Dynamically established transmission paths in the future Internet – proposal of a framework

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Abstract. An idea of a global system for dynamic contracting data paths in the global IP network is presented. System scalability and efficiency is based on the current natural hierarchy of Internet providers. Architecture of the bandwidth market service accomplishing operation of such system is outlined. Benefits from dynamic provisioning of such dedicated paths with QoS guarantees are shown. Utilization of various technologies for this system is discussed.

Key words: data path, QoS, interconnection, future Internet, NGN, services marketplace.

1. Introduction

Future Internet is now a broad term referring to the technology to be developed in order to meet requirements of contemporary and yet unknown ways users utilise the global communication network. Indeed, openness and ubiquity of future Internet (FI) are the key postulates that imply a series of more specific ones. Following [1], we can recall a few, particularly relevant to the content of this paper: ability of FI to adapt to demand dynamics, QoS support in the large, sustainable economic model for all players. Next Generation Networks (NGNs), being rolled out nowadays in most countries can be perceived as close approximations to FI, save for the fact they address only a part of Internet users.

This is still discussed whether the Internet Protocol (IP) can satisfy postulates for FI, or shall be substituted by some more adequate technology. Theoretically, one can imagine IP sharing the fate of Asynchronous Transfer Mode (ATM) technology, although the today's tremendous diffusion of IP devices make such scenario unthinkable at the first glance.

There is much work in progress on technologies and architectures that would comprise the Future Internet – considerable part of them being sponsored by the European Commission (EC). They effectively cover virtually all aspects of FI: QoS, protocols, virtualisation, interconnection, privacy and trust, economics. With their impressive results, they fail, in our opinion, to address and to harness what is one of current Internet strengths: its hierarchical topology. We do utilise it in our work.

This paper proposes a framework for dynamic contracting data transmission channels in the Internet of the future. We define roles, scenarios, system architecture, and show sustainability of the system by providing basic calculations. While not contesting the work done by the others, we focus on exploiting the current hierarchical nature of the web, and we

propose introduction of mechanisms uniform in all layers of the tiered Internet structure.

The paper is organised as follows. Overview of research projects, mostly supported by the EC Seventh Framework Programme, and their results is given in Sec. 2. Next, functionality of our novel framework is presented in Sec. 3, followed by detailed discussion of scalability issues in Sec. 4. Further analysis of the framework operation in a distributed way is carried out in Sec. 5. Finally, a reasoning is given in Sec. 6 for profitability of the framework for all network players. We conclude in Sec. 7.

2. Future Internet – work in progress

In order to realise the notion of the future Internet, as laid out in [1], one needs to put together and implement three basic components: technology, business model and security. Certainly, they overlap and are mutually dependent; for instance, the cost and constraints imposed by application of security means and trust management framework impacts both technologies for QoS and the way services market operates. However, due to practical reasons they often get decoupled in the process of FI design, e.g. the technology is addressed first, the economics next and, lastly, the security of the network. Such partitioning and sequence of work is reflected in the structure and chronology of EC-sponsored relevant research projects.

2.1. Technology. It seems that technological issues have always had their fair share of attention, resulting in research following network development closely. QoS-enabled technologies have been present from the very start of networking; let us recall X.25 or ATM to name a few of them. Internet protocol, although designed with different guidelines, also has mechanisms for traffic prioritisation and traffic engineering

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(Diffserv, RSVP). In parallel, QoS has been introduced to lower-layer protocols: Ethernet (802.1p standard) and MPLS (MPLS-TE).

Research projects, DAIDALOS, MESCAL, NETQoS and EUQoS [2], studied how to exploit existing technologies in order to provide end-to-end QoS guarantees, taking into account QoS classes mapping when interconnection is required. In short, their outcome has been positive in the sense that it is possible to provide QoS just by utilising the built-in network mechanisms, with specific control plane strategies implemented, like traffic engineering (TE) and connection admission control (CAC). The research by the authors of this paper has also proven that on-demand resource allocation system in IP network (within a single administrative domain) is simple in creation, effective and efficient in operation [3].

With the advent of overlay networks transmitting huge amounts of data, like peer to peer and, in particular, content distribution structured networks, research focus shifted towards the concept of virtualisation. Dynamic acquisition of services from the cloud (e.g. processing, transmission, authorisation, storage) in order to build a new, complex service with added value, is the aim of GENI project, supported by NSF. A virtual distributed worldwide laboratory has been created, with a unified access protocol, opening ways for scientific community to experience and study virtualisation benefits. Resource allocation and charging is done by a single clearing house.

Similar European research projects are RESERVOIR, GEYSERS and 4WARD. RESERVOIR project [4] is oriented towards creation of a management system for cloud computing and FI, defining service description format and providing service query and location, service migration, SLA guarantees etc. In particular, RESERVOIR envisages on-demand federations of transmission service providers, sketching appropriate interfaces to be used by them. GEYSERS presents an application-centric approach to resource reservation, focusing on defining interfaces that allow specification of resources. On the network side, the project defines interconnection interfaces and formulates TE and routing strategies as carbon footprint reduction tasks. Also, interfaces for mutual billing are considered, however abstracted from concrete pricing methodologies. 4WARD covers a broad range of topics related to virtualisation, including generic paths, new architectural framework, network and information management. 4WARD postulates to deploy network management logic at networking devices, thus allowing dynamic resource exploration, acquisition and composition in a scalable way. Finally, STRONGEST project aim is to develop brand new fast optical networks with dynamic path contracting capabilities.

