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Philipp Servatius

Network Economics and the Allocation of Savings

A Model of Peering in the Voice-over-IP Telecommunications Market

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In loving memory of Poldi Reinl

22.11.1977 – 28.12.2007

Preface

The author would like to express the utmost gratitude to everybody who has contributed to this thesis in one way or another. As there are certainly many more such individuals than I could reasonably accommodate here, I list only the most immediate ones.

First and foremost, I would like to thank my mother, Brigitte Servatius. She has always offered her advice and supported my endeavors, most importantly by letting all final decisions rest with me. Growing up (though some challenge this is indeed accomplished) she gave me all the of freedom I desired and with it the greatest of all goods: The confidence that I would choose to do the right thing, or, as often as this could not be determined a priori, avoid obviously wrong choices. Looking back, I could not have wanted much more.

Next, I want to thank all my of close friends. Countless hours spent in their company pushed my productivity and endowed me with the necessary energy to endure. Names shall not be necessary, you know who you are.

Also, I am very grateful for the support of my colleagues at the various institutions that contributed to my doctoral education. In particular I would like to mention Dr. Kazuhiko "Shiofuki" Kakamu, with whom I not only shared an office at the Institute for Advanced Studies in Vienna but also encountered many challenges there. No less Dr. Barbara von Schnurbein, née Styczynska, my colleague at the Chair of Microeconomics in Fribourg; to her I am indebted for many a constructive criticism and for an atmosphere in our office that was second to none. Also Danielle Martin, then assistant at the Chair of Statistics, who has occasionally let me take advantage of her superb math skills should not go unmentioned. The same is true for Bobo, Suti and Yolanda.

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Last but certainly not least, my advisors deserve more than just praise: It is hard to describe what I owe to my first advisor, Prof. Reiner Wolff. Because he did not restrain my research agenda in any way, my curiosity was fueled to a point that lead to something probably neither of us had imagined when I started in Fribourg. This was certainly facilitated by the fact that I had never been overburdened with administrative work (far from it to be honest). I am especially grateful for his painstaking and meticulous revision of this dissertation's first draft. It could hardly have been more detailed. My second advisor, Prof. Hans Wolfgang Brachinger, also deserves my gratitude and a good deal more. He never declined any of my requests and supported me on all academic and extracurricular fronts, especially when it mattered most to me.

But despite all of the helpful input I have received, some errors are bound to remain in this document. Needless to say, the responsibility for these is entirely mine.

Fribourg & Zurich Philipp M. Servatius
April 2011

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Chapter 1
Motivation and Nontechnical Overview

The telecommunications market is one of the most fascinating witnesses of technological progress. Three decades ago "telecommunications" would refer almost exclusively to fixed-line telephony. And international, let alone intercontinental calls were exotic, mainly due to their high prices.

By now, telecommunications encompasses a wide range of possibilities allowing human beings to communicate over a distance on the basis of many different services other than fixed-line telephony. But telecommunications are not limited to human interaction. Various kinds of computer systems exist whose interaction through a telecommunications network is at least not directly initiated by a human action. Fixed-line telephony is barely identified with the expression telecommunications anymore, and the distances covered are no longer pivotal, if relevant at all in some areas, for the pricing of services.[1]

As such, the telecommunications industry is granted a dual role: First, it naturally constitutes an economic sector of its own. According to Sarrocco and Ypsilanti (2007), communication goods and services are the most rapidly growing item of household consumption in OECD countries. But more importantly, telecommunications support and even give rise to much economic activity in other sectors, with a far greater impact. What The Economist (2010) describes in a special report on information management, titled "Data, data everywhere," crucially hinges on the existence of telecommunications networks. This second role is hard to delineate in its entirety, exactly because of telecommunications' omnipresence in the economy.

