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# Incentives in Location-Aware Peer-to-Peer Networks

A Game-Theoretical View

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# Master thesis - problem description

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## Incentives in Location-Aware Peer-to-Peer Networks

### A Game-Theoretical View

Peer-to-peer applications make up a large portion of Internet traffic. Location-aware peer-to-peer (P2P) network mechanisms have been proposed to provide users with better download performance and Internet Service Providers (ISPs) with better control over actual traffic flowing through their networks. Different solutions have been published and deployed to achieve these goals with varying degrees of success.

In this assignment I intend to analyze and identify which strategies can provide economic incentives for both ISPs and users in order to reach widespread deployment of location-aware P2P mechanisms.

#### **In particular my work will:**

- Provide a background study on existing location-aware P2P network mechanisms and their economic implications.
- Collect and describe game-theoretic concepts relevant to model location-aware P2P network mechanisms.
- Build and evaluate the model using elements of game theory and/or simulations.



# Abstract

Over the last decade the popularity and utilization of Peer-to-peer (P2P) applications such as BitTorrent, have sky rocketed. Studies show that P2P-related traffic accounts for about 40 to 50 percent of the overall Internet traffic volume. Moreover, the inherently distributed design of P2P networks, in combination with arbitrary peer selection, have been shown to introduce traffic control problems for Internet Service Providers (ISPs). In particular, the increase in inter-ISP traffic results in a problematic cost increase for ISPs. In order to solve the P2P challenges, a variety of location-aware P2P mechanisms have been published and implemented with varying degrees of success. Although the technical aspects of these mechanisms have been studied quite thoroughly, their adaption and success can arguably only be determined by the entities in power, namely ISPs and its P2P traffic generating customers.

In this thesis a game-theoretic approach is pursued in order to capture the economical interactions of both ISPs and its users when presented with a decision of adapting location-aware P2P mechanisms. Specifically, a game-theoretic model is developed, encompassing the variety of ISP and consumer aspects from traffic domain related costs and P2P performance to Internet access pricing. The model perspective is limited to the decision making between one ISP and its users and it is studied in two steps. First an analytical equilibrium analysis is performed in order to develop general expressions regarding incentivizing actions between the ISP and its users. Finally a numerical analysis is performed, using relevant data found in literature and estimates, in order to identify which strategies that could provide incentives for both ISPs and its users to adapt location-aware P2P mechanisms.



# Sammendrag

Nylige studier relatert til Internett trafikk har vist en stor økning i bruken av P2P-applikasjoner, som for eksempel BitTorrent. Som følge av denne utviklingen, samt de geografisk distribuerte trafikkstrømmene som P2P genererer, har dagens Internettleverandører erfart en signifikant kostnadsøkning på såkalte transit- og peering linker.

Som en følge av den store økningen i bruken av P2P-applikasjoner, samt de relaterte kostnadsøkningene dette medfører, har det blitt publisert mekanismer som forsøker å utnytte lokalitet for å minske den kostbare geografiske distribusjonen av P2P-trafikk . Et mangfold av såkalte lokasjonsbevisste P2P-mekanismer har blitt designet og implementert i løpet av de siste årene, men adopsjonen blant brukere og Internettleverandører er ennå ikke nådd et tilfredsstillende nivå.

I denne oppgaven utvikler vi en modell, basert på spillteori, for å undersøke hvilke kombinasjoner av lokasjonsbevisste P2P-mekanismer og økonomiske strategier som kan skape incentiver for både endebrukere og Internettleverandører. Modellen blir evaluert analytisk og numerisk for å identifisere hvilke strategier som med hensyn på prissetting og teknisk ytelse kan skape et grunnlag for økt bruk av lokasjonsbevisste P2P-mekanismer.





# Preface

This document manifests the final thesis of Audun Follegg, in the field of Tele-economics under the Master's program in Communication Technology at The Norwegian University of Science and Technology, NTNU.

First and foremost, i would like to thank my supervisor Mr. Gergely Biczók, for supporting me with both valuable feedback as well as crucial advice and guidance throughout the project.

Secondly, i would like to thank my friend Mr. Joachim Kruger for valuable discussions and help during my thesis project.

Finally, i would like to thank my fellow students for their support.



# Abbreviations

**P2P** Peer-to-peer

**ISP** Internet Service Provider

**AS** Autonomous System

**ASN** Autonomous System Numer

**P4P** Provider Portal for Applications

**BGP** Border Gateway Protocol

**LOCAM** Location Aware Peer-2-Peer Mechanism

**QoS** Quality of Service

**ISPF** ISP-Friendly Peer Matching without ISP Collaboration

**VPN** Virtual Private Network

**SPE** Subgame-Perfect Equilibrium

**BT** BitTorrent

**CDN** Content Delivery Network

**IP** Internet Protocol

**RIR** Regional Internet Registries

**ICMP** Internet Control Message Protocol

**GNP** Global Network Positioning

**TnT** Transparent Network Tracker

**NP** Network Processor

**GT** Game Theory

**NE** Nash Equilibrium



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# Chapter 1

## Introduction

### 1.1 Motivation

Recently the world wide popularity and utilization of Peer-to-peer (P2P) applications, such as BitTorrent, have experienced a tremendous growth. In addition, studies show that its related traffic accounts for a significant portion of the overall internet traffic volume. Moreover, the inherently distributed design of P2P networks in combination with arbitrary peer selection have been shown to introduce traffic control problems for ISPs as well as causing significant increases in costly inter-ISP traffic. In order to solve the P2P challenges, a variety of location-aware P2P mechanisms have been published and implemented with varying degrees of success. Although the technical aspects of these mechanisms have been studied quite thoroughly, their adaption and success can arguably only be determined by the entities in power, namely ISPs and its P2P traffic generating customers. In order to reveal what kind of technical and economical aspects that could incentivize the adoption of these mechanisms, we it is arguably necessary to study their combined effects on the utility of ISPs and its users. In this thesis, we take a game-theoretical approach to study the combined effect of P2P traffic improvements and pricing decisions on one ISP and its users, in order to identify strategies that could incentivize a broader adoption of Location Aware Peer-2-Peer Mechanisms (LOCAMs).

### 1.2 Objective

The objective of this thesis is, in accordance with the original problem description, to provide insights into what strategies that can provide economical incentives, for both ISPs and its consumers, in order to adopt location-aware P2P mechanisms. Furthermore, this general objective are refined into fulfilling the following tasks.

1. Provide a relevant background study that describes state-of-the-art location-aware P2P mechanisms and underpins the relevance of their application.
2. Develop a game-theoretic model that, within a framework of limitations, is capable of capturing the economic interactions between one ISP and its consumers, when deciding wether to adopt location-aware P2P mechanisms.
3. Analytically analyze the model and derive expressions that represent general boundaries for incentivizing strategies.
4. Utilize results from relevant studies and experiments to identify numeric equilibrium conditions.

### 1.3 Limitations

In order to achieve the objectives defined in Section 1.2, we have made the following limitations for our study:

1. The scope of the game-theoretical model will be the study of one ISP and a finite set of internet subscribers.
2. The game-theoretical model will be enabled by a framework of assumptions.
3. Data that is found very difficult to obtain will be estimated or assigned based on assumptions and reasoning.

### 1.4 Methodology

This section summarize the set of methods that have been utilized when identifying relevant literature as well as for developing and analyzing of the game-theoretic model. We first describe how literature was found in Section 1.4.1 followed by a description of our approach to game-theoretic modeling in Section 1.4.2 and thereafter provide a brief description of our evaluation methods in Section 1.4.3.