Strangely enough, a suite of mature virtualisation technologies elaborated in the abovementioned projects does not proliferate in the network so much they can be tangible by an individual. Certainly, one can watch video on demand or share her own resources or set up a virtual meeting – but all these activities are available via powerful service providers. Those providers naturally make good business based on virtualisation and cloud computing. However, the point is how to make the global network content neutral not only to big players, but to every individual, thus stimulating easy creation of novel services for companies of any size.

What is now available for the end users is the so-called Next Generation Network (NGN). Designed to enrich current plain telecommunication services with a suite of new or still to be invented applications, it defines a set of interfaces for committing appropriate network resources. Thus, we have user-, application- and network-network interfaces, with session initiation protocol (SIP) being proposed for signalling. However, NGN does not encompass basic FI principles as flexible business models or global trust management [5].

2.2. Economics. The lack of economic drivers is the reason why we still speak of future Internet in future tense. It has turned out some time ago that overprovisioning of bandwidth just stimulates demand but does not yield the expected income for the operator. Making it possible to download a Blue Ray movie in half an hour just brings appetite to try yet higher resolution – such scenario resembles investments in ever unwieldy road system.

Appropriate service pricing preconditions success of all services with QoS guarantees. This is valid even for simple scenarios where the service is provided by one provider, as it was examined by QoSIPS project [6]. Service level agreements force the provider to commit network resources, and result in service pricing higher than for best-effort transmission. Therefore it is crucial to make such agreements on user demand. RNAP protocol [7] was proposed that enables spot price calculation in a scenario when a transmission service involves more than one network provider. Such idea was further developed in EC-sponsored M3I project that focused on implementation of transmission protocol endowed with pricing signals accumulating component prices from all domains a flow goes through. CoCOMBINE (Competition, Contents and Broadband for the Internet in Europe) project was, in turn, devoted to analysing position of players on the telecommunication market, with the aim to detect opportunities for real competition. The project abstained from dynamic service contracting and from QoS issues. Such research initiatives were justified because the lack of incentives for incumbent operators, new entrants and content providers to cooperate is evident. Abusive paid peering agreements [8], artificially increased transit costs and hot potato routing, to name a few, are a commonplace.

SMOOTHIT, TRILOGY and ETICS projects constitute the next generation of EC-funded thread of research concerning networking economics. SMOOTHIT is tightly bound to issues of overlay networks and resource virtualisation. Being M3I follower, the project is to study theory and develop technology securing fair share for all entities involved in operation of overlay networks, and for its users. The project focuses mainly on the economics of overlay network setup and operation, and on the technology implementing the results of the theoretical work, with major scope to flatten current hierarchical Internet architecture and make small providers have their share in transit business. TRILOGY [9] develops

both new networking technology (enabling multipath transmission, separation of user identification and location IDs etc. – to avoid clean-slate FI approach, unlike Japanese AKARI project [10]) and tries to elaborate new sustainable economic models for FI stakeholders. Economics of future Internet is studied still in more detail by ETICS: a number of typical FI business scenarios are envisaged, with business roles cleanly identified, including Marketplace Provider, offering various mechanisms of resource trading [11]. Typical resource allocation and cost sharing schemes are presented, currently without their clean mapping to typical FI use scenarios. Regulator role is discussed in detail. Neither ETICS postulates clean-slate FI design approach.

It is quite evident that networking technology is developing fast. New sub-layers like MPLS, driven by OSPF-TE and located between the OSI data and network layers, are the de facto standard, virtualisation of resources is advanced and energy-saving issues are at focus. Meanwhile, economic incentives for a democratic yet sustainable services marketplace are at low ebb: once praised MERKATO bandwidth trading platform, from Invisible Hand Networks, Inc., the flagship of liberalism has just been washed out from the business along with the company. Meanwhile, scientific projects study with equal attention application of advanced game-theoretic auction mechanisms as well as a bit stale congestion pricing ideas.

A free market of networking services can be introduced instantly and forcibly by legal regulations. With a system of subsidies and wise trading mechanism design, a regulator can achieve in such scenario also some social goals, e.g. digital divide reduction. However, such approach is openly criticised by existent big players. It happened so in Poland in case of electricity market, when sell offers got anonymised on the trading platform. This put a threat on power corporations, being at the same time producers and energy distributors, they would distribute their competitors' energy. Decoupling vertically integrated structures is really hard.

Our proposal takes into account the fact that networking market is still far from being regulated. Big operators benefit now from network externalities, and we let them do that, exploiting in exchange the preserved hierarchical multi-tiered structure of the Internet. What we propose is to enable dynamic service contracting as the first step. We believe this will inevitably accelerate the course of events, finally making the competition between providers more and more real. Following the basic economic principles, the end user always profits more if she is given a bigger choice.

3. Proposed framework functionality

This paper contributes to the research on FI by defining concepts of an alternative, economically viable framework within which contracts for dynamically established data paths are made by all sorts of network users. Let us define roles and describe a basic scenario for setting up a data path traversing more than one network domain.

3.1. The roles. There are three roles a market entity can play:

- service user – the party that will use a dynamically contracted data channel (path) with QoS guarantees,
- service provider – the party that can provide the channel to the user – either alone or jointly with other providers,
- service market system operator – the party that runs the service for contract making and maintains business relationships with users and providers.