Many of the telecommunications services nowadays revolve around the internet, which experienced a massive expansion over the last two decades and by far surpasses the telephone network in data transfer capacity. With the expansion came a tendency to duplicate at least parts of the network structure already present from telephony in order to deliver the new services to the customers. This tendency is now bound to reverse itself, as network operators aim to erect *next generation networks*,

[1] See Fransman (2003) for more on the evolution of the telecommunications industry.

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which allow to deliver an unspecified menu of services over but a single architecture. The cost advantages are tremendous, as the marginal cost of a service, given the network, is near zero.

Coming back to fixed-line telephony, this is a service that is or will be offered on the next generation networks as well. To the customer, there is little if any difference, but the underlying technology has changed fundamentally: From what used to require a dedicated network, fixed-line telephony is a mere by-product, in terms of both traffic volume and revenue, on those unified network structures. In this context it is called *Voice over IP* telephony (short *VoIP*), *IP* referring to the so-called *Internet protocol* which is used to route data in next generation networks. As the switch to these new networks has only commenced and is far from completed, it is not only the case that both types of phone lines coexist, but the providers of the new kind, we call them VoIP firms, also are not yet comprehensively interconnected among each other. Their networks are, they even connect to the legacy networks, but the services delivering VoIP telephony generally are not. This gives rise to the *re-routing problem*, pivotal to this dissertation: Due to the lack of services interconnection among the VoIP firms, their range of sight is limited to their own customers. When one of them calls a number assigned to a customer of another VoIP firm, the firms are unaware that the call is initiated and terminated on IP-based infrastructure and so it is routed via the legacy telephone network. Had both firms, though, signed a mutual peering agreement, the call would remain entirely on next generation network architecture and costs for transit as well as for termination could be reduced or even eliminated entirely.

Being exactly at the heart of this study, we want to shed some light on those peering relationships, or rather the lack thereof, and on what national regulators could do to create incentives for peering. This is to be achieved by means of economic models from the fields of game and network theory.

The relevance of VoIP telephony is quickly established on the basis of the large growth of its subscribers. In Switzerland alone, the Federal Office of Communication (OFCOM) accounts for 467 874 VoIP subscribers out of a total of 4 704 497 fixed-line telephony contracts for 2009, up from almost none 4 years earlier. The statistics for many other industrialized countries show similar developments. They are even expected to jump significantly, as soon as the formerly state-owned network operators, who still tend to have by far the largest numbers of subscribers, switch entirely to next generation networks. But even without these changes, the growth is nevertheless impressive. Also, a multitude of recent studies focussing on the transition to IP-based telecommunications networks (and some even straight out on VoIP telephony) has been brought forward by national regulators as well as international organisations like the EU, the OECD, or the World Bank. This not only highlights the importance of these inevitable developments, but also shows that there are difficulties to be resolved on the way.

We now provide the reader with a nontechnical overview of what is to come. This work is subdivided into two parts, where the first serves to introduce selected theoretic concepts, and the second contains their application in a telecommunications setting.

Part I is composed of two chapters, one on the theory of games, and one on network theory in the context of economics. The chapter on game theory covers parts of both its major branches, cooperative and noncooperative games, but the emphasis is on the former. The selection of all content is mostly based on what is required for the application in Part II, but some matters are included to give a more complete picture and especially to facilitate a more thorough understanding.

We begin Chap. 2 with an exposition on the theory of noncooperative games. The strategic form game representation is introduced first. It is a concept modelling the strategic interaction between the players of a game so that all participants choose their plan of action, called strategy, simultaneously. Which strategy to select optimally is, thereafter, the subject of selected equilibrium concepts we present. Most notable is the Nash equilibrium and some of its refinements. In such an equilibrium, no player has an incentive to deviate to another strategy, because he could not gain anything by doing so. The refinements extend this notion to concerted deviations by groups of players.

The second part on noncooperative games covers their representation in extensive form, which models games as a sequential process, i.e. one where the players choose their moves one after another. We introduce another variant of the Nash equilibrium, its *subgame perfect* form, which extends the Nash equilibrium concept to so-called subgames of the original game.