#### 1.4.1 Literature search

In order to identify relevant literature, we have utilized the relevant channels that is available to students such as the university library and search engines such as Google scholar. In addition we have received valuable information regarding relevant research from academic personnel at NTNU. Furthermore, most of the data

that is used in the evaluation of our model have been identified throughout the literature study.

### 1.4.2 Game-theoretic modeling

As a part of our effort to develop a game-theoretic model, we have studied relevant papers, such as [4, 33], in order to identify approaches on how to define the strategies and utility functions of ISPs and users. It is noteworthy to mention that the development of the model, presented in Chapter 3, was the most time consuming effort throughout this thesis. Furthermore, we used academic resources on the subject of Game Theory (GT), such as [20], to clarify what elements that should be included in the model.

### 1.4.3 Evaluation methods

In this section we briefly clarify the methods that have been utilized in order to evaluate the game-theoretical model that have been developed throughout the project. Our evaluation is mainly categorized into two main approaches and they we will briefly described below.

#### Analytical analysis

In order to identify generally applicable results from our model, we have performed an analytical analysis of the model, based on the utility (payoff) functions that have been developed. In the analytical analysis, we have utilized the concept of utility based indifference in order to identify a set of parametric boundaries where the ISP and users receives the highest utility for a given set of strategies.

#### Numerical analysis

In addition to the analytical analysis, we have performed a numerical analysis in order to make more specific inferences with regards to the quantities that are represented in our model. In the numerical analysis, we utilize parametric values that have been identified in relevant literature, as well through data collection and estimation, in order to identify numeric boundaries where different strategies yields the highest payoff for the ISPs and the users. Because some parameters was found very difficult to quantify, we found it necessary to assign values based on assumptions.

## 1.5 Contributions

This section serves the purpose of clarifying what elements in the thesis that should be considered as contributions and not. The background study is to be regarded solely as a summary of existing material, although many illustrations are created to our specific needs. Our contributions are however mainly the development of the game-theoretic framework in Chapter 3 that is used to analyze the ISP-User interaction both analytically in Chapter 4 and numerically in Chapter 5.

### 1.6 Outline

This section clarifies the outline of the thesis with a brief summary of each chapter as given below.

- **Chapter 1**, briefly introduce the motivation behind our study, the concrete objectives and limitations that is set. In addition, it introduces the methodology and a brief overview of the contributions of the thesis.
- **Chapter 2**, provide a relevant background study on the state global internet traffic and the share of P2P, as well as introducing the ISP connection model and the traffic control problem in order to show the relationship between P2P traffic and the increased ISP traffic costs. Finally, a selection of the most relevant state-of-the-art approaches to location-aware P2P mechanisms is explored.
- **Chapter 3**, provide some basic notions of GT and introduce the game-theoretic framework that have been developed throughout this project.
- **Chapter 4**, provide an analytical analysis of the game-theoretical model and identifies analytic restrictions that express when an ISP and its users have incentives for the different strategies.
- **Chapter 5**, provides an numerical analysis of the model, by utilizing parameter values that have been found in literature or through estimation. The model is analyzed for different P2P traffic scenarios and numerical equilibrium conditions is identified.
- **Chapter 6**, discuss future work.
- **Chapter 7**, provides a discussion of the validity of the model developed in Chapter 3 as well as the results found in Chapter 4 and 5.
- **Chapter 8**, briefly summarize our efforts as well as the results obtained in relation to their implications on the adoption of LOCAMs.



# Chapter 2

## Background Study

The background study of this thesis, in agreement with our defined objectives in Section 1.2, provides a firm understanding of location-aware mechanisms, their relevance and their economic implications. To achieve this, we provide an overview of P2P networks and thereafter look at the state of Internet traffic. We explore the ISP connection model and the problems of P2P ISP business models before finally exploring the most relevant location aware-mechanisms that is proposed in literature.

### 2.1 P2P networks in a nutshell

As discussed in [2], P2P network design represents a significant shift from the traditional client-server model in that each computer on the network can share some of its resources, thus creating a system that supports both distributed processing and storage, as illustrated in Figure 2.1. Moreover, there are some general principles that makes P2P systems radically different from the client-server approach. Some of these are:

1. Sharing of resources among the participants of the network.
2. Decentralization of resources, eliminating single point of failures.
3. A self-organized network, meaning that nodes do not need a central coordinator.

As discussed in [12], there are a number of existing applications that utilize the above P2P design principles. Some of the more successful P2P designs include file sharing applications such as Napster, Kazaa, eDonkey and BitTorrent to music streaming services such as Spotify and distributed computing services such as Seti@Home. Furthermore, having briefly described the key principles of P2P networks, we will next examine the current state of Internet traffic with a special focus on the P2P network components.

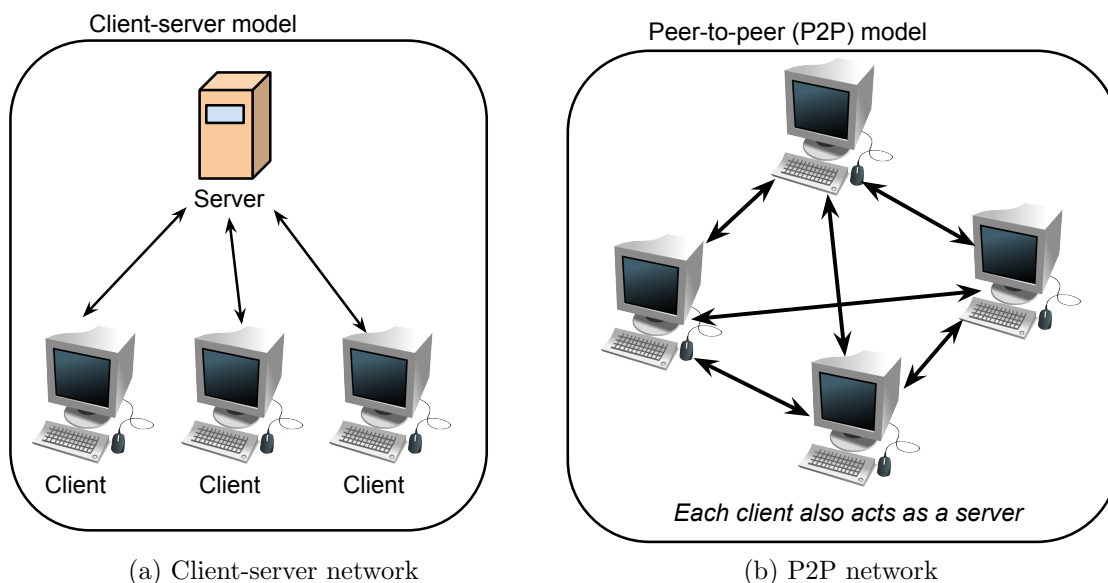


Figure 2.1: Illustration of transition from client-server to P2P model

## 2.2 State of Internet traffic

As the world population is arguably becoming increasingly connected to the Internet, the adoption and dependence on Internet technology based applications is becoming ever more significant. Moreover, a recently published forecast by Cisco in [31] states that the volume of consumer generated traffic traversing the Internet is expected to grow from 12528 Petabytes in 2010 to as much as 58214 Petabytes in 2015. In addition to increased connectivity, innovative Internet based technologies such as the P2P based file sharing protocol BitTorrent [34], have arguably transformed the way digital products are distributed and consumed. In this section we discuss some recent efforts that attempts to quantify the composition of traffic that traverses the Internet, with a focus on the share that originates from P2P technology.

