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Business Network Formation Among 5G Providers

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in the

5G Exchange Project

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"Information technology and business are becoming inextricably interwoven. I don't think anybody can talk meaningfully about one without the talking about the other."

Bill Gates

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Abstract

Digital Infrastructure Action Line
EIT Digital Doctoral School

Business Network Formation Among 5G Providers

by Máté András CSERÉP

Virtualization ensures that in the approaching 5G era online services will be elastic and their deployments will be fast, fulfilling the demand of end-users rapidly and to a greater extent than what is feasible today. Telcos, cloud operators, and online application providers will join forces for delivering ICT services to customers globally. In order to support the mobility of customers, or the mere geographic span of an integrated enterprise application, the service deployments must span over many administrative domains and an assured quality of collaboration among various infrastructure and service providers is necessary. Therefore the vision of the 5G ecosystem is partly founded on the federation of these stakeholders in which they can seamlessly cooperate with the goal of creating the resource slices and the services within for a maximal geographic reach of customers. In this ecosystem, business aspects will greatly influence the technical capability and performance, the cooperative network of the actors will inherently determine availability and end-user prices of certain services. As my Business Development Experience activity at Ericsson Hungary in the 5G Exchange project I collaborated to modeling the business relations of infrastructure providers as a variant of network formation games and examining the avoidance of monopolistic pricing strategies.

Acknowledgements

I would like to express my sincere gratitude to my industrial advisor Dr. Róbert Szabó who provided me an opportunity to accomplish my Business Development Experience project in his team. His guidance and continuous support of my business study, his motivation and immense knowledge helped me in all the time of research.

My sincere thanks also goes to Dr. László Toka, whose extensive knowledge on network formation games and on analytical modeling helped me to conduct this research.

Contents

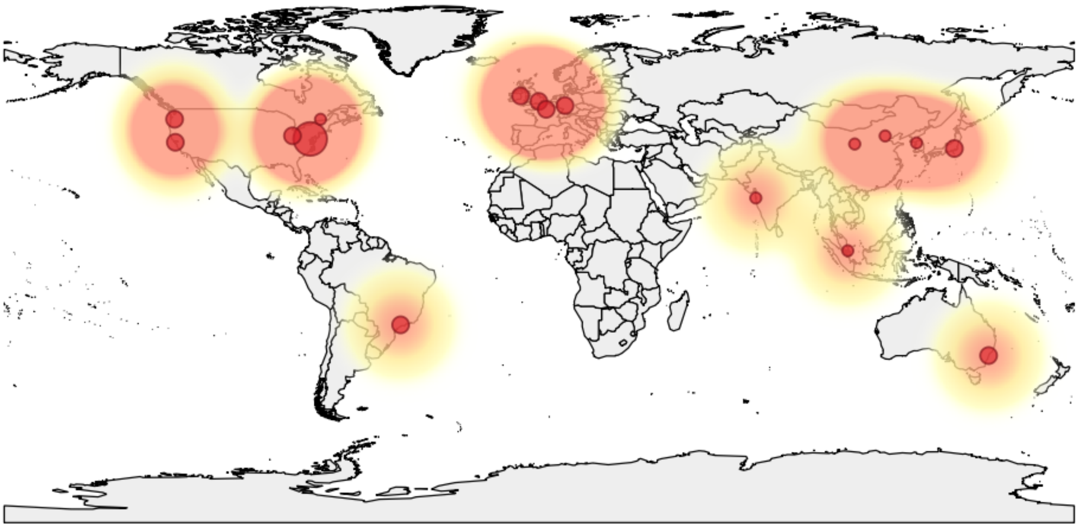
Chapter 1

Introduction

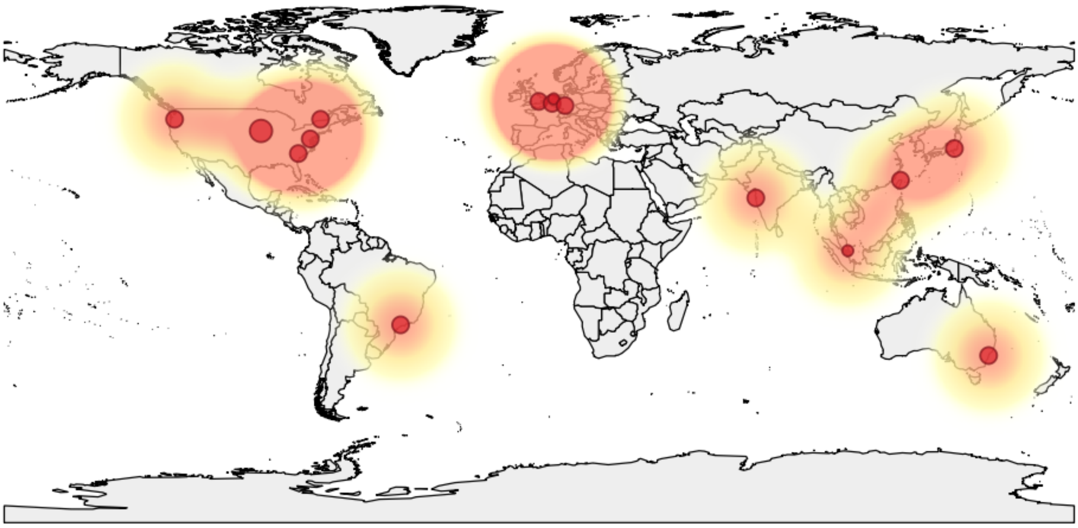
1.1 Problem statement

Keeping the operation of the autonomous networks manageable in today's Internet comes with the price of reducing the level of their interoperability to best effort. Therefore when one considers creating network services that span over multiple operators' domains, they can hardly assure Quality of Service (QoS). The 5G vision however foresees online services to be more sophisticated than today's for which underlying infrastructure providers guarantee end-to-end QoS in *network slices*: low latency and high bandwidth. Furthermore, with the advent of virtualization both in compute and network technologies, faster service creation becomes possible and the reconfiguration of services can be more adaptive, resulting in a completely different service lifecycle management compared to what today's norm is. The concept of *elastic resource slicing* is the key enabler for this, and when multiple providers take part in creating a resource slice, similarly strict dedication to QoS assurance is required from all participants.

Nowadays even major cloud computing and storage providers, like Amazon [1] or Google [2] cannot offer a geographically well distributed ecosystem, as their infrastructure is centralized. Figure 1.1 shows a heatmap of their site locations respectively, with node sizes scaled by the number of zones available at the given locations. The locality of customers is one of the most important driving factors of the appearance of *multi-provider resource slices*. Network requirements of services inherently define the frame of eligible infrastructure for the underlying resource slice: the delay-sensitivity of certain virtual network functions (VNFs) determines the clouds or fogs in which they can be deployed close to the customers for delivering QoS. Another important factor is cost-efficiency: when QoS requisites allow, it can drive the need for multi-domain resource slice creation. Fortunately, Network Function Virtualization (NFV) makes it possible to create flexible



(A) AWS global infrastructure locations.



(B) Google Cloud locations.

FIGURE 1.1: Heatmap of Amazon AWS and Google Cloud site locations scaled by the number of zones.

services in form of Service Function Chains (SFC) of VNFs when the appropriate resource slice has been created beforehand.

Motivated by these factors, the 5G infrastructure providers are foreseen to collaborate in federations. In order to be able to offer locality-sensitive services for their customers globally, they will use the compute and network resources of any of their partner providers. However before dedicated resource slices are provisioned spanning over multiple providers' administrative domains, business agreements have to be established between partners, e.g., on price and QoS guarantee of the infrastructure allocated to the resource slice. For the end-to-end QoS assurance of a resource slice that many actors take part in, distributed negotiations and continuously maintained business relationships might be necessary among the actors. In this work the possible evolutions of the network of business relations in the 5G era were investigated: will it follow the topology of transit and peering relations of the Internet today or will new business relations be established between adjacent or even remote providers similarly to ISPs' "peering" agreements?

The evolution of business relations was tackled as a network formation game in my thesis. The case of two opposing forces were accounted: *i*) the creation and maintenance cost of business relationships that cumulates as a provider establishes contracts with more and more actors, and *ii*) the mediation prices by middleman actors if a provider initiates the creation of a resource slice with another provider with which it has no direct business link. The game was analyzed from the perspective of profit-oriented 5G infrastructure providers in order to characterize this business trade-off.

The rest of my thesis is organized as follows. In this chapter Section 1.2 gives a broad overview of th 5G Exchange project, while Section 1.3 describes general information about my Business Development Experience internship at Ericsson Hungary. Chapter 2 provides an overview of related work in multi-provider pricing and network formation games. In Chapter 3 first a business network model is introduced in Section 3.1, simplified in the terms of Service Access Point locality. This model is formalized as a network formation game in Section 3.2 and analytical results on equilibrium conditions are derived in regarding the maximal middleman price for which no new business links are worth to be created and the trade-off in details. Section 3.3 evaluates a numerical analysis with static parameters and shows the simulation results in a general setting. Chapter 4 lifts the restrictions of the business network model in Section 4.1. With the introduction of dynamically modifiable parameter values and new factors in Section 4.2, defines an advanced numerical analysis environment in Section 4.3, which shows the essence of interplay between the prices, the demand for resource slices, the business topology and examines monopolistic pricing strategies. Results are analyzed in Section 4.4 and possible further work is laid down. Finally the summary of this thesis and my learning outcomes are concluded in Chapter 5.

1.2 5G Exchange

Nowadays market fragmentation has resulted in a multitude of network operators each focused on different countries and regions. This makes it difficult to create infrastructure services spanning multiple countries, such as virtual connectivity or compute resources, as no single operator has a footprint everywhere. Meanwhile network service providers are limited in maximizing usage efficiency of their resources and limited in revenue generation capability from rigid service offerings which often take up to 90 days to provision.

The EU, Horizon 2020, 5G-PPP, 5G Exchange (5GEx) project[1] coordinated by Ericsson Hungary aims to enable collaboration between operators, regarding 5G infrastructure services, with the view to introducing unification via multi-domain orchestration by creating an agile exchange mechanism for contracting, invoking and settling for the wholesale consumption of resources and virtual network services which can be provisioned in less than 90 minutes and rapidly invoked [3]. This will enable network operators, applications providers and other stakeholders in the 5G supply chain to deliver new service value for 5G customers and at the same time creating

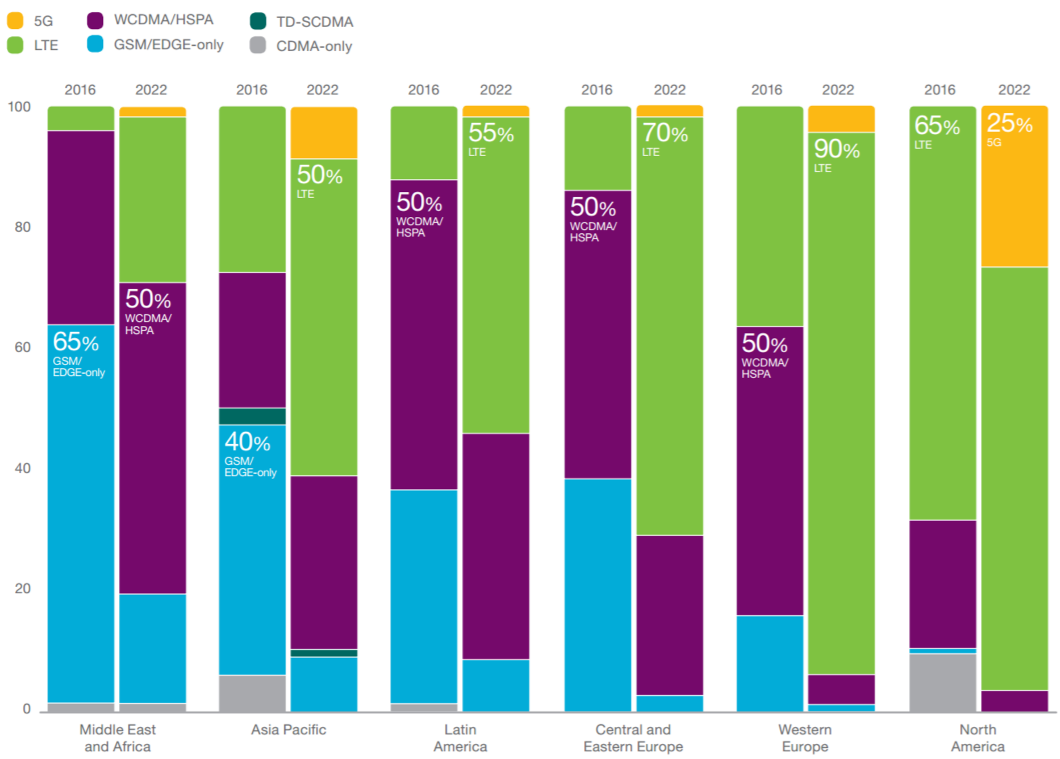


FIGURE 1.2: Mobile subscriptions by region and technology.

[1] http://www.5gex.eu/

and enhancing revenue-generating potential for 5G providers, third party verticals and others in the supply chain.

