bayesian equilibria are derived in case of incomplete information, the entrance of a new competing ISP is modeled with Stackelberg leader-follower game, while subgame-perfect equilibrium is presented in case of repeated games. The verification of the analytical results is based on comprehensive simulations.

The designed data center generation algorithm is based on graph theoretic tools in Service 4.3. The feasibility constraint of the method is derived analytically. In addition, the properties of the proposed scheme are supported by simulations.

4 New Results

4.1 Multi-Path Protection: a Cost Minimizing Resilience Scheme

In this thesis I propose a cost minimizing resilience schemes, which can be used in backbone networks. I use linear programming to formalize the methods. The main feature of the proposed solutions is that the load of a demand is transferred on multiple paths; therefore, fewer resources have to be allocated for protection purposes. Based on this principle several resilience scheme is proposed to handle special failure cases, and to constrain the latency of the data transfer.

Thesis 1. *[J4, J7, C2, C3] I have proposed a cost minimizing routing and resilience method for communication networks, where the working and spare capacities are allocated on multiple paths. I have showed that the proposed Multi-Path Protection (MPP) method provides routing by allocating as few resources as possible. The proposed MPP resilience scheme is formalized with a Linear Program (LP), which does not use integer variables; therefore, the runtime of the algorithm is polynomial. I have proposed several extensions of the method to be resilient against multiple network failures, to constrain the latency of the connection, and to create edge-disjoint paths. I have presented a graph-transformation extension which enables handling a group of SRLG (Shared Risk Link Group) scenarios.*

The methods presented in Thesis 1 reduces the expenditures of network operators in case of the following scenario. The network $\mathcal{N}(V, E, B)$ consists of vertices (network nodes) $i \in V$, of directed edges (directed links or arcs) $ij \in E$, where $i, j \in V$, and of the vector of link bandwidths (capacities) $B_{ij}, \forall ij \in E$. $V^{\to j} \subset V$ and $V^{j \to} \subset V$ denote the set of nodes that have edges with destination (target, termination) and origin (source) in node j; respectively, i.e., the nodes i and k of directed in and out links (arcs) ij and jk respectively adjacent to node j. The cost of allocating a capacity unit of resource in the edge ij is denoted by c_{ij}. The demands $o \in O$ are defined as a traffic pattern O of length of $|O|$, characterized as $o(s, t, b, a, d)$ where s is the source, t is the target and b is the bandwidth requirement of the demand o, while a and d are the arrival time and the departure time of that demand, i.e., $d - a$ is the duration of the session/connection for demand o.

The objective is to route and protect all the demands along more than one path as they arrive one-by-one by using as few resources as possible. Accordingly, the profit of the operator is elevated due to the reduced expenditures. This is a trade-off between the number and the length of the paths with the aim to decrease the total amount of allocated capacities. On the one hand, as k the number of paths is increased

(a) two paths   (b) three paths   (c) asymmetrical load   (d) four paths
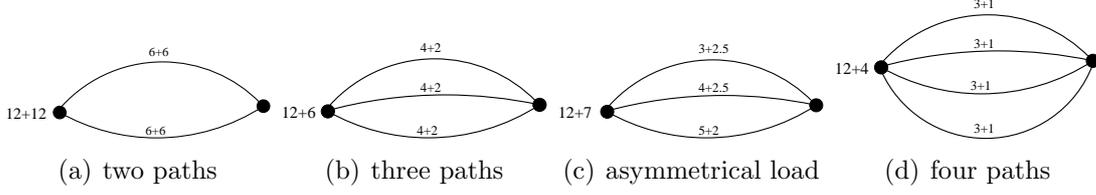
Figure 1: Illustration of the Multi-Path Protection scheme: working and protection capacity allocations for endpoints and for certain disjoint paths

(Figure 1), the protection will be increasingly more efficient, i.e., fewer resources will be allocated along the paths. On the other hand, as the number of (disjoint) paths is increased, first shorter paths are exhausted, then it starts using the longer ones; therefore, the average path length will grow causing increased allocated capacities.

Thesis 1.1. *[J4, C2] I have proposed a cost minimizing routing and protection scheme, called Multi-Path Protection, which allocates as few resources as possible in the network throughout a linear program. In addition, the method is capable to provide only partial protection of the demand; therefore, the protection related costs of the operator can be reduced if necessary.*

In case of the proposed Multi-Path Protection scheme, a demand can be routed and protected with the following linear program:

Variables:

$x_{ij} \geq 0$ working flow over edge $ij \in E$

$y_{ij} \geq 0$ protection flow over edge $ij \in E$

f_{max} the maximum capacity that may be failed

Objective:

$$min \sum_{\forall ij \in E} c_{ij} \left(x_{ij} + y_{ij} \right) \tag{1}$$

Constraints:

$$\sum_{\forall i \in E^{\rightarrow j}} x_{ij} - \sum_{\forall k \in E^{j \rightarrow}} x_{jk} = \begin{cases} -b & \text{if } j = s \\ 0 & \text{otherwise} \\ b & \text{if } j = t \end{cases} \quad \forall j \in V \tag{2}$$

$$\sum_{\forall i \in E^{\rightarrow j}} y_{ij} - \sum_{\forall k \in E^{j \rightarrow}} y_{jk} = \begin{cases} -f_{max} & \text{if } j = s \\ 0 & \text{otherwise} \\ f_{max} & \text{if } j = t \end{cases} \quad \forall j \in V \tag{3}$$
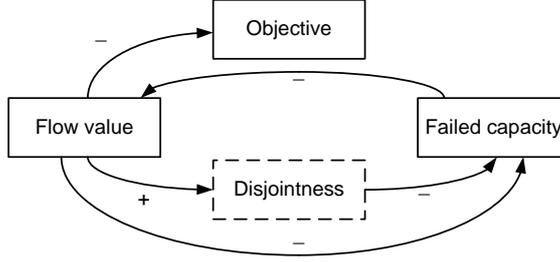
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Figure 2: The feedback mechanism of the Multi-Path Protection method; the objective of the linear program can be decreased by spreading the flow on multiple paths

$$x_{ij} + y_{ij} \leq f_{max} \quad \forall ij \in E \tag{4}$$

$$x_{ij} + y_{ij} \leq B'_{ij} \quad \forall ij \in E \tag{5}$$

To handle d multiple failures the following constraint has to be used instead of (3):

$$\sum_{i,l} y_{ij}^{(l)} - \sum_{k,l} y_{jk}^{(l)} = \begin{cases} -df_{max} & \text{if } j = s \\ 0 & \text{otherwise} \quad \forall j \\ df_{max} & \text{if } j = t \end{cases} \tag{6}$$