There are no limits on the roles a market entity can play. In particular, a small network operator will play service provider for its directly connected customers while, at the same time but not on the same timescale, it must play the user role in interaction with its transit providers. Unlimited access to roles opens more possibilities for added value services like virtual network providers. Characteristically, such polymorphism still supports existence of vertically integrated services because participation in such open market is voluntary.

Despite lack of formal obligations to participate, such framework will eventually make the FI operate driven by the invisible hand of the market. It is just because of giving all roles the freedom of choice:

- for the users – a set of alternative providers and different service marketplaces,
- for the providers – freedom of requesting a price at their will,
- for the market system operators – a multitude of trading mechanisms they can offer.

3.2. The basic scenario. Figure 1 presents our model of the Internet along with key elements of the proposed global bandwidth market and the basic path contracting scenario. Ellipses denote network subsystems, each being under control of a separate market entity (operators or customers). Subsystems are connected by links, and one can always indicate a transit point where the exact border between two subsystems lies. Usually this is a port of a network switch. However, for us a link between subsystems is much more important in network modelling.
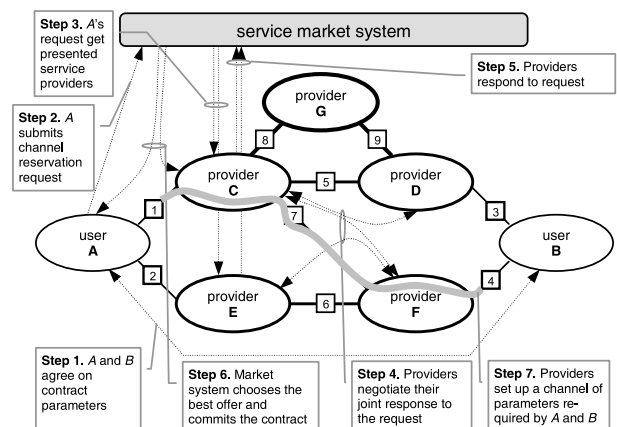

Fig. 1. Interconnection model and basic scenario for path setup

Various line widths in Fig. 1 indicate different importance of market entities and link throughputs. The proposed scenario

for establishing a path with QoS guarantees consists in contracting, via the market, an appropriate transmission channel connecting a pair of transit points.

The basic scenario for contracting the path is as follows:

1. The aim is to set up a communication channel providing connectivity between users A and B, with QoS guarantees. The users, following some arbitrarily chosen and mutually accepted rules, negotiate economic and technical contract parameters, including sets of equivalent transit points, that may serve as path terminations (ie. $\{1, 2\} \times \{3, 4\}$ in case presented in Fig. 1). A and B also agree on who of them will represent their interests and will acquire on the market the data path needed.
2. The legal representative of the two connecting users (say, A, in our scenario) submits channel reservation request to the service market system. The contracts made finally through such system are obligatory –- the winning service provider must set the channel up, and A must make the contracted payment.
3. The request from A is presented by the market system to service providers connected to A's channel endpoints (i.e. to C and E).
4. The affected service providers analyse possibility to satisfy A's request. Specifically, they may perform their own bilateral negotiations with those service providers that connect to B's endpoints (i.e. D and F). Finally, they calculate their offers.
5. The affected service providers submit the offers.
6. The service market system chooses the best of the offers according to the mechanism selected and agreed upon by all market participants.
7. The negotiating parties are notified, network reconfigurations are made, and the data transmission may start.

3.3. Technologies. Contract specification is central in the above scenario. Traditionally, path QoS parameters include the bandwidth (calculated by averaging over time window) and maximum delay. The latter parameter has been undervalued until recently when teleconferencing and online gaming gained their position. The extra parameters include the path setup and teardown times, and the lists of alternative path endpoints for both A and B.

NGN User-Network Interface (NNI) seems to be the most appropriate technology, in which such path demands can be expressed, with Session Initiation Protocol (SIP) being the transport media. SIP has the potential to become the uniform signalling protocol, regardless of the hierarchy level where such reservation scenario takes place. However, technical means of QoS provisioning within every administrative domain are the internal matters of providers managing their domains; they definitely depend on the scale of a provider's network. A short discussion of selected traffic engineering technologies is follows in Subsec. 4.1.

The proposed negotiation layout is asymmetric: the initial choice of the legal representative (A or B) determines the set of operators designated to be notified about the request.

Those ones (C and E), owning the potential contract formally, may benefit from their position while negotiating the connection with their peers (D and F). However, on a truly competitive market such strategy would be profitable for none of them. Moreover, the asymmetry proposed here dramatically improves system scalability, mostly by splitting the burden of negotiations among the market system itself and the market entities.

4. Scalability issues

Global connectivity of the Internet is possible thanks to network providers' interconnection agreements of two kinds: transit (packets transit the provider's network) and peering (packets are sent from source or reach a destination located in the provider's network). Transit agreements are sold to smaller providers by larger ones. Peering agreements are usually made by providers of similar size, without charging each other for the traffic sent or received. Types of agreements made determine position of contracting parties in three-tier internet hierarchy:

- tier-1 — providers able to reach any IP address exclusively by their peering agreements,
- tier-2 –- providers able to reach significant number of IP addresses (also weighted by their traffic volumes) by peering agreements, but they also need transit agreements with tier-1 in order to reach the remaining part of the Internet,
- tier-3 –- providers of internet access to end users, i.e. to customers who are not network operators.