### 2.2.1 Global Internet traffic composition

The composition of global Internet traffic, the traffic that does not remain inside an ISPs network, have recently been studied quite extensively. By analyzing the forecast in [31], we can illustrate how different types of Internet traffic is expected to develop in the period from 2010 until 2015. We illustrate the the forecasted traffic composition development from [31] in Figure 2.2.

File sharing, that in 2010 accounts for the largest traffic portion is expected to be nearly halved by 2015 as Internet video traffic is expected to claim the throne of highest traffic contributor. For the case of Internet video, the development is argued in [31] to be explained by the increasing popularity of video streaming services such as Youtube, Hulu and Netflix, as well as new Internet services provided by television channels. Moreover, [31] estimates that approximately 70 to 80 percent of P2P-based file sharing traffic originates from the exchange of large video files in

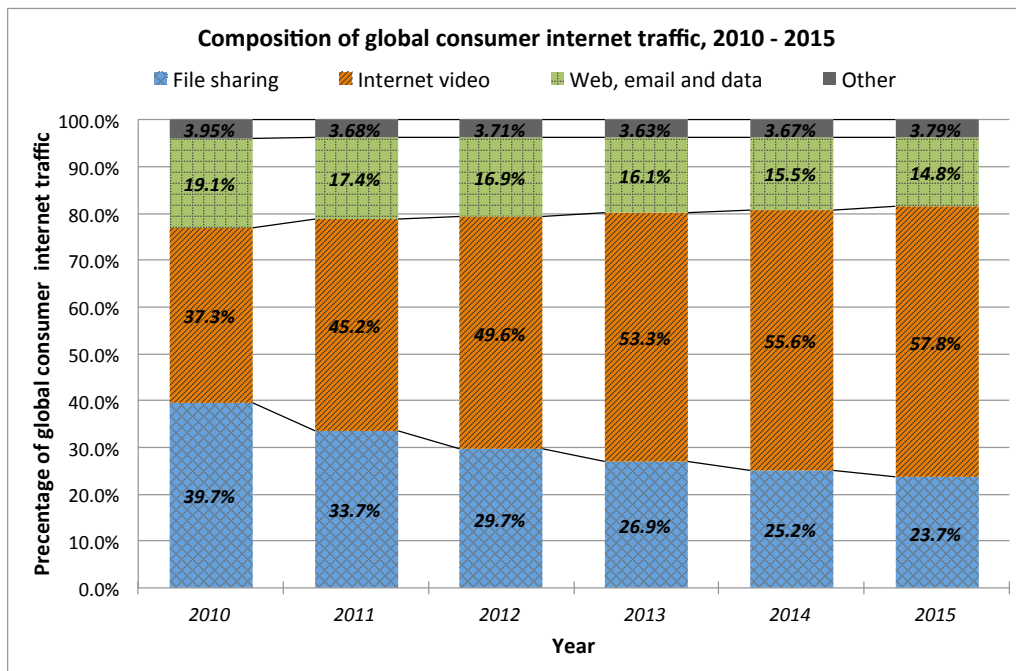


Figure 2.2: Forecasted composition of global consumer Internet traffic from 2010 to 2015. Source: Cisco VNI [31].

2010, thus suggesting that the distribution and consumption of video on the Internet is moving from P2P downloads to online video services.

### 2.2.2 The share of Internet P2P traffic

As we have described some general trends regarding the composition of consumer Internet traffic in Section 2.2.1, we now focus our efforts on the trends of actual P2P traffic. A study described in [18], have done some significant research into the composition of Internet inter-domain traffic by utilizing direct instrumental observation at over 18 global, 38 regional and 42 local network providers in Europe, America and Asia. Findings in [18] supports a trend that indicates a decreasing volume of P2P traffic in the global setting, from roughly 40 percent of all inter-domain traffic in 2007 to 20 percent in 2009. In addition, studies of Chinese networks in [39] indicate that majority of P2P traffic originate from P2P file sharing applications such as BitTorrent, eDonkey and Gnutella. The latter is supported by the Cisco forecast in [31], showing that P2P file sharing traffic accounts for nearly 82 percent of file sharing in general and over 30 percent of total consumer Internet traffic.

**Is P2P really a problem?** Given the above discussion, revealing indications that P2P traffic is decreasing, we find it important to clarify that although the share of P2P, in relation to the global Internet traffic, might be decreasing; the traffic volume of P2P is increasing. *In fact, as illustrated in Figure 2.3, the traffic volume of P2P file sharing traffic is estimated by [31] to double in the five years from 2010 to 2015.* Furthermore, novel P2P video streaming techniques might add to this number.

In the next sections we further clarify why increased P2P traffic is a problem for

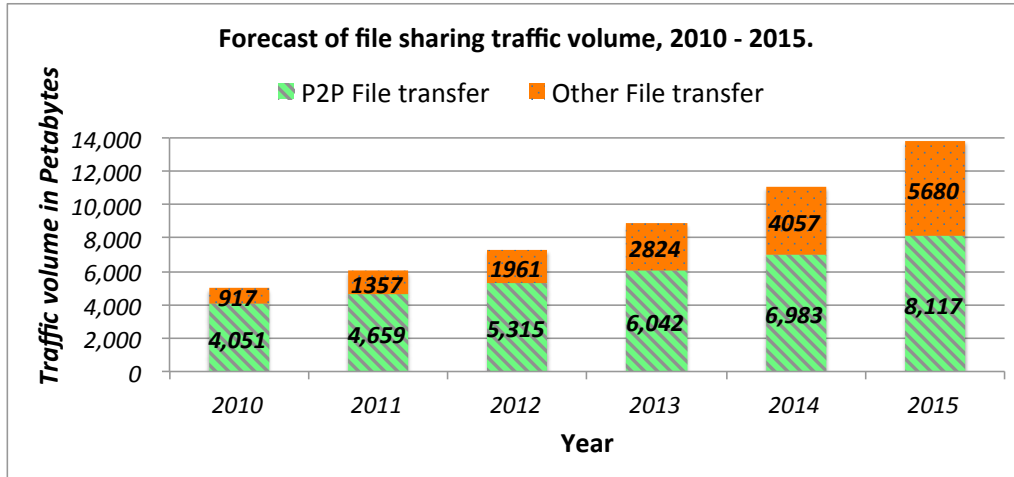


Figure 2.3: Traffic volume forecast of file sharing traffic, 2010 - 2015. Source: Cisco VNI [31].

ISPs and potentially for its consumers.

## 2.3 The ISP connection model

Having explored the current trends in the Internet traffic domain, we have found that P2P traffic makes up a significant portion of the global Internet traffic. Furthermore, as discussed in Section 2.1, P2P networks are by design oblivious to the underlying physical network and is thus more difficult to control. In this section we present a simplified overview of the connection model for a typical ISP in order to understand the ISP related problem with P2P traffic.

**The role of an Internet Service Provider (ISP).** As the role of an ISP might be unclear, we want to define it before continuing. DrPeering provides a convenient definition in [24], stating that the role of an ISP is to connect end-users and businesses to the public Internet. However obvious, an ISP has to provide its customers with reachability to all the networks that make up the global public Internet as illustrated in Figure 2.4.