Figure 1.2 shows the expected penetration of 5G services by 2022 according to Ericsson estimates. It confirms the established life cycle of 10 years for a new wireless generation to have a real impact on the market [4]. The 5GEx infrastructure services will provide a crucial role in making 5G happen as they provide the foundation of all cloud and networking services. 5GEx aims to enable, through operator collaboration, a unified European infrastructure service market integrating multiple operators and technologies, where service provisioning is fast and automated and which results in stronger economy via economies of scale.

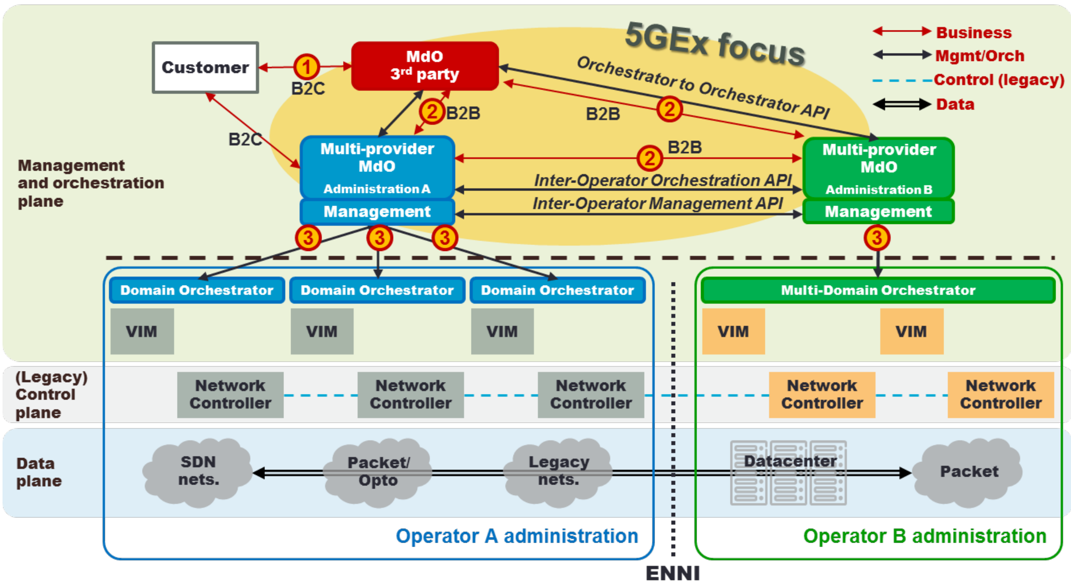


FIGURE 1.3: 5GEx reference architectural framework.

5GEx is working on a reference architecture specification and prototype implementation [5] of a multi-domain service and resource orchestrator, leveraging a number of key enabling technologies like Network Function Virtualization (NFV) [6] and Software Defined Networking (SDN) [7]. This reference architectural framework of multi-domain orchestration is shown in Figure 1.3. As an EU-funded, Horizon 2020 project, the consortium members rely on their previous FP-7 project activities in the field of network function virtualization, notably UNIFY [8], T-NOVA [9] and ETICS [10]. In order to bootstrap collaboration among stakeholders of future 5G service providers, even a 5GEx sandbox testbed was formed [11], which offers an European-wide 5G ecosystem deployment of the implemented functionalities in near-production networks. The collaborating telco partners of this *5GEx Sandbox* are shown in Figure 1.4, validating the high density of geographical locations and the availability of service locality compared to classical cloud infrastructure providers showcased in Figure 1.1.

FIGURE 1.4: The partners hosting testbeds for the sandbox.

1.2.1 Robotics use case

To bring the theory closer a simple use-case scenario is introduced in details in Figure 1.5 which can present all aspects that will be analyzed later.

Consider an autonomous factory where there is a network service needed to control the producing robots within the building. This task can be considered as a highly delay sensitive task that has to be deployed as close as it is possible to the factory (or in the factory itself). Also the enterprise customer who manages the factory would like to monitor the factory from an other location (an other country or region) so it needs connectivity to the factory from the headquarter of the company for example. Also assume that the monitoring happens through a web based visualization tool which collects data directly from the robot control service running on-site at the factory. Note that this service is not sensitive for delay so it can be deployed somewhere behind the edge of the network. The assumption corresponding to the price of these kind of data centers says the closer it is to the edge of the network the more expensive it is. This motivates the actors to use "Amazon-like" data centers if possible and only use on-site ones if it is required. As we go forward with the example we can recognize, these services has to be connected together which results a so called service chain what must be also connected to the company HQ.

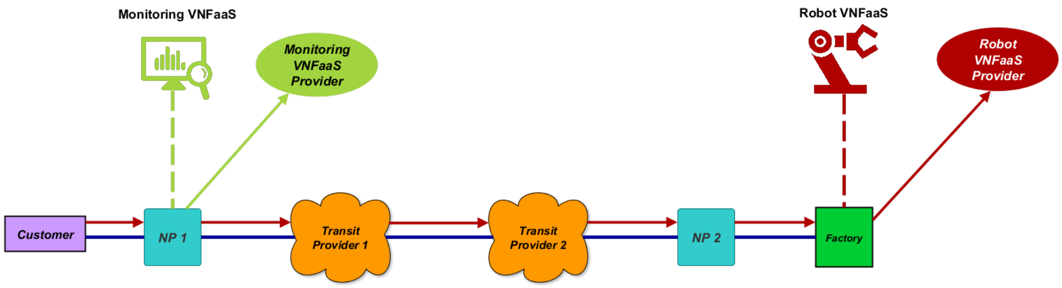


FIGURE 1.5: 5GEx business and network model.

By following the consideration of one-stop shopping in this example it is enough from the user to contact one operator to get the whole service chain deployed. The Customer Facing Provider[2] (CFP) avoids to show how it managed to create each services for the user, the result is enough for the customer. In this case the CFP is responsible for the followings:

1. Purchase the robot control service (VNF).
   (Maybe in the form of software license.)
2. Deploy this robot VNF to the mini data center running close enough[3] to the factory.
3. Purchase visualization and monitoring service VNF.
4. Deploy visualization service. (This is not delay sensitive.)
5. Connect the services into a service chain and provide access to it in the factory HQ.

The CFP has a wide spread of choices to provide the service chain and the connectivity to it. These will be detailed and grouped later but for example the two extremes are the solution when CFP contracts all involved actors (for the connectivity, service deployment, VNF purchase) and when CFP purchase the whole bundle from an other provider. In case of the latter one the CFP acts the same as the enterprise customer did in the previous example while the other provider takes the place of CFP.

[2]The customer is in connection with this operator.
[3]Close enough is defined by delay on the technological side.

1.3 Business Development Experience

I am a doctoral candidate in the PhD School of Computer Science at the Eötvös Lóránd University of Budapest. The duration of my Business Development Experience lasted from September, 2017 to February, 2018. I have spent this 6 months at Ericsson Hungary joining the 5G Exchange project.

Ericsson is one of the leading providers of Information and Communication Technology (ICT) to service providers, with about 40% of the world's mobile traffic carried through their networks. Founded by Lars Magnus Ericsson in 1876, the comprehensive portfolio of the company now ranges across Networks, Digital Services, Managed Services and Emerging Business; powered by 5G and IoT platforms. During the over 140 years long history of the company, it has grown to have more than 100,000 employees with Research & Development (R&D) at the heart of its business. With approximately 24,000 employees dedicated to R&D activities and more than 45,000 granted patents, Ericsson has one of the strongest intellectual property rights portfolios in the industry.

1.3.1 Research topic

My task at Ericsson Hungary was to contribute to the definition and validation of the novel 5GEx business layer, including a business information model, economic and market mechanisms that promote efficiency of multi-domain services by introducing cost functions into a Proof of Concept (PoC) business simulation and orchestration system in order to simulate the 5G Exchange ecosystem to evaluate business models, coordination models and incentive schemes (e.g. pricing strategies) in a multi-provider environment. As a variant of network formation game my focus was on *i*) how to model the game, defining the required assumptions and parameters, *ii*) determining the constraints of the game and *iii*) and identifying actor strategies allowing a smooth migration from todays structure to the 5G Exchange vision.

My motivation was strengthened by my academic doctoral topic which is focused on geoinformatics, tightly combined with distributed processing, cloud computing and cloud infrastructure. Previously I have also been participating in the 5GEx project as a researcher at Ericsson Hungary, thus acquiring a broad overview of the project.

1.3.2 Research team

At Ericsson Hungary I became part of a smaller research team of 4 people led by my supervisor Dr. Róbert Szabó. We joined the *Ecosystem Analysis, Mechanism Design and Innovation Potential Taskforce* in the 5GEx project, which allowed me collaborate with our following international partners both from the industrial and academic area, gaining broader insight and the opportunity to discuss questions and issues with them.

- Deutsche Telecom
- Telenor
- Telefonica
- Orange
- Hewlett-Packard
- Media Network Services (MNS.VC)
- RedZinc
- Athens University of Economics and Business
- Budapest University of Technology and Economics
- University College London

During my Business Development Experience project Ericsson Hungary provided me office and laboratory space, IT equipment and access to their computer network in their Research and Development Center. The Budapest Node of EIT Digital also offered me a room in an innovative environment shared with other enthusiastic doctoral candidates accomplishing their BDExp. Fortunately these two locations were fairly close to each other.

Chapter 2

Related Work

In this chapter a general overview of related work in multi-provider pricing and network formation games is taken. There is no existing research that would tackle the pricing aspects of network or resource slices that are created by many actors; nor that investigated the specific cost factor due to maintaining business relations or the price of mediating business contracts to this end in a multi-provider setup.

A recent survey [12] reviews pricing models for resource management in cloud networking. Most of the collected works propose the application of dynamic pricing, as it increases seller's profit when two product characteristics co-exist: first, the product expires at a point in time, second, capacity is fixed and it is costly to be augmented. The term cloud networking is understood in a multi-administrative domain scenario in which network and data center domains interact with each other. Nevertheless, the exhaustive collection of related work presented in [12] does not include research results that tackle both multiple providers and various resource types to sell.

Fabrikant introduced the network formation game [13] that models the dynamic creation of networks by selfish node-agents without central design or coordination. In their model nodes pay for the links that they establish, and benefit from short paths to all destination nodes. The authors studied the Nash equilibria of the game, and derived results about the "price of anarchy", i.e., the relative cost of the lack of coordination.

Corbo studied a network formation game [14] where links require the consent of both participants and are negotiated bilaterally, and compared these networks to those generated by the earlier model of [13] in which links are formed unilaterally. Their empirical analysis demonstrated that the average price of anarchy is better in the bilateral connection game than the unilateral game for small link costs but worse as links become more expensive. Another work that tackles bilaterally agreed contracts is presented in [15]: cost is incurred to a node from four sources:

1. routing traffic,
2. maintaining links to other nodes,
3. disconnection from destinations the node wishes to reach, and
4. payments made to other nodes.

The authors study the game in perspective of a variation on the notion of pairwise stability. The difference compared to our work is that our model accounts for the "routing" term as income-generating, instead of making it a cost-increasing term. Large computer networks such as the Internet are built, operated, and used by a large number of diverse and competitive entities. In light of these competing forces, it is surprising how efficient these networks are. An exciting challenge in the area of algorithmic game theory is to understand the success of these networks in game theoretic terms: Network formation games are widely used to investigate the principles of interaction that lead selfish participants to form efficient networks. The book chapter [16] analyzes a number of various network formation games in terms of the efficiency loss that results from selfishness.

Dhamdhere investigated [17] how the Internet ecosystem has been rapidly evolving from a multi-tier hierarchy built mostly with transit (customer-provider) links to a dense mesh formed with mostly peering links. They studied this evolutionary transition with an agent-based network formation model that captured key aspects of the interdomain ecosystem, e.g., interdomain traffic flow and routing, provider and peer selection strategies, geographical constraints, and the economics of transit and peering interconnections. Their model predicts several differences between the Hierarchical Internet and the Flat Internet in terms of topological structure, path lengths, interdomain traffic flow, and the profitability of transit providers.

The same authors published an agent-based network formation model for the Internet at the Autonomous System (AS) level in [18]: ASes act in a myopic and decentralized manner to optimize a cost-related fitness function, capturing key factors that affect the network formation dynamics, such as highly skewed traffic matrix, policy-based routing, geographic co-location constraints, and the costs of transit/peering agreements. As opposed to analytical game-theoretic models, which focus on proving the existence of equilibria, this is a computational model that simulates the network formation process and allows to actually compute distinct equilibria (i.e., networks) and to also examine the behavior of sample paths that do not converge. We find that such oscillatory sample paths occur in about 10% of the runs, and they always involve Tier-1 ASes, resembling the Tier-1 peering disputes often seen in practice. In one of their more recent work [19], the same authors investigate why a large percentage of transit providers use an open peering strategy. They also examine the impact of an open peering variant that requires some coordination among providers.