The principle behind the resource minimization of the Multi-Path Protection and familiar resilience schemes is illustrated in Figure 2. The feedback mechanism's workflow is as follows. The objective of LP is to minimize the reserved capacities in the network. As the value of the flow decreases the value of the objective function decreases as well. The only way to decrease the value of the is to reduce the value of failed capacity (f_{max}). How can this be decreased? If the flow is spread over several disjoint paths in the network then the capacities on the edges are decreased, resulting a reduced value of failed capacities.

Thesis 1.2. *[C3] I have proposed an enhanced version of the resilience scheme, called Improved Multi-Path Protection (IMPP), which is able to compute the cost minimizing resource allocation faster as it uses half as much LP variables as the original MPP scheme. Moreover, I have proposed a graph transformation method that enables the IMPP method to handle a group of SRLG scenarios, in particular where the links belonging to the same SRLG are connected to each other at least one point. Moreover, I have introduced additional constraints; applying these constraints causes that the IMPP allocates always two, SRLG-disjoint paths.*

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The linear program of the IMPP method, which is able to handle several SRLG scenarios, is formalized as follow:

Variables:

$\quad\quad x_{ij} \geq 0 \quad\quad\quad$ flow over edge $ij \in E$

$\quad\quad f_{max} \quad\quad\quad\quad$ the maximum capacity that may be failed

$\quad L = \{L^1, \ldots, L^p\} \quad$ SRLGs in the transformed graph

Objective:

$$min \sum_{\forall ij \in E} c_{ij} x_{ij} \tag{7}$$

Constraints:

$$\sum_{\forall i \in E \to j} x_{ij} - \sum_{\forall k \in E^{j\to}} x_{jk} = \begin{cases} -b - f_{max} & \text{if } j = s \\ 0 & \text{otherwise} \\ b + f_{max} & \text{if } j = t \end{cases} \quad \forall j \in V \tag{8}$$

$$x_{ij} \leq f_{max} \quad \forall ij \in E \tag{9}$$

$$x_{ij} \leq B'_{ij} \quad \forall ij \in E \tag{10}$$

$$\sum_{\forall ij \in L^g} l^g_{ij} \cdot x_{ij} \leq f_{max} \quad \forall g = 1, \ldots, p \tag{11}$$

Optional constraints:

$$b \leq f_{max} \tag{12}$$

$$x_{ij} = 0 \quad \text{if } B'_{ij} < b \quad \forall ij \in V \tag{13}$$

To be able to handle Shared Risk Link Groups (SRLGs) with Linear Program (LP) I introduced a network transformation model: the edges, which are connected at least at one node, of an SRLG must be converted into several edges. Every edge which belongs to an SRLG has to be split into two three parts with two newly added nodes.

I illustrate the network conversion by an example. A part of a network is drawn in Figure 3(a). The edges with solid lines belong to an SRLG. When a flow of a demand b goes through nodes 1–2–3 the sum of the capacities of the edges in the SRLG (constraint (11) in LP formula) will be $2b$. However, in case of a failure the value of the broken flow is only b. Accordingly, the graph has to be transformed to handle this kind of scenarios; Figure 3(b) shows the modified network. Every edge in the SRLG is substituted with two virtual nodes, then the nodes are connected with

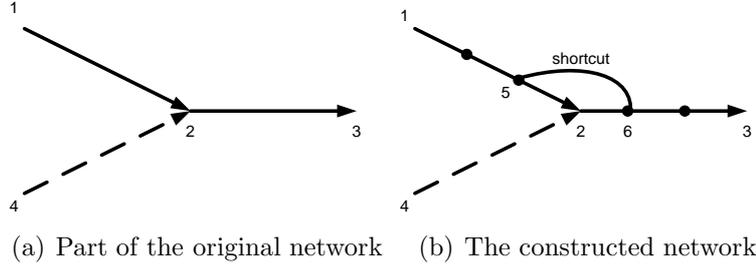(a) Part of the original network   (b) The constructed network

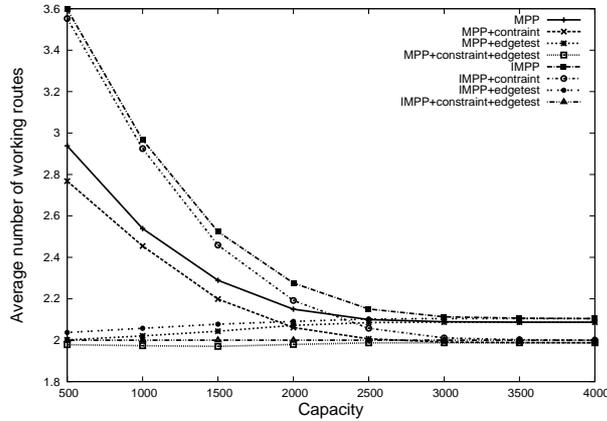Figure 3: Illustration of the graph transformation that enables to handle SRLGs in the IMPP formula

Figure 4: The number of working routes in case of several MPP methods; always two disjoint routes are allocated in case of the extended IMPP scheme

edges. The key part of the model is the usage of shortcut edge, which connects the virtual nodes of the SRLG edges (node 5 and 6). This shortcuts belong to the SRLG, but their flow values will be subtracted form the value of the SRLG; therefore, in case of the specified situation the value of the flow is b. I note that the model gives optimal resource allocation only in those situations, where the edges in SRLG are connected at least at one node; other type of SRLGs may be handled in this way but only with non-optimal resource reservation.