Currently there exist ten tier-1 providers worldwide. They constitute a sort of a cartel; if any of its members is disloyal (e.g. when peering with a tier-2 provider) its own tier-1 peering agreements get broken instantly. Parallel to formal classifications there is the practice: there exist tier-1 providers who do not count much in the sense of traffic volume; also, there exist tier-2 providers so big they get transit agreements practically free of charge. It is very instructive to study internet autonomous system (AS) topology graph, by CAIDA [12]. Level 3 has the biggest number of direct connections with other autonomous systems: 2632. Direct connectivity for subsequent providers in the ranking decreases rapidly, to reach the number of some two hundred for the 50th one.

4.1. Hierarchy. Let us analyse Fig. 2, where the scenario from Fig. 1 gets more complicated. Now no direct links exist between providers C or E, applying for the contract, and their counterparts D and F. C or E must then have a data path of their own with QoS guaranteed, to satisfy such request. They must ask G, H or I to be provided data path to D and F. The chosen offer will, again, depend on the price: in the scenario depicted in Fig. 2 it turns out more profitable for I that wins the contest to have provider L involved, although I peers with J (one possible explanation can be that $I-J$ link capacity is already inadequate to satisfy the request).
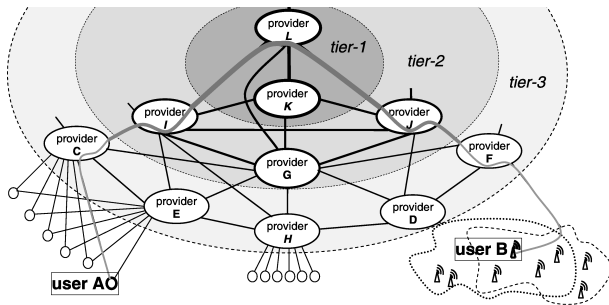
Fig. 2. Traffic aggregation and the current hierarchical Internet structure. Line widths denote link and path capacities

Certainly, flattening the structure, i.e. involving negotiations with higher-level providers on every single retail request would be unreasonable. It would impose on tier-1 providers an enormous volume of channel reservation requests. Involving appropriate technological means to handle such volume would never pay off. This is where the hierarchical nature of the Internet comes into play. Tier-2 providers will maintain a mesh of permanent paths on most frequent relations. The contracts for those paths will undergo only occasional corrections, following daily profiles of aggregated traffic (cf. Fig. 3 where a sample historical traffic profile from one NASK transit link is given).
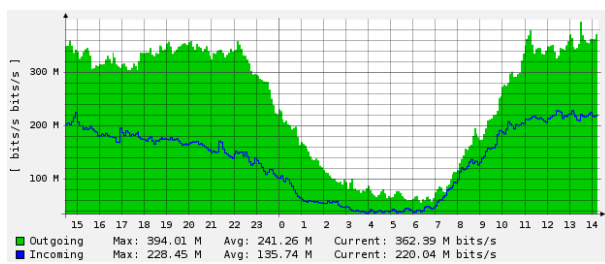

Fig. 3. Typical daily traffic profile in an interconnection link

At the bottom of the hierarchy, instead, frequent contracting will be the common behaviour. For all those providers located in between the strategy for setting up and tearing down paths will depend on the actual and expected traffic volumes: considered setup and provision costs, it may be profitable to set the path up on every single request, or to keep the it until new requests arrive. This gives the whole spectrum of behaviours and opens field to develop advanced strategies that combine prediction and optimisation knowledge for stochastic problems. Tier-3 operators in relations with their customers play the role of providers. However, while applying to tier-2 operators to set up a path, they act as users – they want to contract some bandwidth and use it in the way whatever they like. The same duality of roles happens for tier-2 operators.

Technological means the providers apply in order to set up paths with QoS guaranteed in their own administrative domains are their own business. Currently it is not a problem to map one QoS technology to another at the interconnection point. Thus, in access networks the connectivity provider may prioritise traffic from one application by inspecting port and address IP fields, or lurking into higher level protocol head-

ers. Such technique is favourable for the customer as well: it can be easily reflected in the configuration of the customer equipment.

DiffServ technology with CAC (e.g. RSVP) can be efficiently adopted by small access providers in order to prioritise traffic between access routers and interconnection points. Alternatively, Ethernet traffic prioritisation mechanisms can be used in conjunction with virtual private networks (VPN) technology. Higher up in the hierarchy, MPLS-TE with OSPF is gaining much popularity, mostly for its very efficient traffic forwarding, independence of the link type and fast routing convergence. At the Internet core, however, DWDM with all-optic switching is the only reasonable course now.

It can be estimated that, for the biggest operator, AT&T, the number of directly accessible autonomous systems is about 7000 [12]. If we assume that received requests from/to those systems form a full mesh, then the number of channels to be managed is in the order of 25 million. However, forwarding thousands of contracts to the network core is in this case infeasible. They have to be grouped and put into separate DWDM channels in order to maintain scalability.