Chapter 3

Static Model

3.1 Business Network Representation

The formation of future 5G business networks is highly dependent and thus will be initially based on the current Internet topology. Therefore a tiered structure following today's transit and peering relations was assumed as the initial network model to perform the evaluation on how the new 5G ecosystem may alter this topology. This section presents the basic setup of the later analysis of Sections 3.2 and 3.3 in terms of costs of maintaining business relations, and the price of business middlemen.

3.1.1 Graph model

Figure 3.1 shows an example of the graph model of 5G infrastructure providers. In this model vertices represent *i*) Network Service Providers, also offering compute infrastructure, and *ii*) Service Access Points (SAPs), which are connection points for end-customers. Edges represent business relationships, which, in the initial phase can be either *i*) transit relations (represented by straight lines on the figure), or *ii*) peering relations (represented by dashed lines) between adjacent providers.

The locality of customers and delay-sensitive services are among the most important driving factors of multi-provider ecosystems, therefore we depicted SAPs only at Tier-3 providers as, in general, those provide access service to end-users. Note, while in our vision all network providers are potential 5G cloud providers, SAPs above the Tier-3 level were omitted in this simpler analysis, but will be addressed in Dynamic Model in Chapter 4.

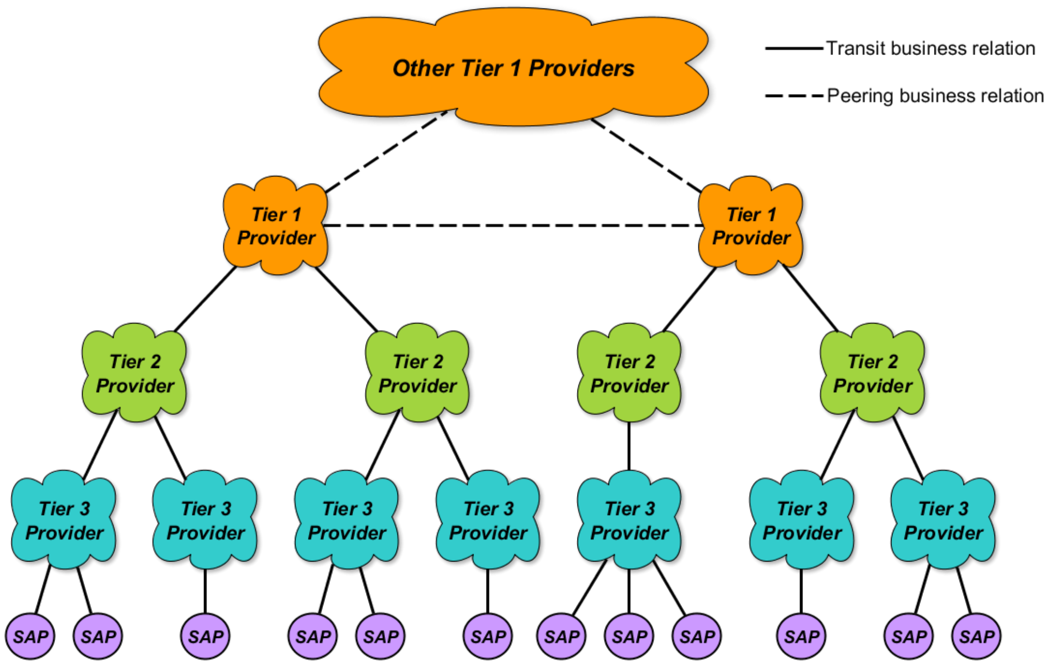


FIGURE 3.1: Tiered business structure of current Internet topology used as the initial graph model.

3.1.2 Technical costs of services

Focus is placed on such multi-domain services in which the end-users of the service are customers of provider A, while they actually use the service within the domain of provider B. In this case provider A buys a resource slice from provider B (and possibly from other providers interconnecting providers A and B). These business agreements were modeled as paths in the graph model connecting two nodes: the buyer of the service is the primary provider of the customer's Point of Presence, while the seller of the service is the provider in whose domain end-users will actually use the service. The delay-sensitive service is therefore deployed at the seller provider's infrastructure close to the SAP of the end-user. Technical parameters of the specific service, such as compute resource demand, onboarding specific VNFs that constitute the service, network QoS to the SAP, etc. must be fulfilled and paid for by the buyer provider. In this multi-actor setup the analysis of the formation of business relations was narrowed down to the pricing and costs of pricing of the services or the resource slices is out of the focus.

3.1.3 Business relations versus middlemen

A service deployment in a resource slice that is mounted on third-party provider(s) infrastructure necessitates pre-established business agreements among the stakeholders. As described in Section 1.1, it is supposed that two "opposing forces" determine how these agreements are made: either by directly negotiating and billing, or through middlemen that provide mediation between the seller and buyer. In the latter case the base price of the resource slice is complemented by the mediation price of the interconnecting providers. The chain of mediating providers can be as long as the number of hops of the path in our graph model. On the other hand, each additional direct business link between providers induces a cost at both parties: establishing and maintaining business contracts have their costs. The opposing effects is clear: while links increase the overall administrative costs, excluding middlemen from services deployed in remote resource slices is beneficial.

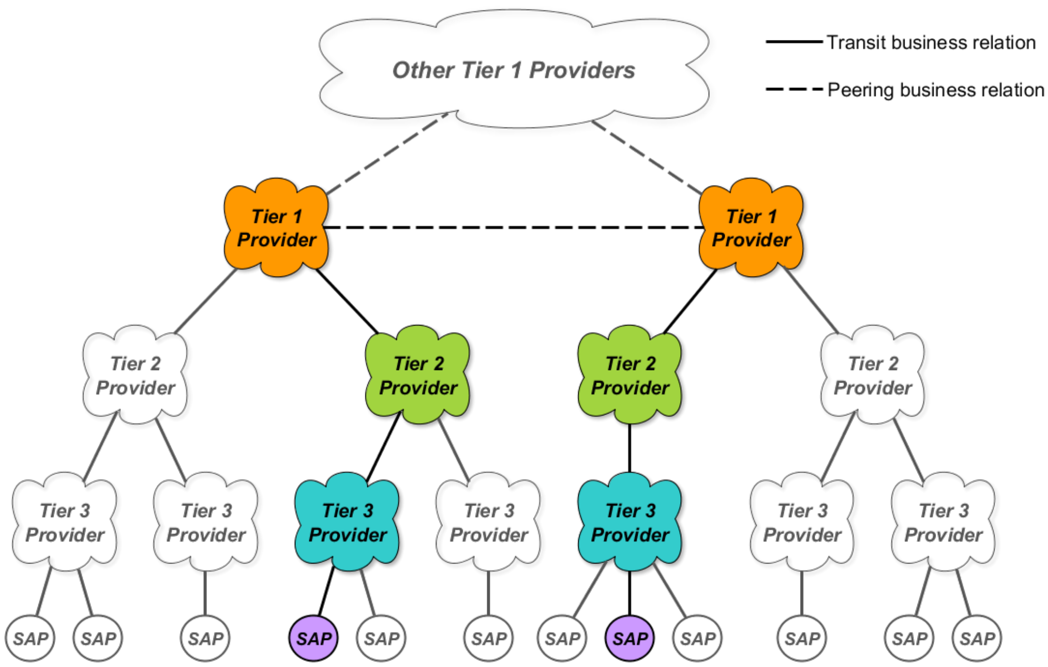


FIGURE 3.2: The original service path between a selected pair of SAPs.

Figure 3.2 depicts the service path between a selected pair of SAPs in an initial tiered graph model. The path goes through the transit relations towards the highest-tier providers in this example.

However, a new service path can be formed by establishing business connections between any two of the involved intermediate providers –

between Tier-2 providers in this example, as shown in Figure 3.3. Observe, that the new business relation does not change the data plane path as the corresponding ISPs are not physically adjacent. Nevertheless, the mediated orchestration path is shortened as Tier-1 providers will not act as middlemen anymore. Again, they will potentially further provide connectivity services, which may be provisioned for the corresponding Tier-2 providers on a different timescale (e.g., for QoS traffic aggregates).

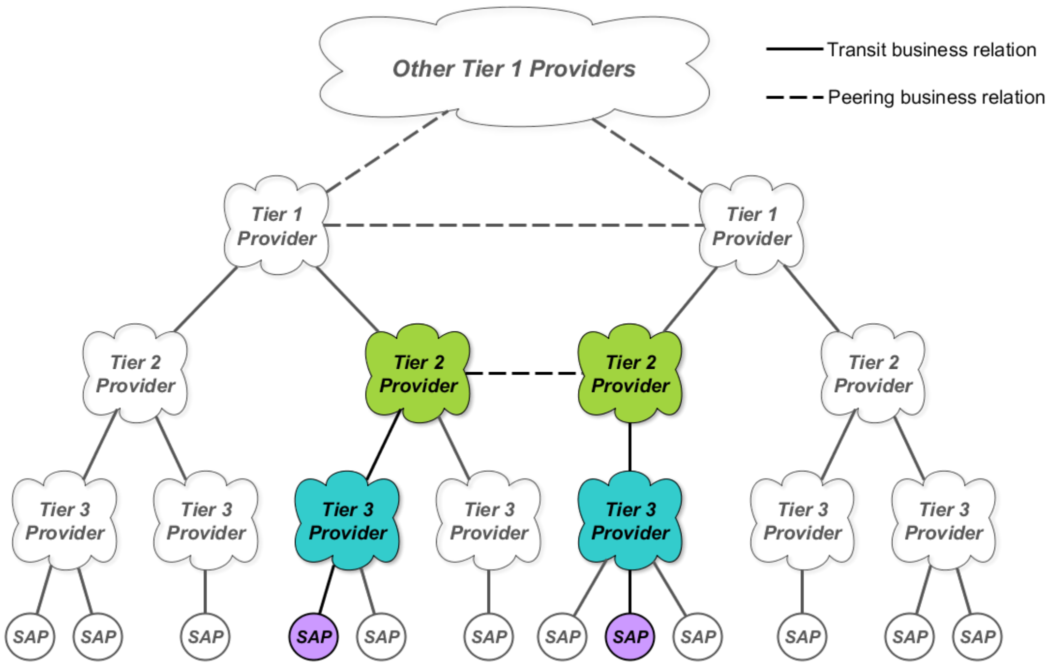


FIGURE 3.3: A new possible service path formed by establishing a new business connection.

3.2 Network Formation Game

In this section a variant of network formation game is defined which will be use for modeling the previously introduced setup, and a few important observations are derived that characterize the equilibria of the game. Note that the main difference between this game variant and the existing ones listed in Chapter 2 is the cost function: first, the distance measure in our case is replaced by middleman costs, second, the cost of each player is reduced by the income generated by being a middleman.

3.2.1 Game definition

For tractability, the same notation as in [14] is used. Let's consider a network formation game in which players are the network service providers. N denotes the player set $\{1, 2, \ldots, n\}$. The strategy set of player i is depicted by S_i and it is the power set of $N \setminus i$, i.e., the collection of possible sets of other players to link with. Let the link between nodes i and j be denoted by s_{ij}, therefore $S_i = \{(s_{ij})_{j \neq i} | s_{ij} \in \{0, 1\}\}$ and $|S_i| = 2^{n-1}$. Each player i plays a strategy s_i out of its collection S_i, and the combination of the strategies of all players provide the outcome of the game. The resulted strategy profile is denoted by $s = (s_1, s_2, \ldots, s_n) \in S_1 \times S_2 \times \cdots \times S_n$. The outcome of this one-shot game is an undirected graph $G(s) = (N, E(s))$ in which a given edge is built if there is consent between the two nodes, i.e., $E(s) = \{(i, j) : i \neq j, s_{ij} = 1 \wedge s_{ji} = 1\}$. That is both players i and j must agree to establish a link between each other in order for it to be created.

Cost function c determines the player cost given the strategy profile out of the combination of strategy sets, i.e., $c : S_1 \times S_2 \times \cdots \times S_n \rightarrow \mathbb{R}^n$. Similarly to related work, the cost incurred by player i when all players adopt strategy s is additive in the cost of the number of connections $|s_i|$ that provider i establishes successfully with other providers, as well as in the sum of the middleman costs of doing business with all other providers. As a novel term, the income that is generated by acting as a middleman in businesses traversing provider i is also accounted. In this game the cost function is defined as follows:

$$c_i(s) = \alpha |s_i| + \sum_{j \in N \setminus i} \beta d_{(i,j)}(G(s)) M_{i,j} - \sum_{j \in N \setminus i} \sum_{k \in N \setminus i,j} \beta \mathcal{I}_{i \in p_{j,k}}(G(s)) M_{j,k} \quad \forall i \in N \tag{3.1}$$

where α and β are the business peering cost and the middleman price introduced in Section 3.1, respectively; $d_{(i,j)}(G(s))$ denotes the number of middlemen on the shortest-path between providers i and j in the business graph G; $M_{i,j}$ depicts the extent of services bought by i from j through whatever path of middlemen providers this business is realized; and $\mathcal{I}_{i \in p_{j,k}}(G(s))$ indicates whether i is on path $p_{j,k}$, i.e., the shortest path between j and k. If no path exists between i and j, then $d_{(i,j)}(G(s)) = \infty$.