Using the introduced additional constraints (Eq. 12 and 13) the number of paths, where the resources are allocated, can be controlled. In particular, if both constraints are considered, exactly two disjoint paths will be used to route the demand. Based on simulation results, I quantified the number of paths in case of several MPP methods; the results are plotted in Figure 4.

Thesis 1.3. *[J7] I have proposed the path-link formulation of the Multi-Path Protection resilience scheme to be able to control the latency of the transmission, a crucial*

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socio-economic aspect. The routing and protection paths of the demand can be adjusted based on the pre-selection of the feasible paths. The Path-based Multi-Path Protection (PMPP) approximates the optimal MPP solution as the number of the selectable paths increases.

The LP formalization of the PMPP method is as follow:

Variables:

$x_p \geq 0$ flow realizing the demand on path p

$f_{max} \geq 0$ the maximum capacity that may be failed

Constants:

$\delta_{ep} = \begin{cases} 1 & \text{if } e \text{ belongs to path } p \\ 0 & \text{otherwise} \end{cases}$

Objective:

$$min \sum_{\forall p \in P} \sum_{\forall e} x_p \delta_{ep} c_e \tag{14}$$

Constraints:

$$\sum_{\forall p \in P} x_p = b + f_{max} \tag{15}$$

$$\sum_{\forall p \in P} x_p \delta_{ep} \leq f_{max} \quad \forall e \in E \tag{16}$$

$$\sum_{\forall p \in P} x_p \delta_{ep} \leq B'_e \quad \forall e \in E \tag{17}$$

Optional constraints:

$$b \leq f_{max} \tag{18}$$

$$x_p = 0 \quad \text{if } \exists e \in p : B'_e < b \quad \forall p \in P \tag{19}$$

In the LP formulation only the feasible paths are used, which are the elements of the P path list (e.g., those paths that have no more then n hops between the end nodes). In case of the original MPP method, every possible path can be used to route the demand between the end-points. Contrary, in case of Path-based MPP only a subset of the paths can be applied, e.g., the paths are selected based on the number of hops. Accordingly, if more and more paths are allowed to be used, the resource allocation of the PMPP method approximates the minimal resource allocation of MPP.

4.2 Pricing Internet Access for Loyal Customers

Customer loyalty as part of user behavior has significant impact on the Internet Service Providers' (ISPs) price setting strategies. Therefore, I have studied the pricing strategies of local Internet access providers in case of loyal customers. The notations used in this section are summarized in Table 1.

Thesis 2. *[J2, J3, C5, C6] I have proposed pricing strategies for Internet Service Providers with loyal customers in three main scenarios. First, I have investigated the pricing under uncertainties, where the ISPs do not have complete information. Second, I have showed what decisions have to be made if a new ISP enters a local market. Third, I have investigated long-term price setting strategies where the ISPs are aware of the future consequences of their current decisions.*

I have created a novel customer loyalty model, which is based on the price differences of the service providers. Let d be the price difference, meaning that if the price of a user's ISP is more than the other ISP's price plus d, then the user will be a switcher, i.e., the user leaves his/her ISP for the other one. The demand function is modeled as a constant function until a border price (α), if at least one of the ISPs set a price less than α, all the users buy Internet access but above α, none of them buy subscription.

I apply a few assumptions to model the ISP pricing problem. I suppose that ISPs offer flat-rate subscriptions because deploying a usage-based sophisticated pricing scheme would be too costly for the ISPs in general. I further assume that the consumer demand for Internet access is constant until the border price, i.e., the demand function is inelastic; this assumption is realistic in developed countries. Moreover, I assume that the ISPs cannot discriminate the subscribers with different prices, i.e., the users have a single reservation price. Finally, I suppose that every ISP plays rationally, i.e., selects its profit maximizing strategy.

Table 1: Notations

l_i	loyal customers of ISP$_i$
p_i	access price of ISP$_i$
d_i	price difference at which the customers of ISP$_i$ become disloyal
α	the highest price at which the Internet access can be sold
c	unit cost per customer
Θ	weight of the future in ISP's decision

4.2.1 Strategies under Uncertainties

Uncertainty can have at least two different meaning in ISP price setting games. On the one hand, a service provider might play mixed strategy because there do not exist a pure strategy equilibrium. In this case, the ISP has to set access prices with certain probabilities to have maximal profit. The price of the ISP is not the same every time; thus, the price is uncertain. On the other hand, an ISP knows exactly only the number of its users. The number of other ISPs' subscribers as well as the price difference are unknown. The ISP can set its price based on its beliefs resulting an uncertain price setting strategy.

Formation of Game A (Two-player ISP price setting game with price difference dependent loyal customers, G_A). Consider a local Internet access market, where two Internet Service Providers exist. The price setting game of the providers can be modeled as follow:

- **Players**: the Internet Service Providers, $i = 1, 2$; ISP_i has l_i loyal customers

- **Strategies**: the price of the Internet access, the decision of ISP_i is $p_i \in [0, \alpha]$; players play once as a single-shot game

- **Payoff functions**: the payoff of ISP_i is

$$\Pi_i = \begin{cases} (l_i + l_j)p_i & \text{if } p_i < p_j \text{ and } |p_i - p_j| > d_j \\ l_i p_i & \text{if } |p_i - p_j| \leq d_i \\ 0 & \text{if } p_i > p_j \text{ and } |p_i - p_j| > d_i \end{cases} \tag{20}$$

Figure 5 illustrates the payoff function (Eq. 20) in two different scenarios; the payoff of ISP_1 is plotted while the price of ISP_2 is fixed. Figure 5(a) presents the payoff function if the border price is not smaller than the price of ISP_2 plus the price difference. Until $p_2 - d$, ISP_1 has every subscriber; its profit is proportional to its price. If ISP_1's price is higher than $p - d$ but lower than $p + d$, ISP_1 provides Internet access only for its own customers. If ISP_1 sets a too high price, larger than $p_2 + d$, ISP_1 does not realize any profit because its subscribers switch to ISP_2. Figure 5(b) shows the payoff if the border price is lower than $p_2 + d$. In this case, ISP_1 keeps its customers and realizes profit until it sets a price smaller than α. In the figures, the highest point of the first linear segment is lower than the second's because the profit is proportional to the price. However, this is not always the case, e.g., if ISP_2 has much more users, then ISP_1 realizes higher payoff with low prices.