4.2. Asymmetry. We have started the reasoning from the symmetrical case, where the contracting parties are at the same level of the hierarchy. In many applications this is the case: consider exemplary scenarios of videoconferencing, database replication or distributed scientific laboratory operation. However, on contemporary mass market the far end of a path is at powerful content or application provider, located close to the Internet core. From the business point of view, it is the content provider that should request setting up a path to the customer because it is in better negotiation position and relieves the customer from annoying negotiation procedure. But from the technical point of view, tier-1 operator whom the provider is connected to has no incentive to project every retail request on its core network configuration. Therefore, the solution should be to make the customer authorise the content provider to act on the local market on behalf of the customer itself in order to establish the path between the provider and the user.

5. Market partitioning

Efficient and effective system operation depends mostly on global network topology, reflected in the system architecture. Consider the infrastructure required to establish a contract as in Fig. 1, with regard to the hierarchical network structure, as in Fig. 2. Such infrastructure is presented in Fig. 4. There exist many independent market services (MS), i.e. trading platforms with functionalities as described in Subsec. 3.2. MS role is to handle requests for setting up paths, to collect offers, to choose the winners and to supervise channel provisioning. They implement in a distributed (and uncoordinated) way the logic of our framework. They may appear in the network freely, without any restrictions as to the type and size of customers they serve. It is in the interest of both MSes and customers that MSes locations be widely known.
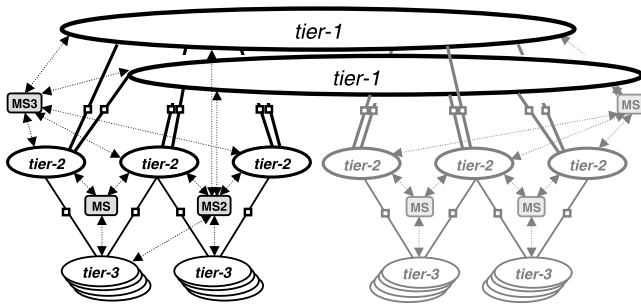
Fig. 4. Processing requests by many independent market services

A customer committed to contract a path chooses a MS and places the request. The MS chosen will be the one, or ones, where his providers are active, too. The request contains a list of all possible transit points that the customer and his/her far end partner are connected to. Those two sets determine a Cartesian product of possible entry/exit points for this connection. On request reception, MS delivers it to all providers that the requesting customer is connected to. Those providers are obliged to come up with their offers for establishing the channel. MS selects the winning offer, and commits the contract.

In the scenario above user requests are distributed only to those providers that the customer is already connected to. Such approach is definitely scalable. In the scientific community there were initiatives to organise a similar system without regard for network hierarchy. It were small operators that, by loose federations, might take over a part of interconnection traffic, nowadays handled by tier-1 oligopoly and the like. However, according to practitioners' judgement the unit price for bandwidth in such setting would be even higher than now, due to the economy of scale (thick links are relatively much cheaper). Moreover, either scalability of such a flat system would definitely be poorer, or the solutions – suboptimal. Deficiencies of such approach have been emphasised in Fig. 2 and the related scenario description.

Let us notice that all contract requests look the same, regardless on the importance of the requester. Down in the hierarchy they flow more frequently and concern smaller resources. Up in the hierarchy, where statistical multiplexing takes place, they appear occasionally and concern bigger resources. MS's logic is transparent and universal one. It should be quite easy to partition the global network both geographically (national legal systems) and vertically (hierarchy layers) in order to distribute the workload across many MSes – cf. Fig. 4. Moreover, there is open room for competition between MSes, on the basis of their margins and suite of market rules they offer. Providers serving requests can register to many MSes, but the requestors can place requests to one MS at a time.

6. Economical sustainability

Let us now study economic consequences of introduction of a system for dynamic data path contracting. Assume that, in general, user requests for network services form a Poisson process with intensity λ per single user, and the mean holding time h. User requests are therefore allowed to overlap.

6.1. Do-nothing scenario. User requests can be roughly divided into two categories: those made by elastic applications, and those made by inelastic ones. An elastic application uses TCP and tries to take as much bandwidth as possible, while each inelastic application requires a well-known amount of bandwidth b; no less and no more. It is reasonable to assume TCP communication as prevailing for both types of applications; it is, indeed, ubiquitous today, also for multimedia distribution. Let us develop a formula characterizing provider's income while serving only elastic applications on a single link (a do-nothing scenario, DN). The elastic traffic intensity is

$$E_0 = n_0 \lambda h, \tag{1}$$

where n_0 is the number of users running elastic applications. The traffic intensity is expressed in Erlang units. Assuming TCP fairness, a single elastic application is given on average the bandwidth

$$b_0 = \frac{C}{E_0}, \tag{2}$$

C being the link capacity. To emphasize the fact that such best-effort network setting is completely unsuitable for inelastic applications, estimate the probability of inelastic application being given bandwidth less than b. In such event there is at least the total of $\lceil C/b \rceil$ applications running simultaneously. Such situation is analogous to request blocking in queuing system with $\lfloor C/b \rfloor - 1$ processors, and the appropriate probability gets calculated with Erlang B formula

$$B(E_0, N) = \frac{\dfrac{E_0^N}{N!}}{\displaystyle\sum_{i=0}^{N} \dfrac{E_0^i}{i!}}, \tag{3}$$

with $\lfloor C/b \rfloor - 1$ substituted for N. If we assume, for instance, the elastic traffic intensity of just two Erlangs, then an inelastic application requiring 10 Mbps (a typical HD streaming) in a 100 Mbps will experience data loss probability of 0.00004. Such streaming quality deterioration is already clearly visible.