As in [14], this game model represents a network setting in which links are costly but good connectivity is desirable in order to minimize the number of middlemen to pay off. Also, the more links a provider has, the more likely it is going to act as a middleman, which generates income, hence lower total cost. Providers seek to minimize their costs defined in Equation 3.1. Assumed that the cost of an additional business link α, the middleman price β and the service deployment request matrix M are fixed, the game boils down to the following question: which new links are worth to be created in order to save cost.

3.2.2 The effects of link creation

For various types of equilibrium, stability conditions, efficient graphs, lower and upper bounds on the price of anarchy in classic network formation games, we refer the reader to [13], [14], [16]. However, note that the models therein are different from ours. The game variant closest to ours is presented in [15], but unlike to that model where a player's go-through traffic incurs cost, in our setup the more shortest paths traverse a node, the more income is generated to that provider. For their setup the authors proved that the stable outcome of the game is always a tree, as more transit paths and the link creation are not balanced by the value creation of lower distance to other nodes, once the graph is fully connected. In our game, on the other hand, the resulting graph $G(s)$ can be a tree intuitively only for high link creation cost α: both lower distance to other nodes, and more traversing business paths decrease the cost, therefore if link creation is relatively cheap, it is beneficial.

As depicted in Section 3.1, an initial tiered topology of providers is assumed. The goal of the work presented in this section is to provide a sufficient condition under which there are no new links created by the providers. If this condition is satisfied, the initial tiered topology is therefore an equilibrium of the game.

Assumption 1. *There are business links between providers originally, and these links organize nodes in a tiered topology, denoted by G^0, such as the one depicted in Figure 3.2.*

Let us number the tiers from top to bottom, $1, 2, \dots, t$, and let t^i indicate the tier that provider i belongs to. Let us denote by C_i the set of providers that can be reached downwards in the tiered topology through provider i, i.e., $C_i = \{k \mid i \in p_{j,k}\ \forall j \mid t^j = 1, t^k > t^i\}$, preferring peering links in Tier-1 to peering links in lower tiers. Now the parametric cost saving on new link creation is deduced.

Lemma 1. *Given Assumption 1 holds, the highest cost reduction a new link between two nodes, denoted by i and j, can achieve is*

$$2\beta(t^i + t^j - 2)|C_i||C_j| \max\left(M_{kl|k\in C_i, l\in C_j}, M_{kl|l\in C_i, k\in C_j}\right) - 2\alpha$$

Proof. Providers i and j, belonging to tiers t^i and t^j respectively, would both make a cost reduction for their children in C_i and C_j by interconnecting themselves with a new link and thus lowering the second term of Eq. 3.1 of the children. At most $t^i - 1 + t^j - 1$ middlemen in upper tiers are shortcut from cross paths between the two sets of children with the new link. This number might be lower if any peering links exist between parents of i and j, or if they have the same Tier-1 parent. Note that a full mesh is assumed among Tier-1 providers in G^0. The cost allocated to middlemen is proportional with the extent of the business which is upper bounded by $\max\left(M_{kl|k\in C_i, l\in C_j}, M_{kl|l\in C_i, k\in C_j}\right)$. The number of business relationships is given by $|C_i||C_j|$, hence the result starting from the following formula:

$$\sum_{k\in C_i}\sum_{l\in C_j} \beta(t^i - 1 + t^j - 1)(M_{kl} + M_{lk}) - 2\alpha.$$

□

Hindered by the complexity in a general tiered topology setting, the following assumption on the number of children each node has, and of businesses leaf nodes are made.

Assumption 2. G^0 *contains a number of Tier-1 nodes connected in full mesh, and a tree subgraph under each Tier-1 node in which intermediary nodes have at least k children, and all leaf nodes are at the same depth t. Furthermore, any pair of leaf nodes exchange M amount of business; intermediary nodes do not act as service sellers or buyers.*

Given the specific tiered topology of Assumption 2, now it can be proved that the highest cost saving can be attained with new peering links in the topmost tier.

Lemma 2. *Under Assumption 2, the higher tier the nodes belong to, the larger the cost saving that is attained if they create a new link.*

Proof. Under Assumption 2 the size of C_i and C_j are lower bounded by the number of leaves of perfect k-ary trees: $|C_i| \geq \frac{k^{t-t_i+1}-1}{k-1} > k^{t-t_i}$. The cost saving of two nodes i and j by creating a link is $2\beta(t^i + t^j - 2)k^{2t-t^i-t^j}M - 2\alpha$.

By expressing $x = t^i + t^j$, it is easy to see that this cost saving is higher when $\frac{x-2}{k^x}$ is larger. As $k \geq 2$ and $x \geq 3$, the maximum is attained if $x = 3$, i.e., $t^i = 1$ and $t^j = 2$, or $x = 4$, i.e., $t^i = 2$ and $t^j = 2$. □

3.2.3 Sufficient condition for status quo

Let us assume dynamic pricing of top-tier providers in terms of mediation prices with the aim of excluding the economic reasons for new business links: as set out in the beginning of this section, the interest of our game is in the pricing of middleman services when the goal of transit providers is to keep the status quo, i.e., eliminate the motivation of low-tier providers for creating business peering links. The peering link exclusionary pricing for the topology that was assumed above is derived.

Theorem 1. *Under Assumption 2, if all providers keep their price below* $\frac{\alpha}{k^{2t-3}M}$, *then topology* G^0 *is an equilibrium.*

Proof. A given provider i's cost changes when a new link, let say with provider j, is created the following way. First, the cost grows by α, the link creation cost. Second, it pays less to middlemen when doing business with other providers that are closer to j than to i: the cost saving to j is d_{ij}, and it is $\sum_{k|d_{ik}>d_{jk}+1} d_{ik} - d_{jk} - 1$. Third, the new income lowers i's cost which is generated by new transit business i being on more shortest paths: $|\{k, l\}|$.

It is easy to see that the top-most tiers lose business if peerings are created underneath them. In such a topology G^0 that satisfies Assumption 2, the maximal middleman price β for which no new links are worth to be created between any two providers is given by $2\beta(t^i + t^j - 2)k^{2t-t^i-t^j}M - 2\alpha \leq 0$ from which the upper bound on β is $\alpha\frac{k^x}{(x-2)k^{2t}M}$ with $x = t^i + t^j$, according to Lemma 2. Result is yielded for $x = 3$. □

Since no provider has interest in losing business, as a consequence of Theorem 1, the high-tier transit providers have an incentive to keep their middleman prices low. The fact that they want to preserve the status quo of transit-like business relations among providers has an overall positive effect on the ecosystem: the mediation price of establishing multi-domain services between remote (in the business sense) providers is upper bounded. This bound is dictated by the topology and the link creation cost.

3.3 Numerical Analysis

In order to perform further analysis on the theoretical results derived in Section 3.2 a simulation environment was constructed.

3.3.1 Simulation setting

Since the examination is focused on the evolution of the business agreements that define today's Internet, a topology following its scheme was required as an initial state. Therefore the input topology of the simulations is the one introduced in Section 3.1: 3 tiers and an additional layer of SAPs below Tier-3 was created, one for each Tier-3 provider to summarize the demands of corresponding customers. To be aligned with the requirement on minimum width applied in Section 3.2, a random number of children was picked for each node in the tree from a uniform distribution between 5 and 10. Thus the simulation consisted of approximately 300 providers.

Instead of a constant value for all SAP-to-SAP demand of service, heterogeneous demand was assumed, e.g., regional hot spots that customers from other regions are more likely to pick for deploying services in resource slices. Accordingly, the business matrix was constructed by using Gaussian functions that peek at a randomly selected providers.

The link creation and middleman costs, α and β as described in Section 3.2, are parameters that can be analyzed relative to each other. The α parameter was fixed to 1 and perform simulations with several β values.

3.3.2 Iterative simulation

The simulation is divided into rounds with each containing a complete analysis: all providers try to determine their optimal set of business connections. If there are no further changes from one round to the other, the simulation has converged and the status represents an equilibrium state of the topology.

Within a simulation round, providers check for all other providers if a new connection is worth to establish based on the cost function defined in Section 3.2.1. If the selected partner also decides to create the connection, a new business relation (an edge in the graph) will be added to the topology. Existing business connections are also examined in each simulation round whether their maintenance is still beneficial to both parties or not – disadvantageous connections are dropped.

3.3.3 Simulation results

After running hundreds of simulations with several initial setups final topologies from the perspective of various metrics were compared and depict in the following figures.

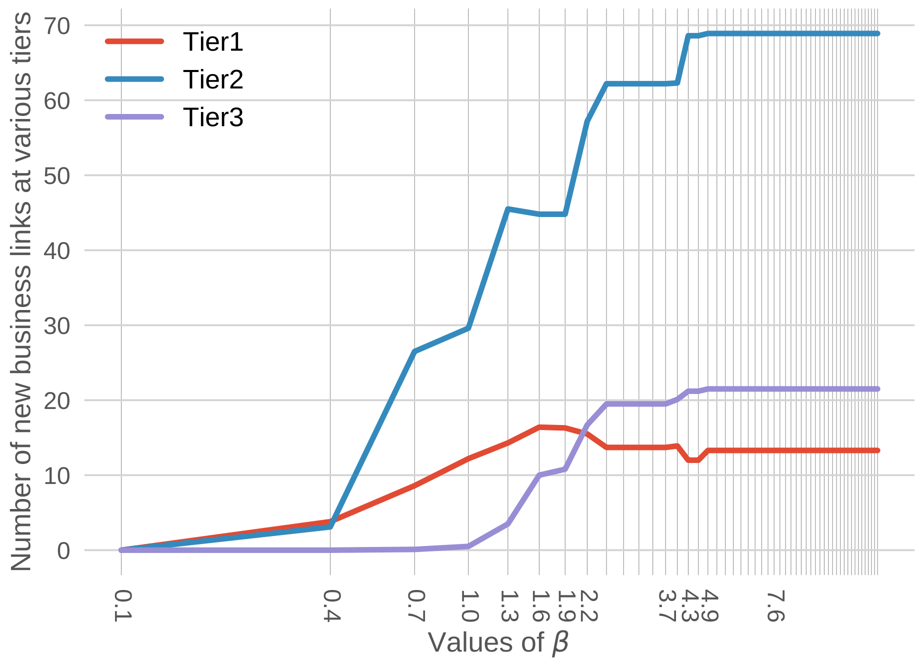


FIGURE 3.4: Number of new business connections, by tiers, for various β values.

In Figure 3.4 we can observe how the alteration of middleman prices, β's value, transforms the structure of the initially tiered topology. The figure shows the number of new connections, separated by tiers, comparable for various middleman prices, shown on a logarithmic x axis. In the left-end middleman cost is low enough to strongly limit the establishment of new business peerings. As β grows compared to the maintenance cost of a business relation, i.e., α, every provider starts to shorten their business paths in order to avoid expensive middlemen in upper tiers. As both parties must agree to form a business peering and the traffic demand between Tier-3 providers is rarely large enough mutually, most business connections involve at least one upper-tier provider. Simultaneously, the remaining aggregated "transit" business towards the top-tier providers is reduced, therefore some of the initially established business relationships for Tier-1 providers are dropped in the later iterations of the simulation. Approximately $\beta = 4.3$ is the point where providers route most business through peerings.

Intuitively the more popular a Tier-3 provider's locality is, the shorter the paths others would like to reach it through. Based on Figure 3.4 all together 4 interesting cases were picked: *i*) $\beta = 0.4$ - limited number of business peerings in all tiers, *ii*) $\beta = 1.3$ - connections of Tier-1 providers is around its peak, *iii*) $\beta = 2.2$ - Tier-1 providers drop some connections while business peering is on the rise in Tier-3 and *iv*) $\beta = 7.6$ - a convergence in the number of new business connections has been reached. Figure 3.5 depicts the total

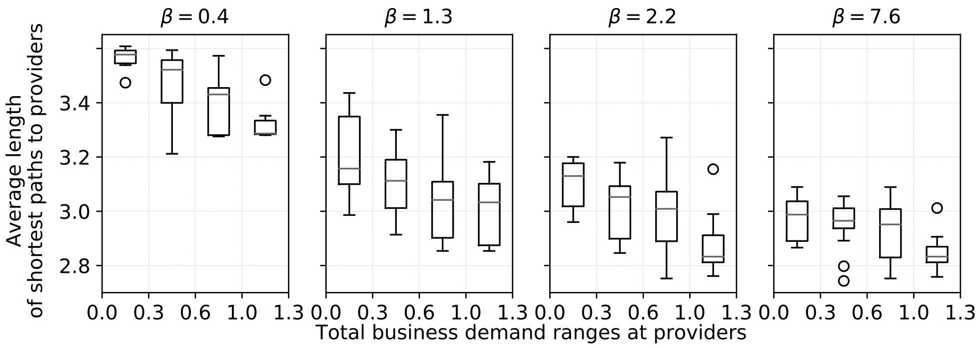


FIGURE 3.5: Average length of paths to providers by the amount of service sold.

amount of service sold by the providers (sum of the corresponding column in the business matrix) divided into four value ranges, while on the y axis the asverage path length to the providers belonging to the particular range is visualized. For all four β values a decreasing trend can be noticed on all sub-figures. A global decrease of lengths is also observable as the value of β is increased, making the establishment of new business connections more beneficial.