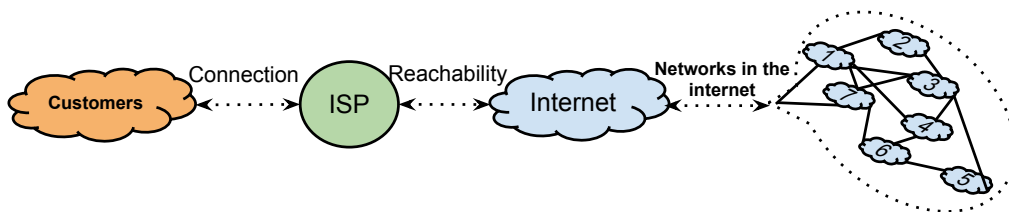


Figure 2.4: Illustration of the ISP connection role in relation to customers.

Obviously this feat must include establishing physical interconnections with other networks already connected to the Internet. What might be less obvious is the

business model for such interconnections. In [21, 24] these business relationships are classified into what is known as Internet transit and Internet peering.

### 2.3.1 Internet transit

Internet transit is defined in [24] as a business relationship where one provider ISP sells access to all the destinations in its routing table, thus enabling a customer ISP to access and be accessed from any of the destinations in the provider ISP routing table. As a result, a transit relationship extends the reachability of a customer ISP.

**95 percentile billing method.** The 95 percentile billing method is argued in [22] to be the most common framework for economic compensation in a transit relationship. As furthermore described in [22] the method is enforced by the transit provider collecting 5 minute samples of the traffic volume in Mbps on the physical link that connects the transit provider with the customer ISP. For each sample, the maximum value of either upstream or downstream traffic volume is chosen and the samples are thereafter ranked from high to low. At the end of a billing period the provider use the 95 percent measure of the sorted samples to calculate the billable traffic volume, thus ignoring the 5 percent highest samples.

**Transit pricing.** When a billable traffic volume  $T_t$  (in Mbps) is determined, the transit provider charges the customer ISP at a transit price  $p_t$ , such that the cost of transit for the billable period is  $T_t \cdot p_t$ . As mentioned in [22], transit providers often operates with volume discounts based on transit volume commitment levels. In such a setting the customer ISP pays less per Mbps the more overall traffic volume it commits itself to pay for. Furthermore, a historic and projected overview of transit prices for the US market is presented in [22] and shown in Figure 2.5.

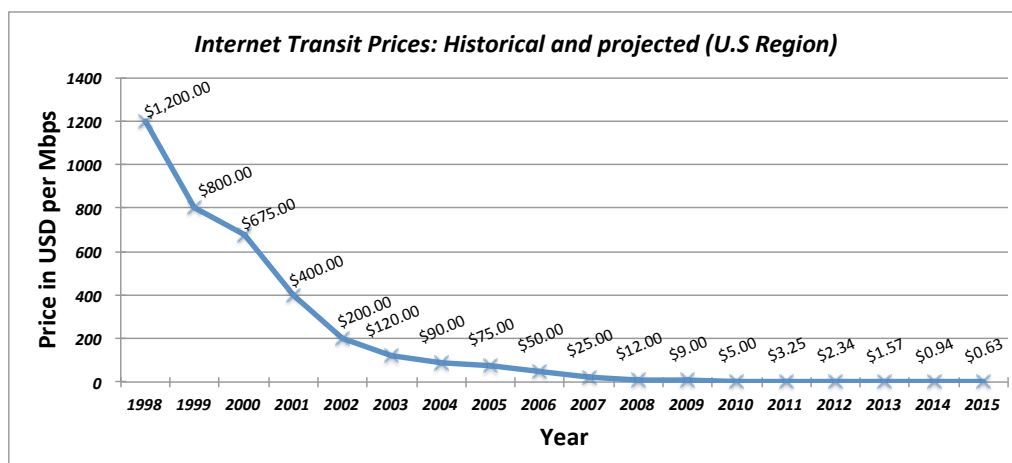


Figure 2.5: Internet transit prices for the US region: Historical and projected. Source: DrPeering International [22].

From the price overview in Figure 2.5, we observe a huge decline in Internet transit costs, but acknowledge, however, from our findings in Section 2.2 that Internet traffic is also growing tremendously fast. It is clear that transit costs can add

up to significant amounts for ISPs, and in many situations a peering relationship is arguably beneficial.

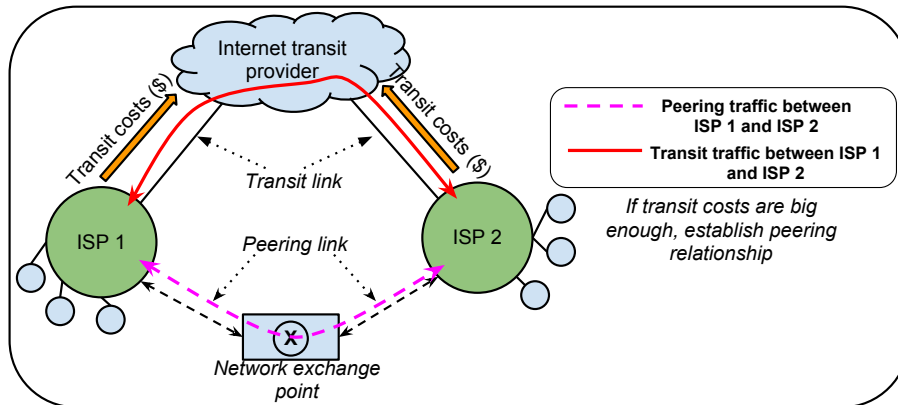


Figure 2.6: Illustration of ISP transit and peering relationship

### 2.3.2 Internet peering

Having the discussed the Internet transit relationship, we now explore the situation that arises when two ISPs have approximately symmetric amounts of traffic that flows between the them. If the traffic between these ISPs is distributed through a transit provider ISP as illustrated in Figure 2.6, the two customer ISPs might actually collectively pay the transit provider twice for the traffic. If the costs of establishing and maintaining a direct connection between the two customer ISP networks is lower (or comparable) to the transit costs, it is argued in [24, 22] that the ISPs should establish a peering relationship. Internet peering is moreover defined in [24] as a business relationship whereby companies, such as ISPs or Content Delivery Networks (CDNs), reciprocally provide access to each others customers. Moreover, [32] describe two types of Internet peering:

1. **Free peering:** is a peering relationship where traffic is free within the limits agreed upon by the peering parties.
2. **Paid peering:** can be described as a peering relationship where one participant gets some form of settlement fee or compensation from another participant due to asymmetric traffic between the two parties. Although it is similar to a transit relationship, the pricing is assumed to be much cheaper than transit.

## 2.4 The traffic control problem

In this section we introduce the traffic control problem that according to [38] is highly relevant to the business of ISPs today. This problem involves how network applications, such as P2P applications, can utilize ISPs network resources in a efficient and fair way. Especially the dynamic traffic flows of network oblivious P2P

traffic is thought to fundamentally change the network traffic control problem. In order to explore this problem, we first describe the ISP perspective on traffic control.

### 2.4.1 ISP traffic control

First and foremost, any ISP needs to control its network traffic in order to secure a stable operation. As described in [38], problems ranging from congestion on network links to disconnection can degrade the performance of the network and thus lead to diminished customer satisfaction.