In order to assess operator profit, let us define utility function for best-effort transmission services, $u_0(b_0)$. It is constructed using a commonsense assumption that user satisfaction is proportional to average bandwidth obtained while using network, moreover, it is continuous and increasing. Very often u_0 is assumed to be in logarithmic form, which is done rather for convenience in calculations. Real utility functions may be not so regular and, most of all, they are fuzzy. Utility function can be perceived as the maximum amount of money a user is prone to pay for a service, but it may be used also in macroeconomic sense, as the average income, reflecting user churn due to dissatisfaction at service levels. The operator profit from best-effort services is therefore

$$Q_{DN} = n_0 u_0(b_0) = n_0 u_0 \left(\frac{C}{E_0} \right). \tag{4}$$

We assume all costs to be zero so far.

6.2. Prioritize contracts scenario. Let us now consider the effect of providing dynamic bandwidth contracting capabilities in the link (prioritize-contracts scenario, PC). The provider decides upon the maximum number N of contracts to be served at a time. The other requests are discarded, and we assume this fact not to change their Poissonian nature. The operator profit is now

$$Q_{PC} = (1-B)Eu(B) + n_0u_0\left(\frac{C-(1-B)Eb}{E_0}\right). \quad (5)$$

Formula (5) first component is the income from contracts made (and paid for) on demand: $E = n\lambda h$ requests are processed, n being the number of inelastic application users. (Here, for clarity, equal usage intensities are assumed, regardless of application type.) However, due to blocking with probability B, only $(1-B)$ fraction of requests is successfully served. Blocking probability $B(E, N)$ is considered here to influence utility of such application, $u(B)$, perceived by a user. The second component of (5) stands for best-effort services income, however with bandwidth reduced by what has been assigned to prioritised contracts, i.e. by $(1-B)Eb$. Observe also an obvious constraint, $Nb \leq C$.

Provisioning of dynamically contracted services comes at the cost of best-effort bandwidth reduction. The difference

$$\Delta = Q_{PC} - Q_{DN} = (1-B)Eu(B)+$$
$$+n_0u_0\left(\frac{C-(1-B)Eb}{E_0}\right) - n_0u_0\left(\frac{C}{E_0}\right) \quad (6)$$

contains two last terms expressing the loss of income from best-effort bandwidth reduction, resulting in smaller average bandwidth available per elastic application, and smaller utility. In practice, $u_0(b_0)$ is usually assumed to be concave, meaning that users' valuation of bandwidth unit is bigger when they are given less bandwidth. Assuming $u_0(b_0)$ concave or linear, we can write

$$\Delta \geq (1-B)Eu(B) - n_0u_0\left(\frac{(1-B)Eb}{E_0}\right) =$$
$$= (1-B)n\lambda hu(B) - n_0u_0\left(\frac{(1-B)nb}{n_0}\right). \quad (7)$$

Therefore, with $\Delta \geq 0$ it is profitable for an operator to provide dynamically contracted services with QoS guarantees. To take a closer look at practical meaning of (7), let us further assume utility functions in a simple, linear forms:

$$u_0(b) = \alpha b, \quad (8)$$
$$u(B) = \beta(1-B), \quad (9)$$

which gives us the condition for business profitability, by substituting (8) and (9) to (7), as:

$$(1-B)n\lambda h\beta(1-B) - n_0\alpha\frac{(1-B)nb}{n_0} \geq 0,$$
$$(1-B)n[\lambda h\beta(1-B) - \alpha b] \geq 0, \quad (10)$$
$$\Delta = \lambda h\beta(1-B) - \alpha b \geq 0.$$

From the operator point of view, B is the only design variable in (10), the rest being determined by its business

environment. It is clear that minimizing B increases the profitability, as compared to (4). Therefore, the operator is encouraged to accept as many contract request as possible. Let us denote the minimum blocking probability in such setting by $B^\star$. With the blocking probability minimized the sufficient condition is given by transforming (10):

$$\beta(1-B^\star) \geq \frac{\alpha b}{\lambda h}, \quad (11)$$

i.e. the actual inelastic user's willingness to pay (LHS) must be more than what an elastic user would pay for b (RHS-numerator) if he were using it constantly, and not-occasionally (RHS-denominator).

6.3. The costs considered. Let us now consider the influence of costs on operator strategy for providing dynamically contracted services. To set up a channel for simultaneously serving requests, the operator must incur a lump-sum fee s, independent of channel size. Additionally, to maintain the channel of size Nb, the operator is charged Nr monetary units for the same time unit that is used to describe the requests intensity λ. For a given set of parameter values, the operator strategy can be either to maintain a fixed-size channel (strategy M), with long-term profitability

$$Q_M = (1-B)Eu(B) - Nr \quad (12)$$

or to reset channel size, adjusting it to the actual number of requests being processed (strategy A), with profitability

$$Q_A = Eu(0) - Er - n\lambda s. \quad (13)$$

In (13) we assumed the possibility for the operator to buy a channel of any size from one or more providers, thus the blocking probability amounts to zero. The costs are proportional to traffic intensity (maintenance) and to the mean request rate (setup fee). No incentive exists for any mixed strategy here: an operator either maintains a fixed-size channel, avoiding setup fees and taking risk of his channel being underutilized, or it adjusts the channel size to the actual number of requests being processed, incurring recurrent fees as small as possible but paying for relentless channel adjustment operations.