The length distribution of business paths in the topology is presented in Figure 3.6: it shows the number of middlemen along the shortest business paths in the stable topologies created for different values of β. The maximum value this metric can obtain is 4, as in this case there are no shortcuts in the tree: the shortest path is through Tier-1 providers. One can realize how routes shorten as β grows, while most connections are formed between upper-tier providers, hence many 3-hop and 4-hop paths. The number of paths with 0 middlemen is close to 0 in all scenarios, verifying that peerings were rarely formed between Tier-3 providers, as concluded in Figure 3.4.

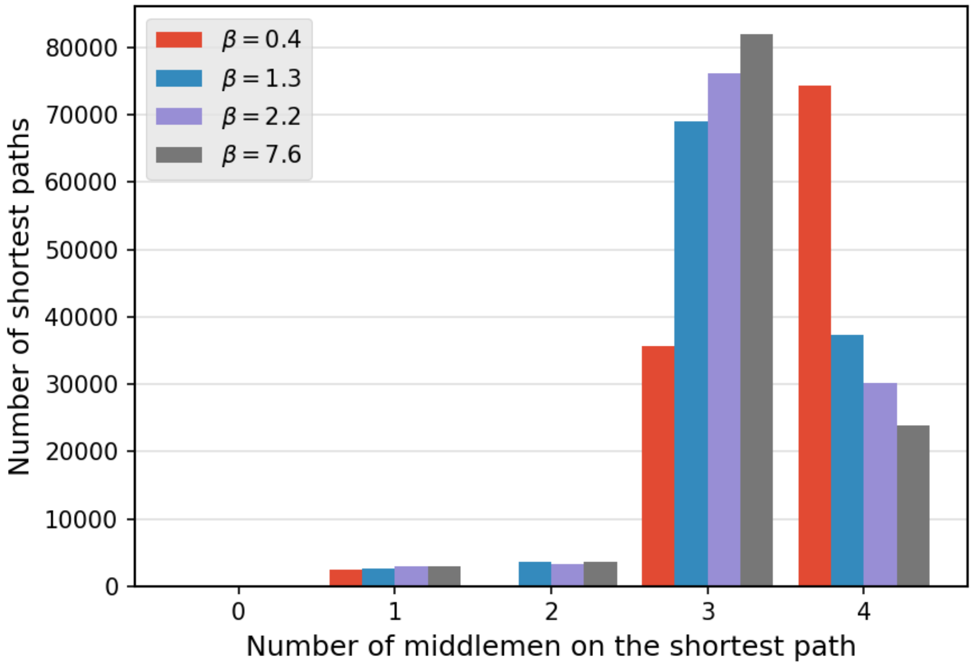


FIGURE 3.6: Number of shortest paths by the number of their middlemen.

Chapter 4

Dynamic Model

4.1 Extended Graph Model

While the initial business network graph used in Static Model, Chapter 3 was based on the current Internet topology, as described in Section 3.1.1, some considerable simplifications were introduced, namely *i*) the network has a fixed number of 3 tiers, and *ii*) only Tier-3 providers have SAPs. Figure 4.1 displays the structure of the initial business graph model used for the advanced dynamic simulation evaluated in Section 4.3. This model is based on the business network representation defined in Section 3.1, but with the before mentioned restrictions lifted, enabling an *i*) undefined number of network provider layers, *ii*) SAPs on all tier levels[1] and *iii*) a varying depth of providers on the different branches of the graph model. Note that network providers without any sub-providers must have SAPs for trivial business reasons.

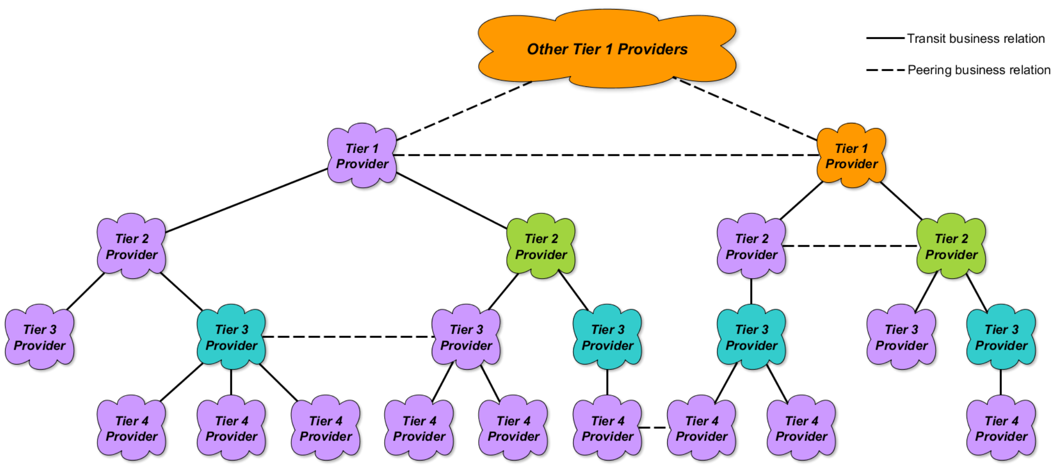


FIGURE 4.1: Advanced tiered business structure of potential 5G cloud providers, purple colored providers connecting to SAPs.

[1]Network providers with higher tier level can have SAPs for high demand services of *Content Providers*, like Netflix.

4.2 Extended Business Network Factors

Further progress on a more realistic modeling were made by improving the existing and introducing new parameters to support more advanced and intelligent player strategies of the network formation game.

Dynamic Mediation Price The middlemen price, β was a static and graph-widely global parameter in the network formation game described in Section 3.2. As mediation prices could frequently change in the 5G ecosystem and defined by the individual actors, the value of this parameter should be dynamically configurable and determined by the players (the providers) based on their individual strategy.

Mutual Interest for Business Negotiation In the static model presented in Section 3.1, no specified mutual interest for business link establishment was required – except to be financially beneficial for both parties. This enabled the formation of asymmetric remote connections where the interacting parties could have significantly business traffic demands towards each other. To prevent such unrealistic scenarios, business peering connections are only allowed to be formed when the aggregated service demand between the 2 providers has a comparable quantity: their normalized difference is below a given threshold $\gamma \in [0,1]$: $abs(T_{i,j} - Tj, i)/max(T_{i,j}, T_{j,i}) < \gamma$, where i and j are the 2 interconnecting providers and $T_{i,j} = \sum_{k \in N \setminus j} \mathcal{I}_{i \in p_{k,j}}(G(s))M_{k,j}$ is the aggregated traffic from i to j based on the service deployment request matrix M introduced in Section 3.2.

Switching Home Provider With a dynamic, provider-dependent mediation price, and a strict demand threshold ratio requiring symmetric amount of traffic for business negotiations, higher tier providers could easily monopolize the share of business traffic unavoidably flowing through them and choose a strategy to constantly raise their mediation price (β_i) without an upper limit. As a solution the switching of home providers ("rehoming") is supported for all providers under Tier-1 for a defined global cost δ and in a configurable tier-local range R_t for tier t. Note, that this is also a simplistic implementation of multi-homing without giving up the tree structure of the transit relations in the network graph.

As we can observe the demand threshold (γ) and the home update cost (δ) both introduce anti-monopolistic policies to counter the effects of dynamically set middlemen prices by the providers.

4.3 Numerical Analysis

The simulation environment demonstrated in Section 3.3 was further developed to support the analysis of the extended model and characteristics introduced in the previous sections.

4.3.1 Simulation setting

The applied topology scheme of the simulation followed the extended business network graph introduced in Section 4.1 as an initial state, with the following specification: 4 tiers and an additional layer of SAPs below Tier-4 was created, one for each Tier-4 provider to summarize the demands of corresponding customers. A random number of children was picked for each node in the tree from a uniform distribution between *i*) 5 and 10 at Tier-1[2], *ii*) 1 and 10 at Tier-2, *iii*) 0 and 10 at Tier-3. Thus the simulation consisted of approximately 1500 providers.

The construction of the business traffic matrix defined in Section 3.3.1 was extended with the demand generation between SAPs of different tier levels, producing a larger volume of demand towards SAPs on higher tier levels, since they are considered content providers in this setup.

Among the cost and price factors presented in Section 4.2, the link creation price, the demand threshold ratio and home provider update cost (α, γ and δ respectively) had fixed value per simulation and were analyzed relative to each other. The middlemen price, β_i had a dynamic value on a provider basis and could change between each iteration round in a simulation.

4.3.2 Player strategies

The iterative framework of the simulation introduced in Section 3.3.2 is maintained. The ultimate goal for each provider is to maximize its individual payoff, defined as follows:

$$pr_i = \sum_{j \in N \setminus i} \sum_{k \in N \setminus i,j} \beta_i \mathcal{I}_{i \in p_{j,k}}(G(s)) M_{j,k} \quad \forall i \in N \tag{4.1}$$

using the same notion and introduced variables as in Section 3.2.1. However the basic and general player strategy of determining their optimal set of business connections is expanded into a range of strategies to play. In each round all providers can select from the following actions.

[2]The number of Tier-1 top providers was generated between 5 and 10 also.

Establish remote business connections The provider checks all other providers on its tier level if a new connection is worth to establish based on the cost function defined in Section 3.2.1. If the connection is also advantageous for the selected partner and the requirement of demand ratio specified by γ is met, a new business relation can be added to the topology. Existing business connections are also examined in each simulation round whether their maintenance is still beneficial to both parties or not – links generating more cost than payoff are dropped.

Adjust mediation price The provider examines how the last update of β_i parameter towards interconnecting providers affected its payoff. To meet the ultimate goal of pr_i maximization, an increased payoff results in a positive and a decreased payoff in a negative feedback for the last action and determines the new action. In case the last modification of β_i did not affect the payoff (above a predefined ϵ), then the provider can either follow an aggressive strategy and increase β_i, or a defensive strategy and decrease β_i – in the hope of attracting new lower-tier providers from its competitors.

Rehoming The provider checks all providers from the upper tier and in the configured distance as described in Section 4.2, whether switching to that new home provider would result in lower overall cost despite the additional cost of home update (δ).

The probability for each strategy is defined by uniform distribution. If there are no further changes in 3 consecutive rounds, the simulation is considered converged and the status represents an equilibrium state of the topology.

4.3.3 Model validation via numerical evaluation

In order to study how the fixed parameters of *i*) the business link creation and maintenance cost (α), *ii*) the demand threshold of mutual interest for business connection establishment (γ), and *iii*) the home provider switching cost (δ) can influence the topology of the business network, the behavior of player strategies and how they can be optimized against each other, the simulation was executed and examined with various setups.

The results of the evaluations are displayed in Appendices A, B and C for possible configurations of α, γ and δ respectively – due to their large extent. Observations on the validation of the model can be summarized as follows:

Business cost Increasing the cost of new business connection establishment and maintenance, ranging from $\alpha = 0.5$ (cheap) to $\alpha = 30$ (expensive) and even $\alpha = \infty$ (represents disabling the feature) drives more traffic towards the higher tiers, as business connections on lower tiers became unsustainable and more orchestrated business paths will path through the upper tiers. Figure A.1 verifies this finding. Note that the overall number of changed connections shown in Figure A.2 does not follow this pattern, as the creation of business connections are replaced with frequent rehoming due to the individual monopolizing strategy on the mediation price.

Demand threshold The threshold of allowed normalized difference between the aggregated traffic demand of peering partners was raised ranging from $\gamma = 0$ (complete disable as an exact match of service request toward each other is unlikely) to $\gamma = 1$ (all beneficial link formation is enabled regardless of demand ratio). Figure B.1 presents how higher γ ratios produce more business connections overall in the graph and thus restricts the monopolizing strategy on the mediation price. Figure B.2 verifies this result based on the payoff.

Rehoming cost Finally, by increasing the home provider update cost, ranging from $\delta = 0$ (free) to $\delta = 50$ (expensive) and even $\delta = \infty$ (represents disabling the feature) enables higher mediation price values as rehoming is becoming unaffordable, shown on Figure C.1. The results are also verified by the payoff history displayed on Figure C.2. We can also observe in Figure C.3 how the reducing possibility of home provider update results in rapid business connection formation.

4.4 Results and Further Work

The validation of the dynamic model and the numerical analysis showed in Section 4.3.3, that without remote business connections and rehoming, the general strategy for all providers to maximize their payoff defined in Equation 4.1 results in the unlimited increment of the local β middlemen prices determined by the individual providers, as they can monopolize their position and the constant amount of service request traffic handled. The availability of forming business links with other providers and the option to switch their home provider hinders this monopolization as providers with overpriced β values will either loose their lower tier providers (due to rehoming) or significant amount of the business traffic passing through them will be diverted on lower tiers (by remote business connections). This countering effect against monopolistic middlemen price strategies can be weakened by configuring business link creation expensive (through α) or hard to comply (by γ), or by the high cost defined for home provider update (δ) or by its over-restrictive distance range R_t for a given tier t.