Thesis 2.1 (Equilibrium analysis of Internet pricing game with price difference dependent loyal subscribers). *[J3, C5] I have shown by analysis that*
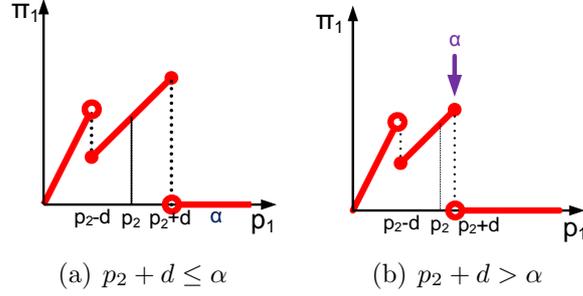
(a) $p_2 + d \leq \alpha$	(b) $p_2 + d > \alpha$

Figure 5: Illustration of the payoff function

(i) G_A *with incomplete information, where ISP_i knows exactly α, d, l_i and has a commonly known belief about the probability distribution of the value of l_j, has a single pure strategy Bayesian equilibrium at (α, α) with payoffs $l_1\alpha, l_2\alpha$ if the followings hold:*

$$\frac{\boldsymbol{E}l_2}{l_1 + \boldsymbol{E}l_2} \leq \frac{d}{\alpha} \tag{21}$$

$$\frac{\boldsymbol{E}l_1}{\boldsymbol{E}l_1 + l_2} \leq \frac{d}{\alpha} \tag{22}$$

Furthermore, I have formulated the condition of the existence of the only pure strategy Bayesian equilibrium $(\alpha, \dots, \alpha)$ in case of the generalization of G_A for N ISPs:

$$\forall i : 1 - \frac{l_i}{l_i + \sum_{j \neq i} El_j} \leq \frac{d}{\alpha} \tag{23}$$

(ii) (α, α) *is a Nash equilibrium of G_A where the ISPs have users with diverse loyalties d_1 and d_2 if*

$$\frac{l_i}{l_i + l_j} \leq \frac{d_i}{\alpha} \quad i = 1, 2 \tag{24}$$

Moreover, I have shown that if there exist disloyal users on the market, the game does not have a pure strategy Nash equilibrium, i.e., the ISPs cannot maximize their payoffs using their pure equilibrium strategies.

(iii) *the G_A game, if there does not exist a pure equilibrium, has the following mixed*
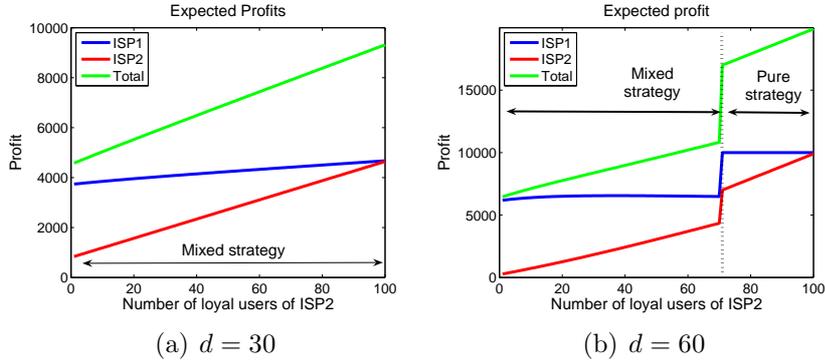
Figure 6: Expected payoffs if ISP_2 has different number of loyal users

strategy equilibrium with cumulative distribution functions as follow:

$$F_i(p) = \begin{cases} 0 & p_i < \frac{l_i}{l_i+l_j}d \\ \frac{p - \frac{l_i}{l_i+l_j}d}{\alpha - \frac{l_i}{l_i+l_j}d} & \frac{l_i}{l_i+l_j}d \le p_i \le \alpha \\ 1 & \alpha < p_i \end{cases} \quad (25)$$

Figure 6 shows the effect of the loyal user base size on the expected payoffs. I plot the profits of the ISPs and the total profit simultaneously. The minimal price difference is in Figure 6(a) 30 and 60 in Figure 6(b); the price difference affects the expected payoffs. The plots of the lower value are continuous meaning that in this case the ISPs are playing always their mixed strategies. The profit of ISP_2 increases better as it has more and more loyal users. The jump in Figure 6(b) presents the change between the mixed and the pure strategies. The expected payoff of ISP_i is constant or a really slightly decreasing as ISP_2 has more loyal users.

4.2.2 Dynamic Market

I have studied the Internet access pricing problem when a new ISP enters to a local ISP market. I model the entry situation with a sequential game. First, the entrant ISP selects an action: it can enter to the market or not. If the entrant ISP decides to enter, the incumbent providers have two possibilities: set a low enough price to keep all of its customers or set a profit maximizing price.