We consider the two scenarios without taking into account the background best-effort traffic and profits from it. We assume here that profitability preconditions for dynamic channel contracting are met ($\Delta \geq 0$), and the operator extends the contracted paths towards other networks, which requires trunk channel acquisition. To indicate the optimal strategy, one needs to verify profitability of both strategies, and to compare them afterwards. Applying, for simplicity, (8) and (9), to (12) and (13) respectively, we get

$$Q_A = n\lambda h\beta - n\lambda hr - n\lambda s =$$
$$= n\lambda h\left(\beta - r - \frac{s}{h}\right), \quad (14)$$
$$Q_M = n\lambda h\beta(1-B)^2 - Nr =$$
$$= n\lambda h\beta[1 - B(n\lambda h, N)]^2 - Nr. \quad (15)$$

For (14), the interpretation is simple: user maximum utility β must compensate for a unit maintenance fee and for

setup fee expressed over the contract duration. For (15), the profitability depends on the choice of N, and is optimal for $N^\star = \arg\max_{N \in \mathcal{N}} Q_M$. Since $B(n\lambda h, N) \xrightarrow[N \to \inf]{} 0$, Eq. (15) tends to minus infinity, for N increasing, and is discrete concave. Therefore, it is sufficient to examine the sign of Q_M for $N = 1$, as moving from 0 to 1 gives the maximum possible growth of Q_M. As $B(E, 1) = E/(1 + E)$, the condition for (15) being positive for $N = 1$ is

$$r < \frac{\beta E}{(1 + E)^2}. \tag{16}$$

This is a quick test for profitability of strategy M – if this is passed, one may look for $N^\star$. If both strategies turn out to be profitable, one have to compare them

$$Q_M - Q_A = (1 - B)Eu(B) - Nr - Eu(0) + Er +$$
$$+ n\lambda s = n\lambda h[\beta(1 - B)^2 - \beta + r] - Nr + n\lambda s, \tag{17}$$

maximizing (17) w.r.t. N.

6.4. Contract making through a trading platform: a game.
Until now we considered profitability of providing on-demand data path contracting capabilities, assuming that customers are in business relationship with just one provider. Here we introduce a contract making platform where operators compete. Users are no more customers of one operator: they place bids for a service and choose the offer that is cheaper. If the offers have the same prices, one of them is accepted at random. Since the users are in big number and the services being sold are in big number, and the user pays according to his own bid, we can assume that each single user decision is imperceptible in the macroscopic sense. In other words, users are price-takers. However, service providers are few, and they influence each other's decisions: they play a game.

Let us consider a case when two providers, X and Y belong to such auction-driven market. The information about each auction outcome is known to both providers and, since the auction is repeated and the users – homogenous, providers have learnt users' utility function. Let us further assume both providers to act according to M strategy, i.e. maintain a channel that has been bought from some provider higher in Internet hierarchy. Only in such setting the auction-driven market system can be scalable worldwide.

Provider X, maintaining a channel of capacity $N_X b$, responds to a user bid with service price p_X only if the number of requests currently being serviced by it is less than N_X. The same applies to provider Y. Otherwise, a provider does not participate in the auction – it is busy. Obviously, the best price asked by a provider, while the other one is in busy state, is equal to user utility u. True competition and gaming occurs when both X and Y have free resources. Let us observe that, if both X and Y want to participate, they must ask equally: $p_X = p_Y = p$. In such case their payoffs amount to $p/2$ each , as the winner is chosen randomly. Such solution is not a stable one: each operator has the incentive to decrease the price asked and take the whole market. Naturally, this leads to a price war; the absolute limit for p is determined by the channel rental cost, r. The channel utilization for a given E is

$$\frac{E(1 - B(E, 2N))}{2N}, \tag{18}$$

where $N = N_X = N_Y$ is the number of channels reserved by X and by Y. Therefore the payoff must compensate for rental cost r of a not-fully utilized channel:

$$\frac{p}{2} = \frac{2rN}{E(1 - B(E, 2N))}. \tag{19}$$

If X and Y collude, they may ask the prices equal to user utility. Collusion is not an uncommon phenomenon: take, for instance, mobile telephony prices.

It is interesting how, in our setting, it is possible for a new entrant operator to grow and compete, on equal terms, with the incumbent. Let us consider a service market with just one operator, X. Naturally, it asks $p_X = u$ for its services, where $u(B)$ depends on X's resources, N_X. However, if Y decides to enter, it may start with some modest $N_Y < N_X$. Consequently, users are given $N_X + N_Y$ channels, the blocking probability decreases and $u(B)$ grows. Now the probability that all N_Y channels possessed by Y and all N_Y channels possessed by X are occupied, and a request must be served by the remaining $N_X - N_Y$ channels possessed by X, is $B(E, 2N_Y)$. Utilization of Y's channels is therefore

$$\frac{1}{2}E(1 - B(E, 2N_Y))\frac{1}{N_Y} \tag{20}$$

as the two above resources are loaded equally. Consequently, the overall blocking probability for the system is $B(E, N_X + N_Y)$ and utilization of X's channels amounts to

$$\left[E(1 - B(E, N_X + N_Y)) - \frac{1}{2}E(1 - B(E, 2N_Y))\right]\frac{1}{N_X}. \tag{21}$$