Results showed that even with an adequate configuration of parameters α, γ, δ and R_t, monopolistic scenarios can still occur due to the uninformed heuristic of the network formation game, meaning players act on their individual strategy without considering the played strategy of other players. Therefore if a provider i succeeds in collecting a critical amount of lower-tier providers (e.g. by setting a cheap β_i initially to deliberately bait them), then those providers can no longer rehome economically to another provider j if i raises β_i significantly. Having a large share of lower-tier providers, i would still be part of most service request paths, thus β_i would still be included in the cost function defined in Equation 3.1 – beside the additional β_j. Home provider switching made impossible and β_i on the rise, its child providers only option to counter the monopolistic strategy followed by i is to interconnect into (almost) a full mesh, detouring most service requests from i. By e.g. Tier-2 providers forming a new full mesh to eliminate Tier-1 providers from their traffic, the initial assumptions of the topology are severely violated, as Tier-2 providers start to act as a new top Tier-1 layer, but the model presented in this chapter is incapable to follow this change of roles.

An example for such topology deformation is showcased in Figure 4.2. In this figure providers are color coded from Tier-1 to Tier-4 level with blue, orange, green and purple colors respectively; node sizes are scaled by the amount handled traffic of each provider. We can observe that most Tier-2 providers connect to one of two Tier-1 providers, composing a business topology where neither of them can rehome anymore as discussed before. We can also see how nodes with the largest sizes are Tier-2 providers, managing more traffic than Tier-1 providers, representing a deformed topology where they act as Tier-1 top providers, but the model is unable to follow this change.

Further work will include the experiment with more informed heuristics enabling providers some level of collaboration; and the evaluation of multiple consecutive simulations: fine-tuning the input parameters based on the examination of the previous game to enforce the topology assumptions to be met, but still be able to analyze the effects of each parameter have on network formation and pricing strategies.

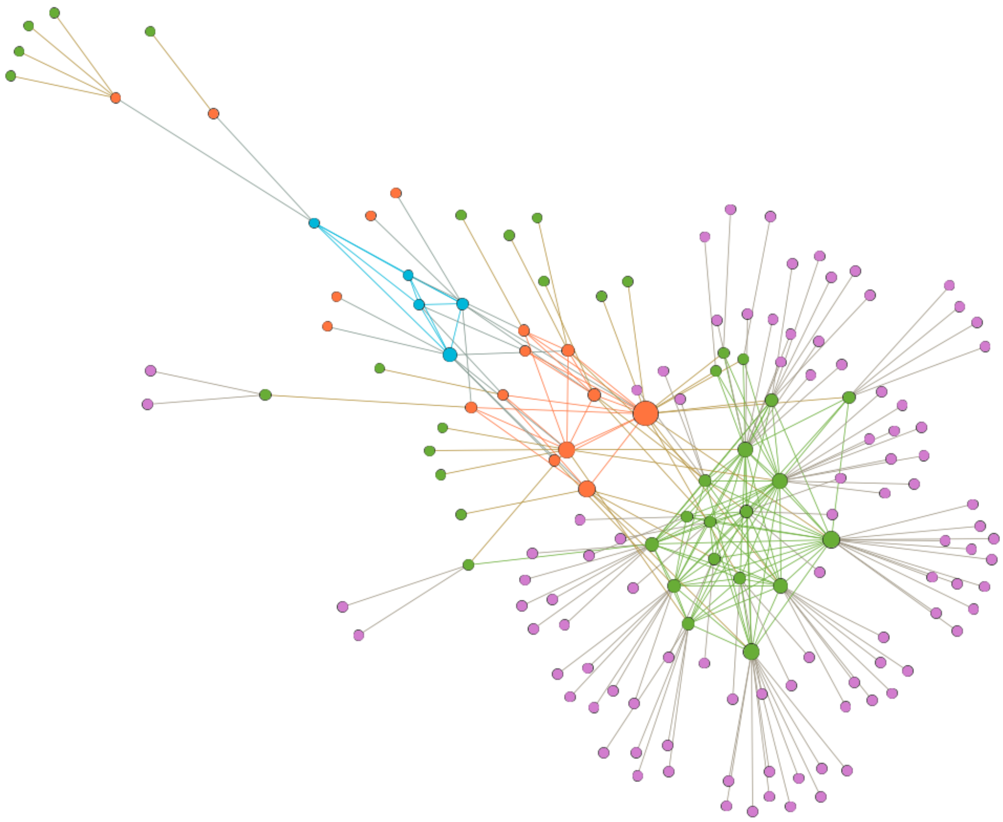


FIGURE 4.2: A deformed converged business network topology. Tier-1 nodes are depicted with blue, Tier-2 nodes with orange, Tier-3 nodes with green, Tier-4 nodes with purple color. Nodes sizes are scaled by the volume of traffic handled.

Chapter 5

Conclusions

5.1 Discussion

Cloud computing has proliferated in the recent past as the *de facto* standard thanks to offering cheaper and easier solutions for IT services. Distributed computing seems to be the next major step forward to maximize service performance in a cost-efficient way. Market fragmentation, however, will make it necessary for Telco providers to cooperate (and to ompete) in their distributed cloud offerings. What kind of business relations will emerge among Telcos is an open question. There are new alliances formed, e.g., ngena[1], by key stakeholders to pioneer solutions. The EU H2020 5G Exchange project[2] aims at establishing the technical enablers for an open coopetitive (competitive cooperation) ecosystem for multi-provider network service management. In the frame of our actor-role and business case analysis we set the goal to systematically analyze possible emerging business structures for distributed cloud offerings. Given, however, the current multi-tier ISP hierarchy for global connectivity services, we started our analysis by looking into why, when and how the current ISP structure may transform into new business relationships.

The thesis defines a network formation game starting from the tiered ISP hierarchy, in which players are the ISPs themselves; link creation represented business relationships with a maintenance cost; operational costs and incomes were calculated based on paid transit costs and incomes from being a middleman (offering transit services). New business relationships (links) were allowed among actors of the same tier level. Connectivity and distributed cloud services were routed along the traditional and the enriched ISP structures respectively, since new business relationships do not necessarily imply physical adjacency of the corresponding providers.

[1] http://www.ngena.net/

[2] http://www.5gex.eu/

With further assumptions (see Section 3.2.2) a formal upper bound on the middleman price as a function of peering costs and topology attributes was derived, i.e., if ISPs would like to preserve the current status quo with respect to their transit relationships, then they have to keep their middleman (mediation) prices low. The analytical results' dependency on the topology promised different price tags for each tier.

In the numerical analysis games with different middleman costs were simulated for various initial ISP topologies. The analysis of the middleman price tag thresholds in a 3-tier hierarchy revealed that with increasing middleman costs the number of business connections to be established also rises until when a convergence state is reached where no new peerings are affordable due to the lack of traffic demand. Results also showed that the mutual desire for peering among the lower Tier-3 level providers rarely occurs, instead the intermediate Tier-2 providers manage to attract most of the new business due to their capability of aggregating the transit demands of the sub-ordinate ISP levels. Results on the static model were published in the *IEEE INFOCOM*[3] conference proceedings [20].

After reaching the boundaries of the static model and simulations evaluated with global peering and middleman price values, I turned towards extending the business network representation with new factors introduced in Section 4.2, like the possibility of home provider switching and the improved definition of mutual interest in business link establishment to shape a more realistic model. Middleman prices was transformed into local and dynamic values for each provider, enabling to exploit multiple player strategies and the dynamic analysis of the maximum achievable revenue for a player in the view of its individual middleman price strategy. Simulation results show the relation how the various parameters can be configured to avoid monopolistic pricing strategies.

5.2 Learning Outcome

My internship at Ericsson Hungary allowed me to gain insight into economic mechanisms, novel business models, business processes, collaboration and service/business coordination models, and also to assess the innovation potential of 5G Exchange – a large international PPP[4] enterprise project – in the described area. Automated business simulation and examination was

[3] IEEE International Conference on Computer Communications
[4] Public Private Partnership

a basically new field for me which I enjoyed a lot to explore. Beside success I have also managed to experience the challenges of scaling up a theory to evaluate it on a large simulated business network; to analyze and verify the results.

The Business Development Experience internship and also the whole Doctoral School program of EIT Digital was a great opportunity for me, since I have managed to master new business related skills beside my original profession as a computer scientist. Beside my technical viewpoint I learned a new business aspect to consider when facing an issue or coming up with an idea, and how to connect my research and expertise to something that has market value. I was also able to improve how to draw attention, how to present myself or my idea and how to extend and manage my professional network in order to be able to achieve my goals.

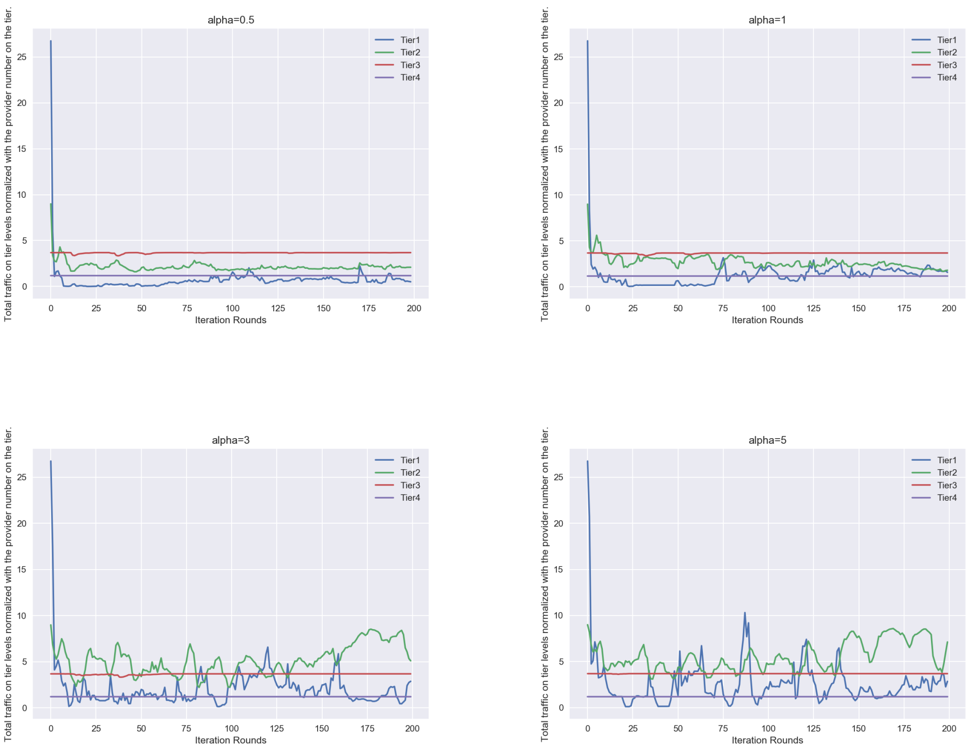
Appendix A

Evaluation of Business Cost

This appendix presents the numerical results on how the cost of business link creation (α) influences the mediated orchestrated paths passing through each tier and the creation of new transit or peering relations.

A.1 Normalized Traffic History

Figure A.1 shows the accumulated business traffic flowing through each provider, aggregated by tier level and normalized with the number of providers on the tiers. As the value of α is increased the maintenance of business connections are getting more expensive and unsustainable on the lower tiers with less aggregated traffic. Hence more mediated orchestrated paths will pass through the higher tiers, generating more traffic there.



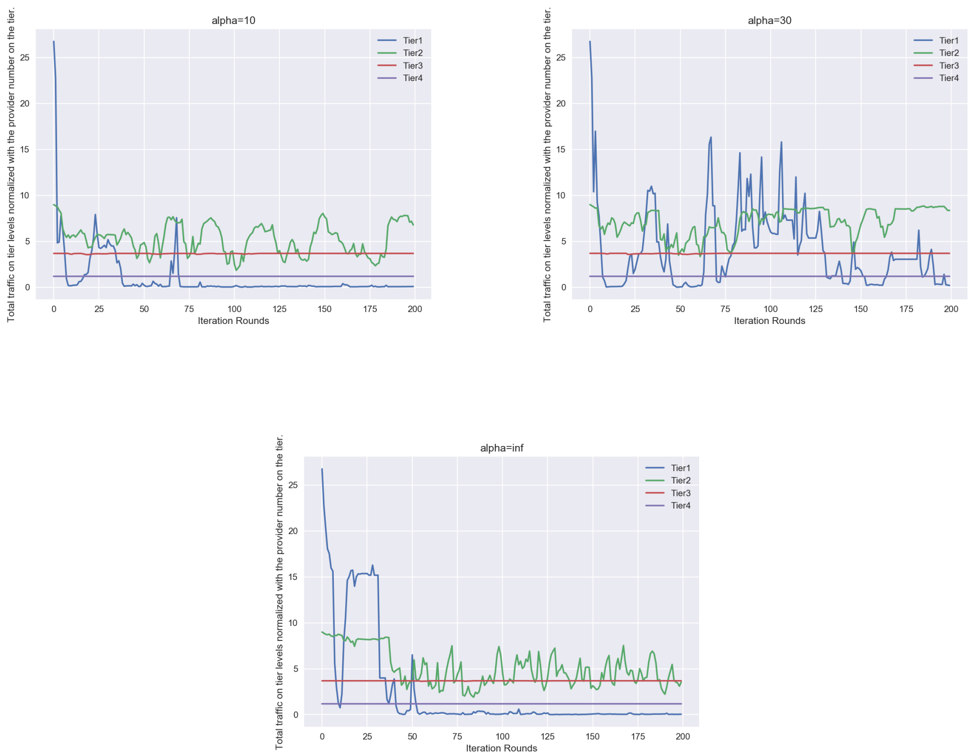


FIGURE A.1: The normalized traffic in relation to the link creation cost.