Next in Chap. 2 comes the consideration of cooperative games. We first define the notion of a cooperative game, in which players can make binding commitments and achieve a surplus through cooperation within a coalition. A *characteristic function* assigns the corresponding value to each possible coalition of players. Depending on whether there even exist overall gains from cooperation and how these gains specifically arise and change within and over different coalitions, we can classify cooperative games and assign certain properties to them.

Finalizing the section on cooperative games, we draw on the much-cited example of the *Tennessee Valley Authority*: In this example, it is shown how the joint realization of three projects (improved navigation on the Tennessee river, flood control, and the generation of electricity, each through dams) can cut costs significantly as compared to their independent completion.

The rest of Chap. 2 is devoted to some of the most prominent solution concepts for cooperative games. These concepts determine how the gains from cooperation are or can be distributed among the players. We call such distributions allocations as soon as they make no player worse off than without participating in cooperation. The solutions are best distinguished by their size, i.e. whether they provide a set of allocations or only a unique value. We treat them in this order.

Before the most influential solution concept, the *core*, is introduced, the related *von Neumann Morgenstern solution*, the predecessor is being derived. It is based on a notion of domination and compares allocations to ensure that the outcome contains no two allocations violating this domination. The concept does not appear in the subsequent application, but is very instructive.

Next, the solution called *core* contains all allocations which are efficient and cannot be improved upon by any coalition of players. "Efficient" refers to the fact that the sum of the gains up for distribution stems from cooperation of all players and is exhausted. "No improvement" states that no coalition is allocated less than what it could achieve on its own. We show different conditions under which, regarding the underlying game, a solution in terms of the core exists.

The section on single-valued solutions, also called allocation rules, starts with a general definition and some common properties of these rules and how the latter respond to changes to the game they are based on. The first allocation rule we cover is the *Shapley value*, characterized by three straightforward axioms: Again *efficiency*, allowing for no waste of the overall gains in distribution, *symmetry*, stating that players are served on the basis of their characteristics and not by their labels, and finally, *additivity*, which allows Shapley allocations over different games to be added, if these games are merged. The axioms lead to individual allocations that reflect the average marginal values of a given player joining a coalition. Because the Shapley value is computed according to a specific formula, its existence is assured.

In case these marginal values do not reflect the cooperation in a way considered proper in certain situations, the *Weighted Shapley value*, next in our exposition, can be applied. It allows for a shift within the allocation accounting also for a system of weights assigned to the players. Interestingly, the Weighted Shapley value can be calibrated to yield any solution that is also an element of the core.

The chapter concludes with a brief treatment of the so-called bargaining problem and corresponding bargaining solutions of Nash and Kalai–Smorodinsky. With this we include an alternative approach to allocate the gains from cooperation among a number of players.

In Chap. 3 we turn to network theory in the context of economics. We begin with the basic notions from graph theory to describe a network in more detail before we turn to *communication situations*, which in essence are cooperative games that incorporate a network structure. The latter governs how value can be realized through cooperation among the players. We also extend allocation rules to the network context and list some properties they now can exhibit. In conjunction, we present the *Myerson value*, the first allocation rule to incorporate network structures. One can characterize it by means of two concise axioms: *Component additivity*, which does not allow the allocation of value to an isolated part of the network in excess of what this part can create on its own, and *fairness*, according to which any two players' change in payoffs is identical after the formation or deletion of a link between them.

The subject of the last section of Chap. 3 is the formation of networks. It is modelled along the lines of noncooperative games, in both strategic and extensive form, and also relies on the equilibrium notions introduced there. The players correspond to the nodes of the network, and the strategies reflect the willingness of a player to form links with others. Here, we distinguish between bilateral and unilateral link formation, meaning whether the consent of both players or merely of one player is needed in the formation of a link. The weight lies on the former concept.