**Routing policies.** Additional to stable operation, we explored in Section 2.3 that ISPs might have different kinds of connection models that often are a combination of transit and peering relationships. Because the different connection relationships can vary in their cost aspects, it is arguably important for an ISP to route traffic in a manner that minimize traffic induced costs, as well as securing a stable network performance. According to [18], most network providers use the routing protocol Border Gateway Protocol (BGP) to define traffic routing policies in order to optimize their inter- and intra-ISP traffic flows.

**Forecastable traffic demands.** Furthermore, traditional client-server traffic is, as described in [38], often to some extent forecastable with respect to the demand pattern of that traffic. These demand patterns can be used by ISPs to adapt its routing policies using BGP in order to optimize its business.

Given the brief overview on how traditional ISP traffic control is done, we now shift our focus onto how P2P applications might change the conditions for ISP traffic control.

### 2.4.2 Peer selection in P2P

In Section 2.1 we have provided an overview of how P2P networks work, and the idea of leveraging the sharing of resources between any connected computer in order to act as both server and client. Moreover, the distributed approach of P2P arguably influences the pattern of traffic flows when compared to traditional client-server models. As resources are served and consumed in a dynamic way between spatially dispersed network participants, the traffic patterns can arguably be quite random. In addition to the decentralized design of P2P systems, [7] states that the majority of P2P systems employ an arbitrary peer selection policy where one peer connects to a subset of randomly selected cooperating peers.

To further investigate how this arbitrary peer selection could influence the traffic control problem, we provide a brief overview of peer selection in the P2P file sharing protocol BitTorrent [34]. Please note that we choose BitTorrent because of its popularity and the quality of studies available [5, 26, 19].

#### Overview of peer selection in BitTorrent

BitTorrent as described in [9], is designed as a P2P file-sharing protocol which enables a large user population to distribute large files in an efficient manner. As

additionally explained in [5], BitTorrent file distribution involves the following simplified steps:

**A provider shares a file by:**

1. Splitting the file into a set of smaller pieces (usually 245 KB in size)
2. Generating a *torrent* file that contains meta-information about the whole file and its pieces
3. Registering the torrent with a *tracker*, which in this context is a server that serves the torrent file and keeps track of all nodes that cooperate in the file-sharing session.

When a peer  $p$  wants to download a file, and thus participate in the file-sharing, it follows the following steps:

1. Contact the tracker that hosts the *torrent* for a given file.
2. The tracker then **randomly** selects a subset  $C$  of all the nodes that participate in the file-sharing network and returns it to  $p$
3. Peer  $p$  contacts the  $C$  nodes that it received from the tracker in order to download the file.
4. When  $p$  has all the pieces of the file, it changes to *seed* mode, which means that it have the whole file and is sharing it.

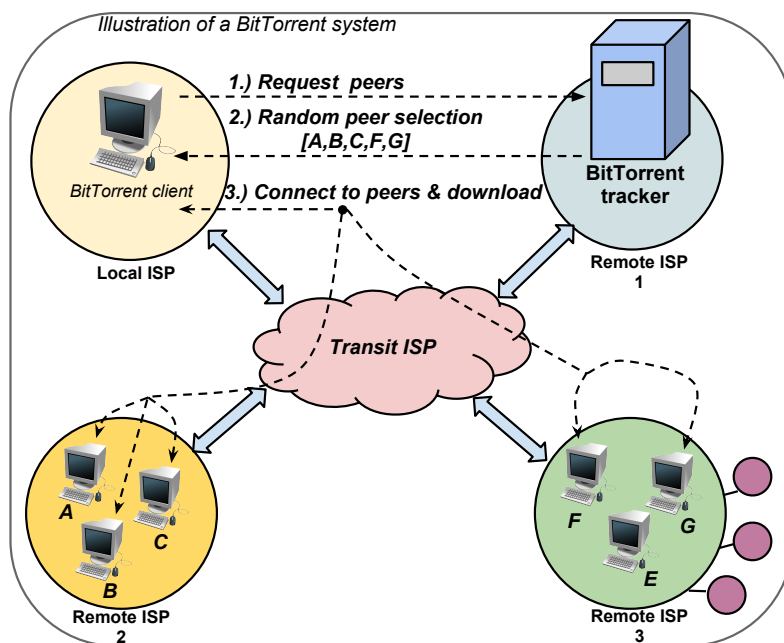


Figure 2.7: Illustration of BitTorrent peer selection

The above description is additionally illustrated in Figure 2.7. Please note that there exists several BitTorrent implementations and that our simplified description is based on [5].



### Effects of random peer selection

Having explored one of many ways of constructing a P2P network, we argue that some of its effects on ISP traffic patterns can be inferred quite intuitively. We identify the following effects that is supported by [7, 38, 26, 19]:

1. **Increased Inter-ISP traffic.** Because peers are chosen at random, traffic streams will be more random and geographically dispersed. Consequentially, the traffic also traverses the networks of multiple ISPs. As a result of the latter, traffic streams have a high probability of traversing cost intensive transit and paid peering links.
2. **Low utilization of local peers.** Another effect of random peer selection is that peers inside an ISPs network do not utilize other peers inside the same network.
3. **High redundancy in downstream data.** As a consequence of not utilizing local peers, data might be downloaded trough transit and paid peering links multiple times and thus potentially lead to significant (and unnecessary) traffic costs for ISPs.

Given the above findings in combination with our notions of the overall increasing volume of P2P traffic, it is natural that mechanisms for controlling peer selection have been developed.

### 2.4.3 Traditional P2P control approaches

Given the previous discussion about ISP traffic control and the problematic effects introduced by P2P systems, it is clear that ISPs have an incentive to manage the increasing volumes of P2P traffic in order to minimize transit related costs. As explained in [38, 7, 30], ISPs have already attempted to limit the inter-ISP traffic induced by P2P traffic. Some of the utilized approaches are:

1. **Blocking.** Some ISPs attempt blocking P2P traffic entirely. But, as described in [30], P2P obfuscation by encryption are making the traffic increasingly more difficult to identify. In addition traffic blocking based on port numbers have recently, as argued in [7], become difficult as many P2P systems now use non-standard ports that is chosen at random.
2. **Traffic shaping.** In order to control P2P streams, an ISP might attempt to limit the bandwidth rate of clients that are utilizing P2P technology in order to decrease the traffic volume that passes through its transit or paid peering links. But due to the problem of identifying P2P traffic as mentioned above, this might be difficult.
3. **Caching.** ISPs could attempt to save copies of for example popular torrent files on an local server, leading local users to download content locally instead of through transit or peering links. However, as mentioned in [7], storage of possibly copyrighted material might introduce serious legal issues.

## CHAPTER 2. BACKGROUND STUDY

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Moreover, both blocking and traffic shaping arguably affect the perceived P2P performance for end-users and might decrease the value of Internet service. As a consequence, these approaches can have damaging effects on the business growth of ISPs.

Given the notions presented here, it can be deduced that P2P traffic can introduce severe inefficiency in both the cost perspectives and traffic control in ISPs networks. Furthermore, the traditional control approaches presented above are arguably not good for either ISPs or their users. The need for more sophisticated mechanisms for P2P

## 2.5 Location-aware P2P mechanisms

Given our discussion on the random peer selection scheme used in BitTorrent in Section 2.4.2, we found that such a scheme potentially could result in a unnecessary geographically dispersed P2P network graph, thus increasing the amount of costly inter-ISP traffic. As described in [30], there are several general approaches that have been introduced to improve the locality of peer selection in P2P networks. In this section we provide an introduction to the relevant approaches.