A.2 Connection Change History

In Figure A.2 the accumulated count of changed (created or deleted) connections is shown for each iteration round. It includes both the result of peering business link formation and rehoming to a new home provider as a transit relation. While with the increment of α the formation of peering business connections are reduced, the update of home providers are boosted to balance the monopolization of dynamic mediation prices (β).

FIGURE A.2: The number of changed connections in relation to the link creation cost.

Appendix B

Evaluation of Demand Threshold

This appendix presents the numerical results on how the demand threshold ratio of mutual interest in business link creation (γ) affects the average mediation price (β) and payoff on each tier.

B.1 Mediation Price History

Figure B.1 displays the average mediation price by tier level for each iteration round. As demand threshold γ is increased from 0 to 1, more asymmetric connection are enabled in the terms of traffic. This counters the monopolistic opportunity of mediation price (β) raise on the higher tiers, restricting the upper boundary of its value.

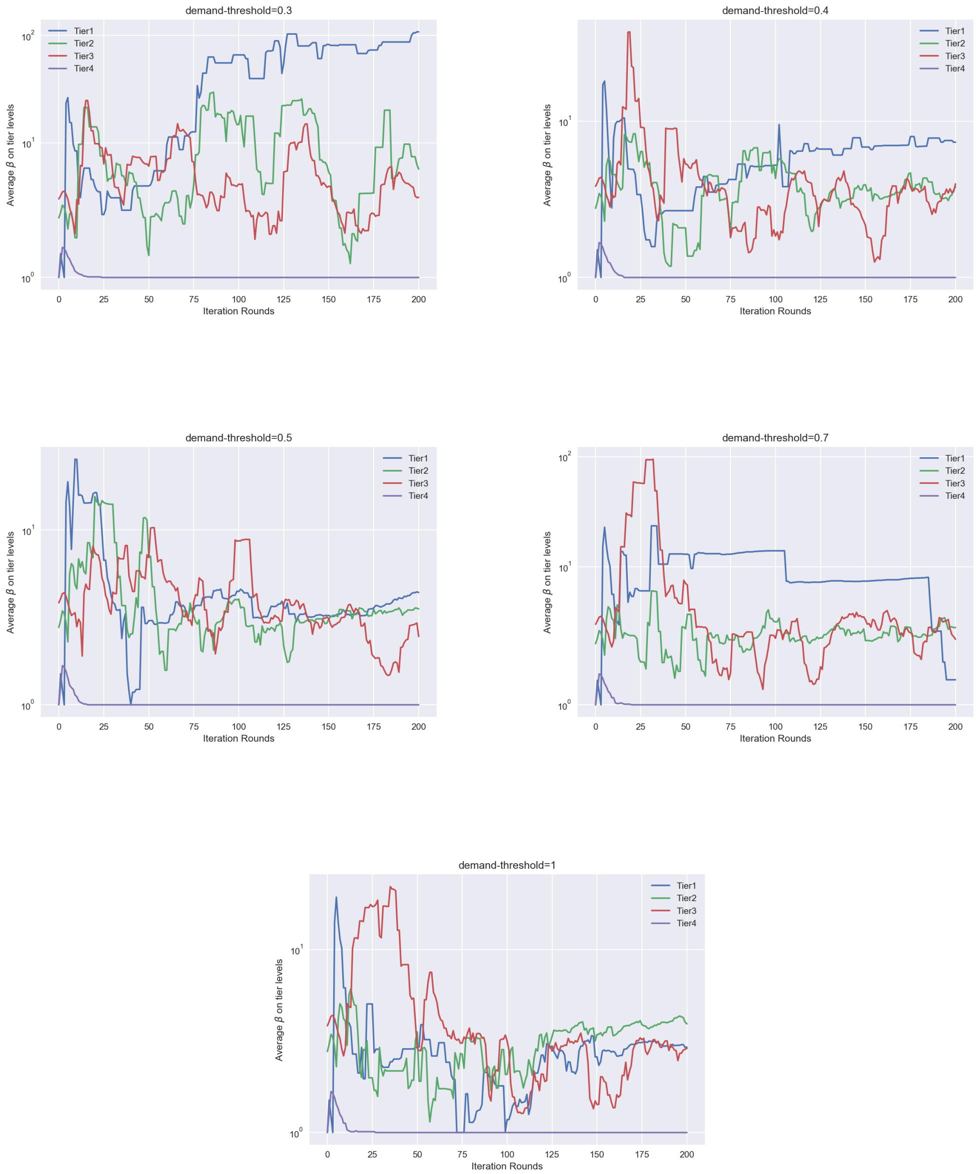
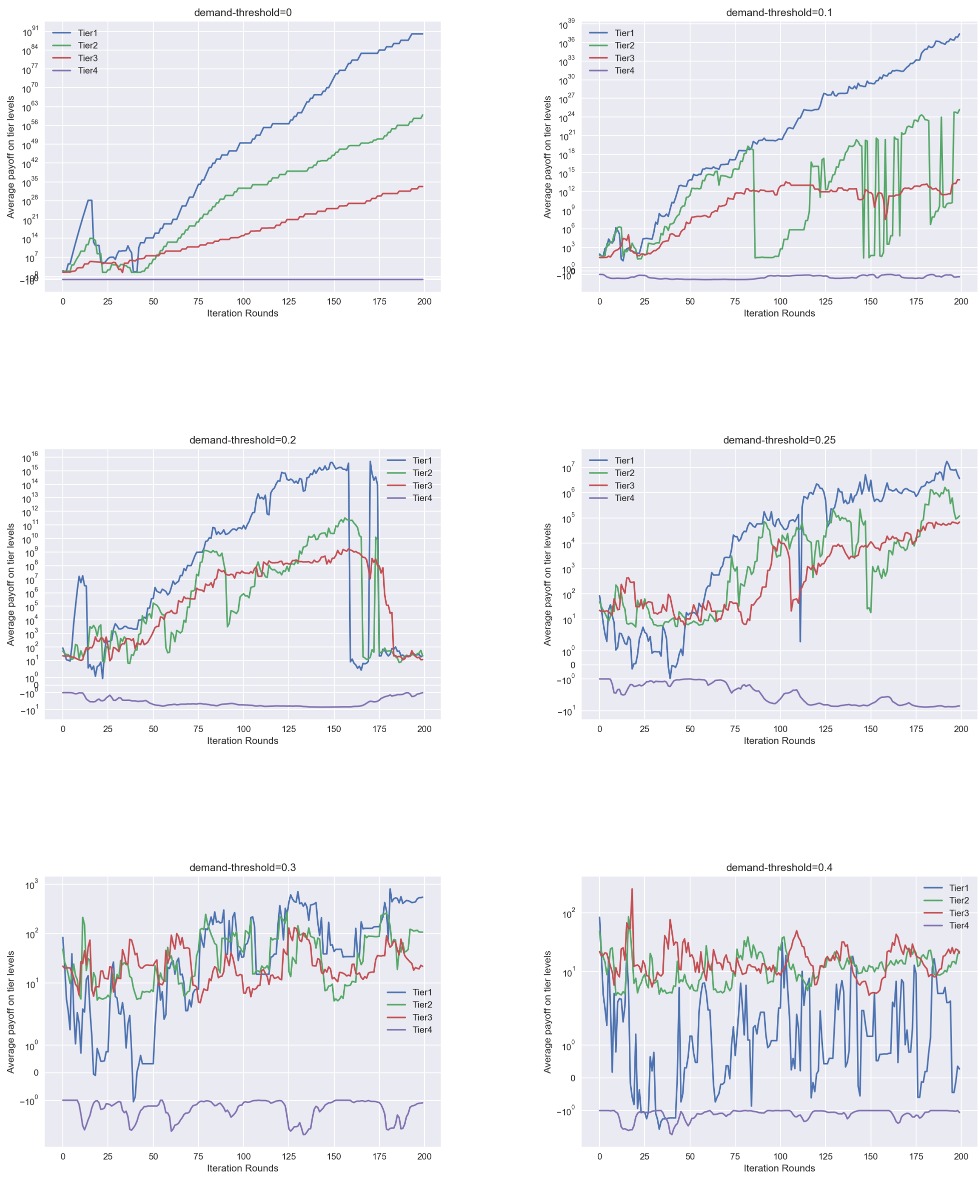


FIGURE B.1: The dynamic mediation price in relation to the demand threshold of mutual interest.

B.2 Payoff History

In Figure B.2 the average payoff by tier level for each iteration round is shown. In correspondence with decreasing trend of β values shown in Figure B.1, with the restrained reachable mediation prices the payoff is also restricted on all tiers.



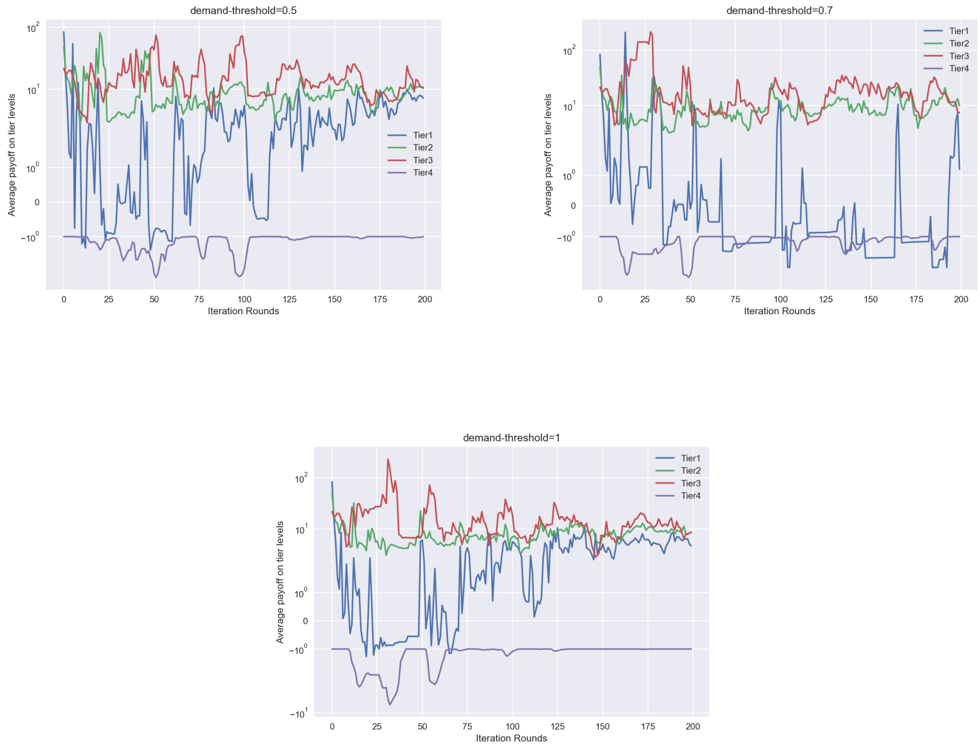


FIGURE B.2: The payoff in relation to the demand threshold of mutual interest.

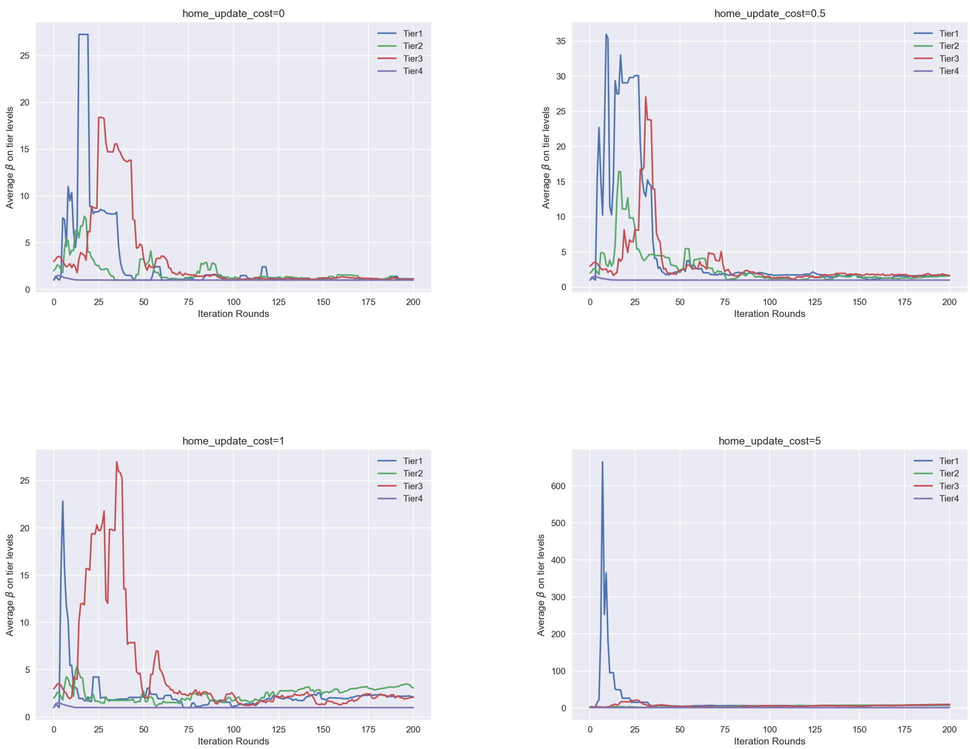
Appendix C

Evaluation of Rehoming Cost

This appendix presents the numerical results on how the home provider update cost (δ) affects the average mediation price (β), the payoff and the creation of new transit or peering relations on each tier.