Although not evident from (20) and (21), with N_Y small Y's channels are always better utilized than X's channels. This is intuitive: X incurs most of the costs of service quality provisioning; it stays ready to serve requests when Y's resources (which are smaller) are already fully used. Figure 5a presents graph of utilization of X's resources for a range of E and N_X, while $N_Y = 1$. Also, the ratio of channels utilization, (20) divided by (21) is shown in Fig. 5b in logarithmic scale. Y's resources are always better utilized (the ratio is more than 1), especially when X's overall utilization is not high, i.e. when the quality of the services is high. Following this scheme, a small operator may grow easily, taking bigger and bigger part of the market, until being on par with the incumbent.

Fundamental economic properties of on-demand data path provisioning have been presented above: profitability of traffic prioritisation, choosing between channel allocation strategies and providers' interplay on a market managed by a trading platform. The numerical and analytical examples presented here demonstrate desirable economic properties of the proposed framework. In practice provider's and customers' characteristics will not be as uniform as assumed here, thus leaving room for more refined market strategies involving market segmentation, price discrimination etc. It is believed that possession of accurate models (e.g. user utility modelling, cost

structure modelling, intelligence on competitors' capabilities) will constitute another important provider's asset on the future internet marketplace.
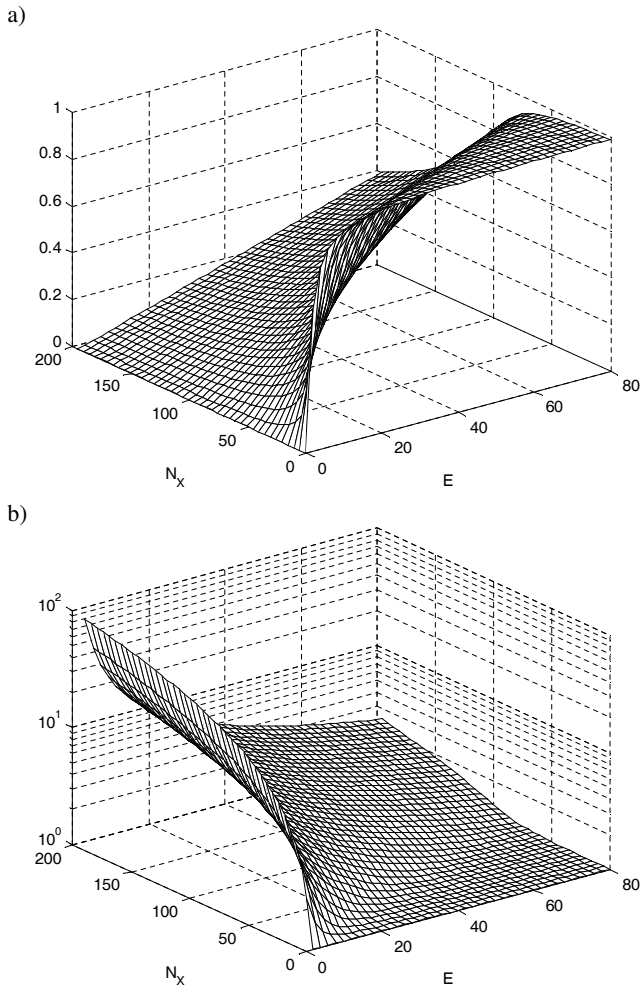
a)

b)

Fig. 5. Utilization of X's resources (a) and the ratio of utilization of Y's to X's resources ((b), logarithmic z scale) for various E and N_X, and $N_Y = 1$

7. Conclusions

The most important feature of the proposed framework is contract aggregation that matches the natural hierarchy of Internet providers, resulting in good system scalability. Profitability of making separate contracts for prioritised traffic was shown, assuming non-monopolist attitude of providers. However, to satisfy such assumption, the market system must gather a critical mass of its users, and the network topology must guarantee that alternative paths for logical channels exist. If we consider e.g. Polish network topology, it turns out that in most cases there is too little competition to make it possible to choose channel provider freely. Nominally, there exist quite a few operators (ca. 600) but the topology of connections is tree-like, and there are relatively few tier-2 competing providers.

Contemporary massive rollout of wireless access technologies will eventually bring big telco players in face-to-face competition. It is not true that they want to avoid it at all costs.

Polish TelArena negotiation platform [13] is a living example of a system where huge operators compete to provide as cheap as possible PSTN service to individual users.

Trading mechanisms offered by market service providers also will form a sort of a competition. A service provider can start with participation in a simple marketplace, like the one analysed in Subsec. 6.4, but gradually it may prefer going for more complex mechanisms, designed with regard for well-known participants' behavioral phenomena, like permanent losers' discouragement [14] or with aim to achieve certain social effects [15].

The framework for Future Internet operation presented in this paper is in close relation to fundamental principles of FI as design for tussle, sustainability and keeping the architecture as simple as possible – cf. [16]. Consequently, it lies close to currently undergoing research done by the others. However, unlike in most large projects we emphasise that current hierarchical web layout and vertical integration of services are phenomena that should be addressed in FI framework and harnessed to make a soft transition to competition-driven content-neutral dynamic resource allocation in the future.

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