Formation of Game B (Internet access pricing on a dynamic market, G_B). The local Internet access market is modeled as follows. The demand for Internet access is constant until an α reservation price. Every ISP has customers who are loyal to

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their provider, formally ISP$_i$ has l_i loyal subscribers. Everyone who has an Internet subscription belongs to an ISP; there do not exist independent users on the market. I model the price difference dependent loyalty of the ISP$_i$'s subscribers with a linear function, a provider looses $L_i = \frac{p_i - p_j}{\alpha} l_i$ customers if ISP$_j$ has a lower price ($p_j < p_i$). The cost of providing Internet access is denoted by c. The formal definition of game is as follow:

- **Players**: the Internet Service Providers, ISP$_1$ is the incumbent with l_1 while ISP$_2$ is the entrant

- **Strategies**: ISP$_2$ decides whether to enter the market, then the ISPs set the price of the Internet access; the decision of ISP$_i$ is $p_i \in [0, \alpha]$, ISPs can have only pure strategies; they play a single-shot, Stackelberg leader-follower game

- **Payoff functions**: the payoff of ISP$_i$ is

$$\Pi_i(p) = p_i \cdot l_i \tag{26}$$

- **Information**: complete

In Figure 7, the G_B game is illustrated with the utilities of the cases both in extensive and strategic form. It can be seen that the threat of ISP$_1$, set c as price, is incredible. If the new ISP enters the market the incumbent can have higher payoff not playing this option. Accordingly, if it is worth for ISP$_2$ to enter, the ISPs will play a Stackelberg leader-follower price setting game where ISP$_1$ is the leader of the game and the entrant ISP$_2$ is the follower. ISP$_1$ sets her price first when the entry of ISP$_2$ turns out, after that ISP$_2$ selects her own price. ISP$_2$ decides about the entry based on the number of users who it will have after the entry, if ISP$_2$ can earn at least C, the cost of the entry, it will enter the market.

Thesis 2.2. *[J2, C5] I have derived price setting strategies for ISPs*

(i) in G_B pricing game, where a new ISP enters to a monopolistic market. The Stackelberg equilibrium prices and market shares of the ISPs are as follow:

$$
\begin{aligned}
p_1^S &= \alpha & p_2^S &= \frac{\alpha}{2} + \frac{c}{2} \\
l_1^S &= \left(\frac{1}{2} + \frac{c}{2\alpha}\right) l_1 & l_2^S &= \left(\frac{1}{2} - \frac{c}{2\alpha}\right) l_1 \\
\Pi_1 &= \left(\frac{1}{2} + \frac{c}{2\alpha}\right) l_1 (\alpha - c) & \Pi_2 &= \left(\frac{1}{2} - \frac{c}{2\alpha}\right) l_1 \left(\frac{\alpha}{2} + \frac{c}{2}\right)
\end{aligned}
$$

(ii) in G_B pricing game, where a new ISP enters to a competitive market with $i = 1, \ldots, n$ incumbent ISPs. The computations yield the following implicit
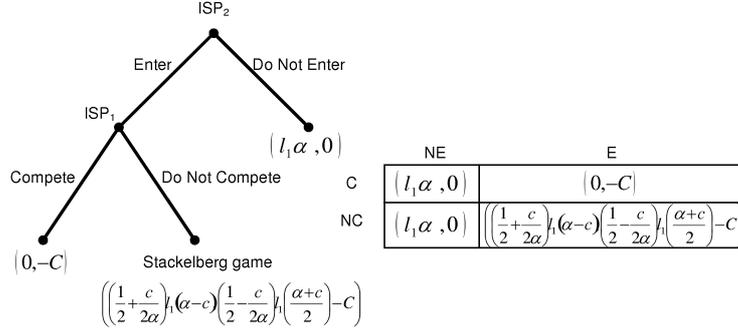
Figure 7: Extensive and strategic form of entering game

expressions for the Stackelberg equilibrium prices:

$$p_k^* = \frac{(2\alpha + c)\sum_i l_i + \sum_{i\neq k} l_i p_i}{2\sum_i l_i + l_k} \frac{1}{2} + \frac{c}{2} \quad k = 1, \ldots, N \tag{27}$$

$$p_j^* = \frac{c}{2} + \frac{\sum_i l_i p_i}{2\sum_i l_i} \tag{28}$$

while the equilibrium market shares of the ISPs are:

$$l_i^* = \left(1 - \frac{p_i^* - p_{n+1}^*}{\alpha}\right) l_i \quad i = 1, \ldots, N \tag{29}$$

$$l_j^* = \sum_i \frac{p_i^* - p_{n+1}^*}{\alpha} l_i \tag{30}$$

The equilibrium prices produce a system of linear equations in case of the competitive market, where the variables are the prices of the ISPs. The equilibrium prices of the Stackelberg ISP price setting game solve the following system of linear equations:

$$
\begin{pmatrix}
1 & -\frac{1}{2}\frac{\sum_{i\neq 2} l_i}{2\sum l_i - l_2} & \cdots & -\frac{1}{2}\frac{\sum_{i\neq n} l_i}{2\sum l_i - l_N} & 0 \\
\vdots & \ddots & & \vdots & \vdots \\
-\frac{1}{2}\frac{\sum_{i\neq 1} l_i}{2\sum l_i - l_1} & \frac{1}{2}\frac{-\sum_{i\neq 2} l_i}{2\sum l_i - l_2} & \cdots & 1 & 0 \\
\frac{l_1}{2\sum l_i} & \frac{l_2}{2\sum l_i} & \cdots & \frac{l_N}{2\sum l_i} & 1
\end{pmatrix}
\begin{pmatrix}
p_1^* \\ \vdots \\ p_N^* \\ p_j^*
\end{pmatrix}
=
\begin{pmatrix}
\frac{1}{2}\frac{(2\alpha+c)\sum l_i}{2\sum l_i - l_1} + \frac{c}{2} \\
\vdots \\
\frac{1}{2}\frac{(2\alpha+c)\sum l_i}{2\sum l_i - l_N} + \frac{c}{2} \\
\frac{c}{2}
\end{pmatrix}
$$

4.2.3 Long-term Strategies

Previous research focused mainly on *short-term* interactions of the ISPs, which is not usually the case in practice as ISPs have to be aware of the *long-term* effects of

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their pricing decisions. Future-aware decision making is even more important if the structure of the local ISP market changes, e.g., a new ISP enters the market. I have addressed the issue of long-term pricing strategies of ISPs on local access markets with customer loyalty.

Internet Service Providers are playing usually their price setting game repeatedly, e.g., they set a new price every month. I have investigated the price difference dependent loyalty model as a repeated game to analyze it as a long-term pricing strategy.