C.1 Mediation Price History

Figure C.1 displays the average mediation price by tier level for each iteration round. The rehoming cost δ is free (equals 0) in the first simulation, but its increment results in home provider update expensive and unaffordable. Hence upper tier providers can introduce higher β values for the mediation price, abusing their monopolistic position.



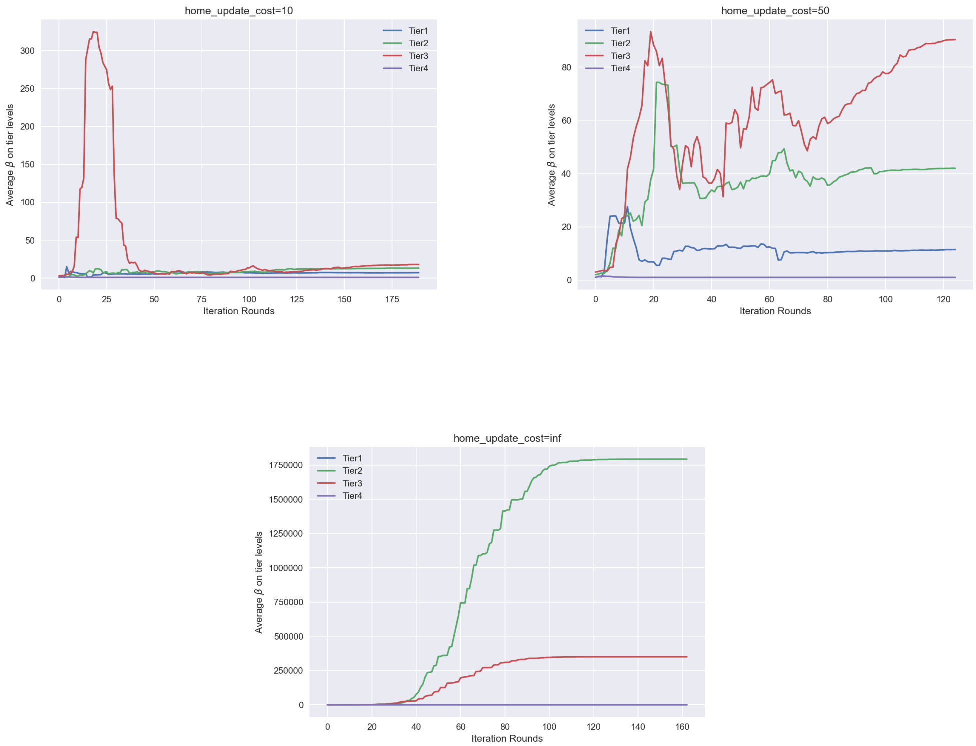
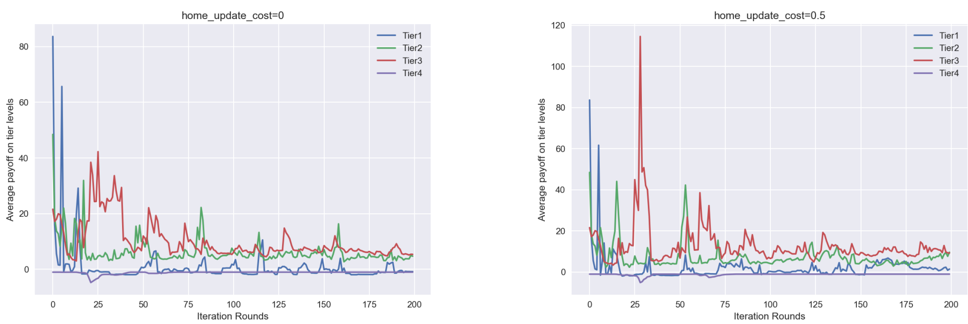


FIGURE C.1: The dynamic mediation price in relation to the home provider update cost.

C.2 Payoff History

In Figure C.2 the average payoff by tier level for each iteration round is shown. In correspondence with increasing trend of β values shown in Figure C.1, with the escalating mediation prices the payoff is also boosted on Tier-1 and Tier-2.



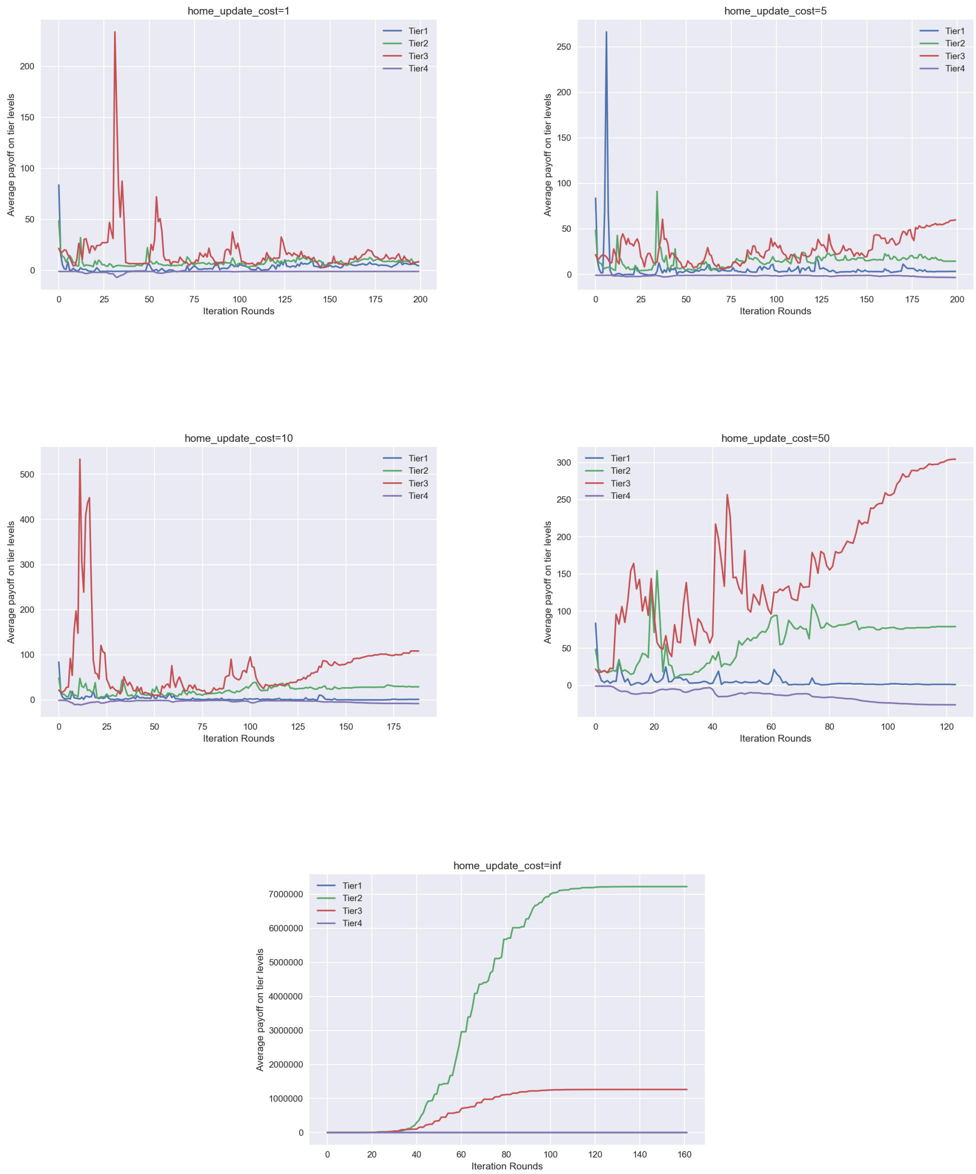


FIGURE C.2: The payoff in relation to the home provider update cost.

C.3 Connection Change History

Figure C.3 shows the accumulated count of changed (created or deleted) connections for each iteration round. It includes both the result of peering business link formation and rehoming to a new home provider as a transit relation. While with the increment of δ the possibility for rehoming reduced, a rapid business peering formation can be observed, especially at Tier-4 to balance the monopolization of dynamic mediation prices (β).

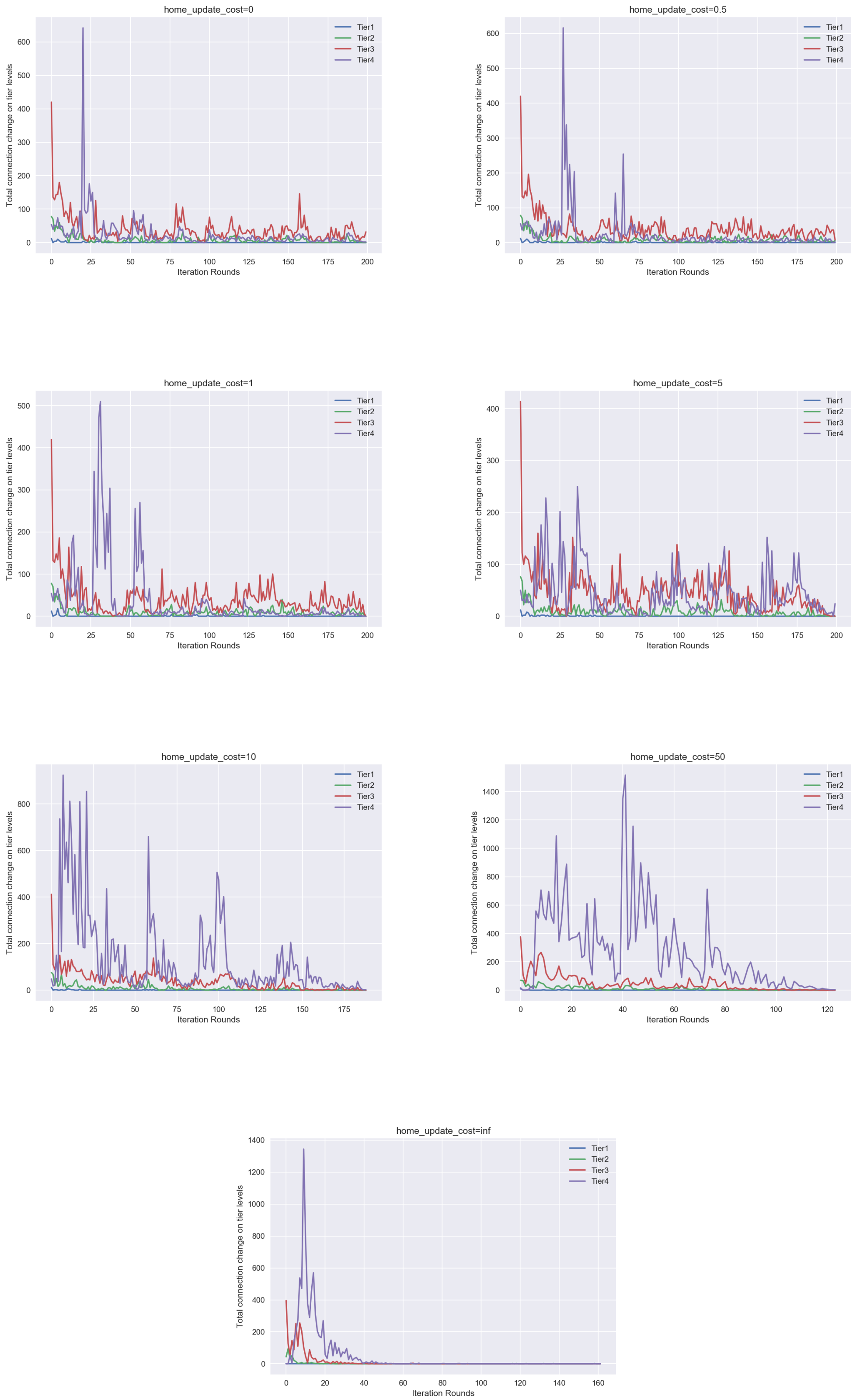


FIGURE C.3: The number of changed connections in relation to the home provider update cost.

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