### 2.5.1 Overview of P2P location-aware approaches

#### IP address based

One approach to locality is the use of IP address information about peers to make more intelligent choices regarding their location. From [30] we have identified two flavors of interest.

1. **Geolocation databases.** Several methods, such as in [13], have been developed in order to infer the geolocation of IP addresses. Furthermore, the location of peers can be extracted from geolocation databases and used for improving the locality of peer matching in P2P networks. However, as argued in [30], this approach ignores the underlying network topology, and might cause slower peers on congested network paths to be selected.
2. **IP prefix.** Another IP address based approach use IP prefixes and IP address allocation data in Regional Internet Registries (RIRs) in order to infer peer locations. Due to IPv4 address overloading this approach do not provide secure location data.

#### Autonomous System based

A more precise description of network locality can be achieved by the utilization of Autonomous System Numers (ASNs) as they uniquely correspond to one ISP. As described in [30], peers in the same network can be identified by performing ASN lookups. A problem however, is that large ISPs can have several unique ASN entries [7], and that peers selected solely by ASN might be located along congested and inefficient internal paths. Additionally, the reduction of inter-ISP traffic in this approach depends on the availability of peers having the requested resources inside one ISPs network.

#### Direct measurement

Another approach, according to [30], is to select peers based on measurements attained by using Internet Control Message Protocol (ICMP)-based tools such as "ping" and "traceroute" in order to find peers with low delay paths. Due to firewall blocking of ICMP packets and the time consumption of measuring all possible peers, this approach is not widely favored.

#### Network positioning

In addition to the above approaches, there have been proposed systems that explore the possibility of creating a network positioning service. Of these, the Global

Network Positioning (GNP) described in [30] and [35], attempts to provide positioning through a so called landmark approach that enables calculation of locations using the geometric distance between a set of distributed reference computers (called landmarks). In addition there are approaches, such as Vivaldi described in [10], that is based entirely on decentralized (landmark-free) computation of network locations. Although promising, Vivaldi requires software to be installed and running on online computers, in order to work.

### Oracle

Other approaches, such as Alto described in [28], introduce the idea of a central oracle service, that P2P applications may query in the peering decision phase. In addition to providing location-awareness, ISPs can register information about their network topology, routing policies and operation costs with the oracle, enabling better possibilities regarding inter-ISP traffic reductions.

### ISP-aided systems

More generally, there are several mechanisms that by design requires implementation in the infrastructure of network providers. LiteLoad described in [14] is one such approach, which attempts to optimize P2P traffic by analyzing, keeping track of P2P nodes that are connected and their respective network paths in order perform active redirections and address replacements.

### Relative positioning

The last approach utilizes the network views of CDNs in order to infer the underlying network topology. Moreover, CDN providers (as argued in [7] ) normally place replica servers close to the network edge in order to provide end-users with good performance. ONO, described in [7], takes the above approach by inferring location proximity between nodes based on CDN redirections.

## 2.5.2 Recent developments

As described in [30], many of the approaches we have briefly introduced above improve the P2P performance of the user, but do not significantly reduce inter-ISP traffic. As ISPs are finding it necessary to either throttle or block P2P traffic because the costly P2P traffic streams, the more recent developments of location-aware P2P mechanisms focus specifically on the ISP requirements. Moreover as argued in [30], the recent developments can be categorized into to provider-aided approaches and client-side approaches. Next, we introduce a subset of approaches that is found to be the most promising candidates for consistent adoption among users and ISPs.

## 2.5.3 Client-side approaches

Client-side approaches to P2P locality are special in the way that they do not require any infrastructural changes by the ISP. Moreover, as these solutions can be realized in software that is designed to run at the network edge, they are easier to realize in terms of cost. As described in [30], these solutions can be distributed as plug-ins for existing P2P systems.

## ONO

ONO, described thoroughly in [7], take the relative positioning approach and is based on recycling the network views of large CDNs. Furthermore, because large CDNs attempt to improve end-user performance by redirecting traffic to lower latency replica servers located at the network edge, it is argued in [7] that by recording the CDN redirection behavior of potential peers, P2P applications could improve traffic locality and performance by selecting the peers that are most frequently redirected to the same replica servers. We provide a simplified illustration of how ONO peer selection is done, based on the description in [7], in Figure 2.8.

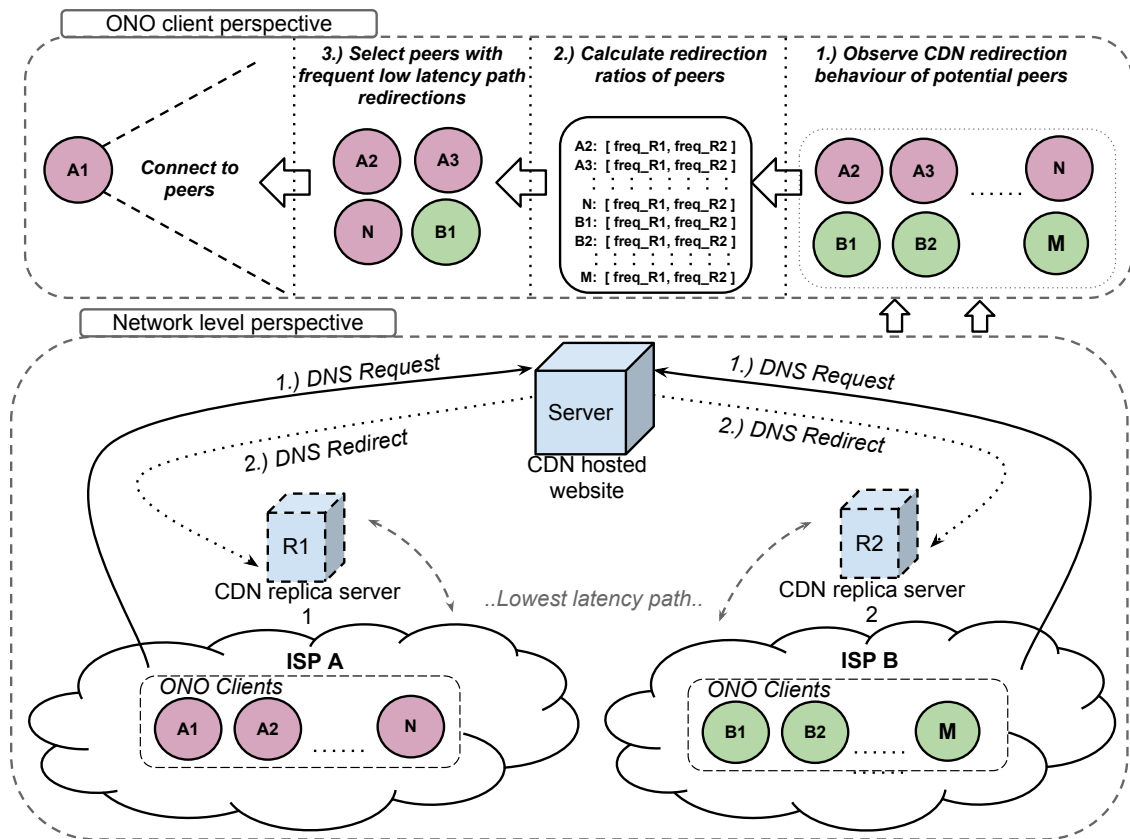


Figure 2.8: Simplified illustration of ONO peer matching

As illustrated in Figure 2.8, ONO clients observe their DNS redirection behavior in relation to different CDN names. By performing DNS lookups and record the frequency of redirections to different replica servers, ONO clients can exchange their records and then select peers that observe similar redirection behavior.