Formation of Game C (Long-term Internet access pricing with loyal customers, G_C)**.** There exist two ISPs on the market, ISP_1 has l_1 loyal customers while ISP_2 has l_2. The repeated game is modeled using discounted payoffs where the price is discounted at each step with discount factor $0 \leq \Theta \leq 1$. Θ expresses the weight of the future in ISP's decision, e.g., if $\Theta = 0$ only current payoff is considered. It is assumed that an ISP can lose its loyal customer only for that specific round of the game, in the next round it will have her loyal users again, e.g., ISP_1 will have l_1 loyal user at the beginning of every round. An ISP's profit is $\Pi_i^{coorp} = l_i \alpha$ in case of cooperation and $\Pi_i^{not} = l_i d$ if it does not cooperate. The formal definition game is as follow:

- **Players**: the two ISPs, ISP_i has l_i loyal customers

- **Strategies**: $p_i \in [0, \alpha]$ the price of the Internet access at ISP_i, players play multiple rounds as a repeated game, the discount factor of ISP_i is Θ_i

- **Payoff functions**: the payoff of ISP_i is

$$
\Pi_i = \begin{cases} (l_i + l_j)p_i & \text{if } p_i < p_j \text{ and } |p_i - p_j| > d_j \\ l_i p_i & \text{if } |p_i - p_j| \leq d_i \\ 0 & \text{if } p_i > p_j \text{ and } |p_i - p_j| > d_i \end{cases} \tag{31}
$$

- **Information**: complete

Thesis 2.3. *[J2, C6] I have shown by analytical computation that the strategy profile "Set α as a price until the other player deviates, i.e., sets lower price with at least d, than play d as a price" is a sub-game perfect equilibrium for the repeated game G_C, where Θ_i is the discount factor of ISP_i, if $\Theta_i > \frac{(l_1+l_2)(\alpha-d)-l_i\alpha}{(l_1+l_2)(\alpha-d)-2l_id}$ holds.*

Accordingly, if the ISPs weight the future incomes at least with Θ then the strategy is optimal in long-term resulting maximal payoffs.

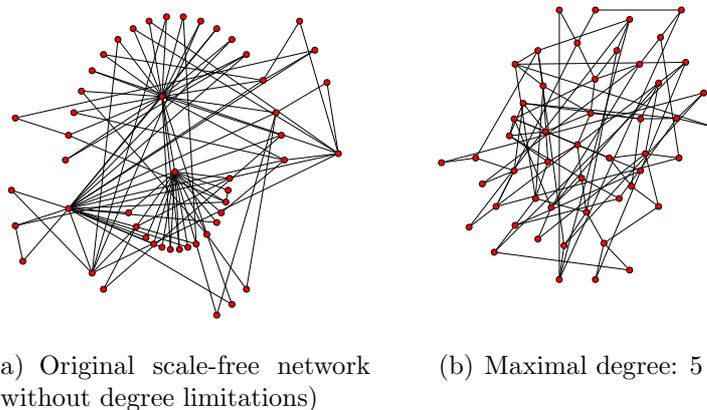(a) Original scale-free network (without degree limitations)

(b) Maximal degree: 5

Figure 8: Illustration of scale-free network inspired topologies

4.3 Scafida: A Scale-Free Network Inspired Data Center Architecture

In this thesis, I propose a novel data center network generation method. The design of the Scafida algorithm follows a radically different approach than that of the state-of-the-art data centers. Instead of creating a symmetric design, the Scafida data centers generate the network probabilistically; accordingly, the structures are asymmetric. Scafida is inspired by biological networks; therefore, it is energy efficient due to its flexibility and scalability.

Thesis 3. *[B1, J1, J9, C1] I have proposed a data center architecture generation method called Scafida. Scafida is inspired by scale-free networks; therefore, it is highly scalable and flexible. The algorithm artificially limits the degrees of the nodes to meet the physical constraints of the network equipments. In addition, I analyzed the impact of the degree limitation on the lengths of the paths in the networks; the path lengths are inversely proportional to the degree limitation.*

Thesis 3.1 (Scafida algorithm)**.** *[J1, C1] I have proposed a data center generating algorithm, called Scafida, inspired by scale-free networks. To meet the physical constraints of network equipments, i.e. the number of ports of switches and servers, the method artificially limits the degrees of the nodes. The algorithm is able to generate data center networks out of any given number and type of network equipments. The Scafida algorithm is presented in Figure 9.*

The proposed Scafida algorithm is based on the scale-free network creation algorithm of Barabási and Albert [14], which is also known as preferential attachment.

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The network structure is generated iteratively, i.e., the nodes are added one by one; a new node is attached probabilistically to an existing node proportional to the node's degree. This phenomenon is also known as the richer gets richer principle. The Scafida method artificially constrains the number of links that a node can have, i.e., the maximal degree of the nodes, in order to meet the port number of network routers and switches.

In order to visualize the Scafida data center architecture concept, in Figure 8 I show two topologies generated with the proposed method. The topology in Figure 8(a) presents an ordinary Barabási–Albert scale-free network, where the maximal degree of the nodes is not limited. Accordingly, some nodes have much more edges than the others; e.g., the three vertices in the middle have more than 10 links. In contrast, Figure 8(b) presents a topology where the maximal degree that a node may have is limited (5 links). The two topologies differ in their node degree distributions; however, their properties are similar (the details are presented in Thesis 3.3).

Thesis 3.2 (Minimum degree constrain). *[J1, C1] I have derived a lower limit of the degree limitation that introduces the relation between the number of nodes (n), links (m), and the degree limitation (t). A constrained scale-free network can be created out of the parameters if the following expression holds:*

$$t \geq 2m \left(1 - \frac{m}{n} \right) \tag{32}$$

This result means that the degrees of the nodes can be decreased only until a specific value; otherwise, the data center network cannot be constructed given the parameters. Accordingly, the proposed formula can be used to check the feasibility of a design.