**Test-bed results.** Furthermore, ONO have been implemented as a plug-in for the Vuze BitTorrent client [1], enjoying a user base of over 120,000 peers in roughly 3,000 networks. Moreover, experimental results in [7] show that over 20 % of ONO-recommended peers are only one Autonomous System (AS) Hop away from the ONO clients in comparison to 2 % with native BitTorrent peer selection. In addition, the experiments show that over 33 % of the network paths found by ONO do not leave

the AS of origin in comparison to 10 % with native BitTorrent. Given the latter results, it can be argued that ONO results in 23 % less inter-ISP traffic than native BitTorrent, because the traffic stays inside the AS. In addition, [7] reports an average download rate improvement of 32 %, when compared to native BitTorrent. Although the results of ONO experiments seem promising for both ISPs and users, the measurements are based on a test-bed environment that does not necessarily reflect real world conditions. Please note that there is a discussion in the academic community regarding the validity of test-bed based evaluations in [8].

### 2.5.4 Provider-aided approaches

Although client-side approaches, such as ONO, show promising results in regards to reducing inter-ISP traffic and improving P2P performance, their success on improving traffic costs for ISPs ultimately depend on the user population installing the plugin. The provider-aided approaches are much more focused on the network provider domain, where design depends on both the physical infrastructure of ISPs as well as their unique knowledge of network information. In this section we explore four typical designs of provider-aided mechanisms, with a special focus on Provider Portal for Applications (P4P).

#### Transparent Network Tracker (TnT)

Transparent Network Tracker (TnT), presented in [16], takes the approach of creating a ISP controlled tracker that overrides the BitTorrent tracker and returns peers that represent ISP-friendly network paths. Specifically TnT approach suggests that ISP routers are extended with Network Processors (NPs) that are dedicated hardware designed to detect tracker queries from P2P clients. Furthermore, as illustrated in Figure 2.9, the tracker queries are redirected to a ISP hosted tracker that returns biased peers to the P2P clients. Although there is only a proof of concept

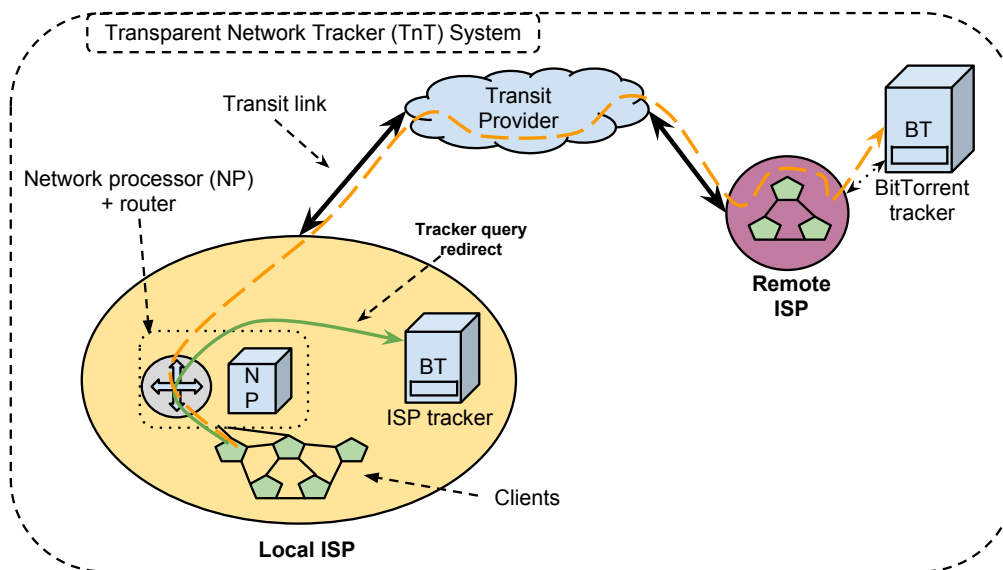


Figure 2.9: Illustration of a Transparent Network Tracker (TnT) System

implementation of TnT available [30], simulations have shown a reduction of inter-ISP traffic from 6 GB with native BitTorrent to roughly 1 GB with TnT enabled. Despite the encouraging simulation results, TnT have a couple of drawbacks. First, recent developments in P2P encryption and obfuscation can potentially make the task of P2P traffic monitoring difficult or unfeasible. Secondly, the requirement of specialized hardware might lead to significant costs for ISPs. Finally, there could be serious legal liabilities involved for ISPs, when hosting trackers of copyrighted material.

### **Provider Portal for Applications (P4P)**

P4P, described in [38], represents a more comprehensive approach to solve the traffic control problem. In contrast to the ISP centric TnT approach, P4P defines a framework that enables ISPs and application providers to cooperate on traffic control. The main principle with P4P, as argued in [30], is that ISPs provide a portal where information such as network topology, policies and cost aspects can be communicated to application providers, making it possible to make optimal peer selections. Specifically, the P4P architecture introduces the concept of an network provider operated portal, called the iTracker, that implements interfaces that enable applications to obtain information such as:

1. Policies regarding link usage, desired usage patterns and congestion thresholds.
2. P4P-distances. A metric that incorporates location based distance and cost aspects between peers.
3. Capabilities, such as on-demand servers or caches that the ISP might provide.

In addition, the P4P architecture introduces the concept of an application specific tracker, called the appTracker, that enables P2P applications and ISPs to share the responsibility of making optimal traffic control decisions. Moreover, in P4P a client registers with its appTracker, that queries the client ISP's iTracker about information, such as distance and cost parameters, of potential peers in order to finally provide the client with an optimal list of peers. We have provided a simplified illustration of this process in Figure 2.10.

Furthermore, global P4P field tests, done in collaboration with Pando Networks [36], have according to [38] shown average inter-ISP traffic reductions of 34 % in addition to an average improvement in transfer completion time of as much as 23%, when compared to native BitTorrent.