Thesis 3.3 (Impact of constraining degree). *[J1, C1] I have shown based on simulation results that the degree constraining of scale-free networks does not increases significantly the average lengths of the paths. In particular, I have shown that the average path length is inversely proportional to the limitation number, i.e.,*

$$l \sim \frac{1}{t - 2m \left(1 - \frac{m}{n} \right)} \tag{33}$$

where t denotes the maximal degree that a node may have in the network. Moreover, I have shown that the degree constraining of scale-free networks enhances the networks' resilience against random failures.

The results of the theses assure the feasibility of the scale-free network inspired data center networks. On the one hand, irrespective of the size of the networks, the average lengths of the paths increase moderately because of the constrained degrees;

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Input:

number of servers (n_{t_0}); number of servers' ports (p_{t_0}); number of t_i type switches $(n_{t_1}, \ldots, n_{t_k})$; number of ports of t_i type switches $(p_{t_1}, \ldots, p_{t_k})$; number of t_i type switches already allocated (a_{t_i}); degree of the node v (d_v); number of links a newly added node has (m)

Algorithm:

1 $G = (V, E)$ // an empty graph
2 $V = V \cup \{0, 1, \ldots, m - 1\}$ // add initial nodes
3 $a_{t_i} = 0; \quad i = 0, \ldots, k$ // initialization
4 $R = \{\}$ // used for preferential attachment
5 $E = E \cup \{(m, 0), (m, 1), \ldots, (m, m - 1)\}$
6 $R = R \cup \{0, \ldots, m - 1\}$ // update the index list
7 $R = R \cup \{m, \ldots, m\}$ // m times
8 $b = m + 1$ // the index of the next vertex
9 **while** $b < \sum_{i=0}^{k} n_{t_i}$ **do**
10     $V = V \cup \{b\}$ // add the node to the graph
11     $T = \{\}$ // store the selected target nodes
12   **while** $|T| < m$ **do**
13   **repeat** $v_t = random(R)$ **until** $v_t \notin T$ // a random item of R
14   **if** $d_{v_t} \notin \{p_{t_0}, \ldots, p_{t_k}\}$ **then**
15           $T = T \cup \{v_t\}; E = E \cup \{(b, v_t)\}$
16   **else**
         // let $d_{v_t} = p_{t_i}$ w.l.o.g.
17           $nasw = 0; ntsw = 0$
18   **for** $j = 0, \ldots, k$ **do**
19   **if** $p_{t_j} > p_{t_i}$ **then**
20                 $nasw {+}= a_{t_j}; ntsw {+}= n_{t_j}$
21   **if** $nasw < ntsw$ **then**
            // the target switch can have more ports
22              $a_{t_i} = a_{t_i} - 1; a_{t_{i+1}} = a_{t_{i+1}} + 1$
23              $T = T \cup \{v_t\}; E = E \cup \{(b, v_t)\}$
24   **else**
25              $R = R \setminus \{v_t\}$
26     $R = R \cup T$ // update the index list
27   **for** $i = 1, \ldots, m$ **do** $R = R \cup \{b\}$
28     $b = b + 1$

Figure 9: The pseudocode of Scafida algorithm
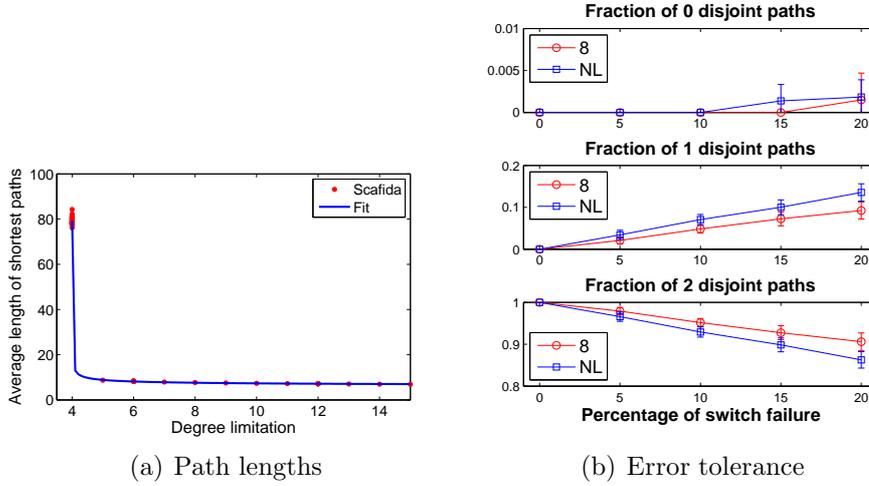
(a) Path lengths   (b) Error tolerance

Figure 10: The impact of constraining the degrees of the nodes

in most cases the increment of the lengths is less than an additional hop. I show the average shortest path length of several networks with 50000 vertices, having different degree limitations; the generation algorithm was used with m=2 (Figure 10(a)). The presented fitting curve estimates the simulation results well as the R-square value of the fit is 0.9994. The lower limit of Thesis 3.2 is utilized in the curve fitting; the value of the fitting curve is valid until the constraint is not violated.

Resulting from their specific structure scale-free networks tolerate efficiently the random failure of nodes [8]. Stochastic failure of network equipments is ordinary in data centers because of their size; therefore, this is a desirable property of Scafida. The impact of constraining degree on the resilience of the architectures is quantified by investigating the number of disjoint paths between every pair of servers. In the simulations, a fraction of the switches fails in the networks; the percentage of the failed switches is scaled from 0 to 20 in steps of 5. 1000-node Scafida topologies are analyzed using several error scenarios; the results are averaged over these simulations. As it is assumed that the servers have two ports, the number of disjoint paths between two servers can be at most two. Accordingly, in Figure 10(b) the ratio of server pairs is plotted; the different figures present different number of disjoint paths. Two extreme cases are shown, one where the degrees are not constrained (i.e., an original scale-free network) and one where the maximal degree is 8. The error tolerance of Scafida is presented best on the last figure, where the results for two disjoint paths are shown. Even if 20 percent of the switches fail more than 90 percent of the server pairs still have two disjoint paths. The error tolerance of Scafida is even better than that of the original scale-free networks because the impact of a failure can be significant in case of a failure of a switch with large degree.

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Therefore, the proposed data center architecture generation method has preferable properties although the degrees of the nodes are artificially limited.

Thesis 3.4 (Power consumption of Scafida data centers). *[B1, J9] I have shown based on simulation results that the power consumption of Scafida data centers is proportional to the number of servers that the architectures have; accordingly, I have shown that Scafida is a energy proportional data center architecture. In addition, I have analyzed the power consumption of state-of-the-art data centers as well; I have shown that these structures do not have an energy proportional design.*

The implication of this thesis is that Scafida is more energy efficient than state-of-the-art data center networks. Energy efficiency is a crucial socio-economic property as it has an impact on the expenditures of the operators and on the environment as well.

The power consumptions of state-of-the-art data center architectures are shown in Figure 11(a) as a function of the number of servers in the structure. The topologies are generated by scaling the parameters of the data center structures; thus, increasing the number of servers in the topology. As the topologies have only one or two parameters, there is only moderate possibility to adjust the properties of the architectures. Therefore, the structures of these data centers are rigid. This rigidity causes the large steps in the curves as to include for example one additional server to a data center, which is completely utilized considering the actual generation parameters, a much larger network structure has to be deployed that consumes more power.

The proposed Scafida data center architecture is highly scalable; therefore, any size of data center can be generated. The power consumption of several Scafida topologies, consisting of commodity switches, are shown in Figure 11(b). The power consumption of Scafida data centers is proportional to the size of the system regardless of the type of the switches. Contrary to the state-of-the-art data centers, where the steps in the power consumption were caused by the structure of the generation methods, in case of Scafida the steps are only due to the scaling of the simulation parameters. Thus, if Scafida topologies would be generated for all the possible number of servers, the curves of the figure would be linear without any significant jumps. This implies that the Scafida data center structure is energy proportional; therefore, it can be applied in those cases too, where the size of the data center increases frequently.
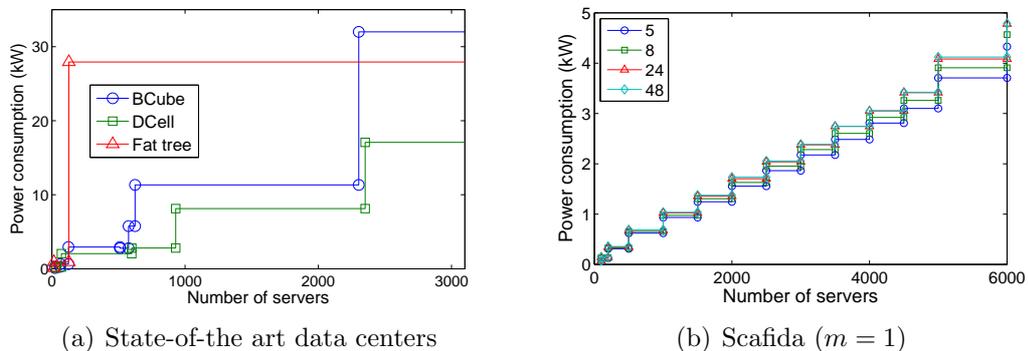
(a) State-of-the art data centers

(b) Scafida ($m = 1$)

Figure 11: Power consumption of state-of-the-art and Scafida data centers

5 Application of the Results

The proposed network resilience methods of Section 4.1 have simple LP formulation that gives the global optimum in polynomial time, making the Multi-Path Protection schemes useful not only as a reference but even acceptable for online routing in networks of moderate size. The main advantage of the schemes is that they require only topology and link state information similar to dedicated path protection does; however, they do not need any information on the routing of all working and protection paths of all the demands as shared path protection does. This makes MPP methods very useful in a multi-domain environment where multiple network operators run the different domains, and they are not willing to share their confidential data, e.g., on intra-domain routing of the demands with their competitors. In addition, the introduced Path-based MPP method (Thesis 1.3) allows controlling the maximal length of the used paths; this feature helps to maintain high availability and to constrain propagation delays resulting better user experience.

The applicability of the proposed ISP pricing strategies of Section 4.2 are twofold. On the one hand, telecommunication authorities can model the impacts of their regulations, e.g., the cost of decoupling of local wires. Based on simulations of different market scenarios, the authorities can create incentives for both incumbents and entrants to enhance the competition on the local ISP market. On the other hand, the presented price setting strategies can be used by local Internet Service Providers as a guideline of their strategic, long-term price setting behavior. As the local ISP markets will be more and more dynamic, an optimal strategy is crucial to remain competitive. The presented strategies can be treated as a starting point for long-term Internet access pricing on dynamic markets. In addition, the results show that ISPs have to change their access prices paying attention to the price differences, a too small price reduction might not result enough new customers. An ISP can expect more profit if

she knows better the price difference of the population as it has an important impact on the prices.

The Scafida data center generation method proposed in Section 4.3 can be used to create more energy efficient data center networks. Scale-free network-inspired data centers are highly scalable; therefore, their power consumption is configurable in fine-grained quantities. While state-of-the-art data center architectures are not energy proportional, the power consumption of Scafida data centers is proportional to the number of its servers. Besides this, another significant implication of the structure is that data centers can be built out of any number of network equipments; i.e., the structure is highly flexible. The presented results are based on the properties of currently available commodity switches; however, as the size of these equipments increases the properties of Scafida data center structure enhance because they will approximate more and more the properties of unconstrained scale-free networks. Due to the fact that preferable properties of scale-free networks hold in case of low node degrees too, Scafida can also be applied in data centers, where the servers are interconnected with each others [22]; the usage of the Scafida method may extremely reduce the diameter of these structures. In addition, the finding of Thesis 3.3 implies that degree-constrained scale-free network topologies may be applied in peer-to-peer systems. On the one hand, the load of a single node can be controlled with the degree limitation while, on the other hand, the diameter of the network, which determines the speed of the localization of the content, does not increase significantly assuming a reasonable degree limitation.

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