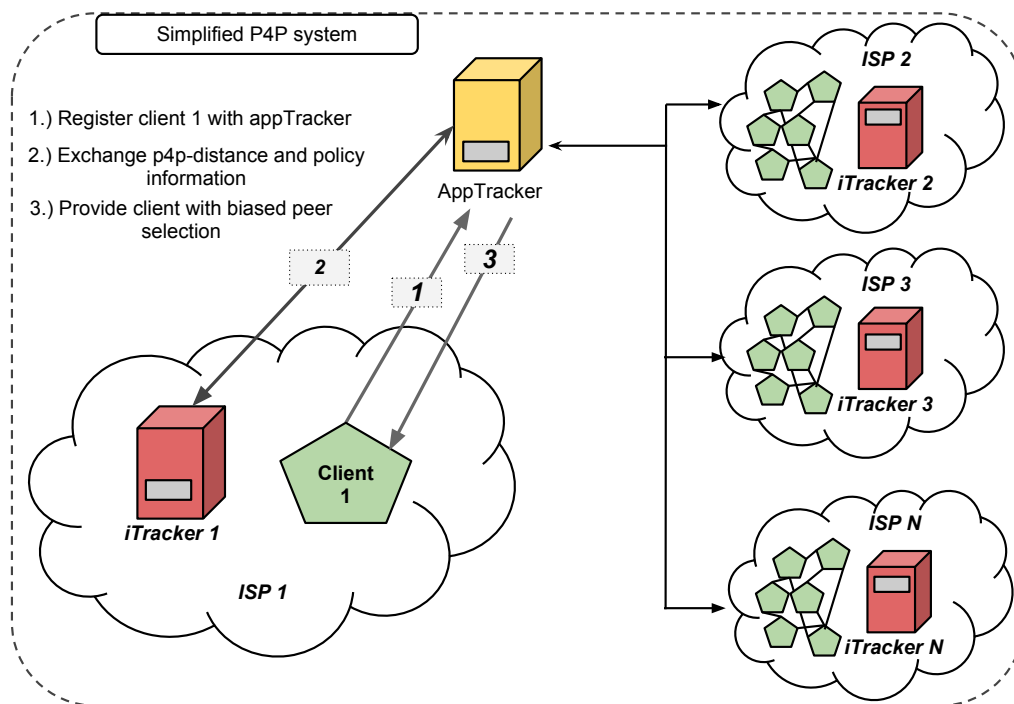


Figure 2.10: Simplified illustration of a P4P system



# Chapter 3

## Game theoretic framework

Having explored the implications and relevance of location-aware P2P mechanisms in Chapter 2, we found that providing both reductions of costly inter-ISP traffic and increased control with network oblivious P2P traffic is of high importance for ISPs. In this chapter we develop a game-theoretic framework in order to capture and model the economic interactions between one ISP and its users when they are presented with a decision of adapting location-aware P2P mechanisms. We start off by providing some basic notions of GT followed by a brief section on the scope of our model before we finally describe the game-theoretic model throughout the remaining sections.

### 3.1 Basic notions of game theory

GT, as described in [20], is a mathematical framework that concerns the study and analysis of situations where decisions, made by a set of two or more players, are mutually influenced by each other. GT is a well suited platform for capturing and analyzing what strategies that among rational utility-maximizing players, provide economic incentives. The branch of GT that concern this kind of decision related battles between individual players is called noncooperative game theory and it will form the basis for our game-theoretic approach. In this section a brief introduction to basic game-theoretical concepts is provided. As the introduction is limited, we ask the reader to consult [20, 29] for more comprehensive material.

#### 3.1.1 Basic elements

Here we briefly describe the basic elements used in noncooperative game theory, before we define different game representations and solution concepts in the next sections. The most basic elements that describe a game is:

1. **Players**, are the individual rational and utility-maximizing decision makers that make decisions that in a game mutually influence the utility (and thus the satisfaction) of other players.

2. **Action set**, represent the possible actions for each player.
3. **Strategies**, is a list of actions a player will choose for each decision available to the player.
4. **Outcome**, represent a state of the game where all players have chosen its pure strategies and is thus a combination of those strategies.
5. **Payoff**, represent the utility a player receives from an outcome.

### 3.1.2 Normal-form game

The Normal-form game representation is convenient when describing a decision situation where all players can be assumed to act simultaneously. Furthermore, simultaneous decisions imply that there is no causality among the players decisions. In the case of two player normal-form games, it is normal to represent the game in a matrix, where cells represent an outcome of the game, rows represent a possible action for player 1 and columns represent a possible action for player 2.

**Definition 3.1.1** (*Normal-form game*). Formally, a normal-form game with a finite set of players can be defined as the tuple  $(N, A, \pi)$ , where:

1.  $N$  is a finite set of  $n$  players, where each unique player  $i \in N = \{1, 2, \dots, n\}$ .
2.  $A$  is the cartesian product of each finite set  $A_i$  of available actions for player  $i$ , such that  $A = A_1 \times \dots \times A_n$
3.  $a = (a_1, a_2, \dots, a_n) \in A$ , is a combination actions taken by each player of the game and defines an outcome of the game.
4. A payoff function  $\pi_i$ , for each player  $i$ , that assigns a real number  $\pi_i(a)$  for each outcome  $a$  of the game.

### 3.1.3 Extensive-form game

In some situations the timing of decisions among players is important, as for example in the game of chess where one player always starts the game. For these situations, the extensive-form game representation is more convenient. In a extensive-form game, the choices of each players is represented by corresponding decision nodes in a directed tree. The root node of the tree graph represent the decision node of the player that initiates the decision making and edges that connect the root node with lower level decision nodes represent possible actions the first player can take. The timing of decision making is thus represented by the levels of the tree. In this thesis, we focus on the special case of finite perfect-information games in extensive form, where perfect information means that any player have available the same information to determine all possible outcomes at the start of the game as in the end of the game.

**Definition 3.1.2** (**Perfect-information game in extensive-form**). Formally we can define an perfect-information extensive-form game as composed of:

1. A game tree  $G$  containing a set of nonterminal decision nodes  $H$  (including the root node), a set of terminal nodes  $Z$  and a set of edges  $E$  that links each decision node to a successor node.
2. A set  $N$  of  $n$  players, where players are indexed by  $i$ ,  $i \in N$ ,  $N = \{1, 2, \dots, n\}$ .
3. A function  $\kappa$  that maps a unique and distinct subset of decision nodes from the game tree to each player  $i \in N$ .
4. A set of actions  $A$ .
5. A function  $\sigma$  that maps an action  $a \in A$  to each edge  $e \in E$ .
6. A function  $\chi$  that maps an origin node  $o$  and a destination node  $d$  to each edge  $e \in E$ , where  $o \in H$  and  $d \in Z$ .
7. A payoff function  $\pi_i$  for each player  $i \in N$  that assigns a real-valued utility for player  $i$  in on the terminal nodes  $Z$ .

#### Stackelberg game

A Stackelberg game, also known as a leader-follower game, is a class of games that concerns with situations where one player, the leader, initiates the decision making and where the second player, the follower, responds to the actions taken by the leader. Furthermore a stackelberg game can be modeled as a perfect-information game in extensive-form with two players ( $n = 2$ ).

#### 3.1.4 Solution concepts

In this section we provide a brief introduction to the most relevant solution concepts in GT.

##### Nash equilibrium (NE)

The possibly most important solution concept in GT for economic applications is the Nash equilibrium. Given a strategy profile  $\hat{s} = (\hat{s}_1, \hat{s}_2, \dots, \hat{s}_n)$  of the game, where  $\hat{s}_i$  is strategy of player  $i$ ,  $\hat{s}$  is a Nash Equilibrium (NE) if no player find it beneficial to deviate from its strategy, provided that all other players do not deviate. Thus NE forms a stable strategy profile, because no players will change their strategies if all players know what strategies all other players are following.

**Definition 3.1.3** (*Nash equilibrium*). A Nash equilibrium is a strategy profile where the strategies of all players are the best response to the strategy of all other players. We define  $s_{-i} = (s_1, \dots, s_{i-1}, s_{i+1}, \dots, s_n)$  as a strategy profile that do not contain the strategy of player  $i$ , where  $-i$  represents all players except from player  $i$ . A strategy profile for all players could then be represented as  $s = (s_i, s_{-i})$ . A strategy profile  $s = (s_1, \dots, s_n)$  is a NE if

$$\pi_i(s_i, s_{-i}) \geq \pi_i(s_i^*, s_{-i}) \tag{3.1}$$

for all players  $i$  and for all strategies  $s_i^* \neq s_i$

### Sub-game Perfect Equilibrium (SPE)

For extensive-form games, there are another solution concept called Subgame-Perfect Equilibrium (SPE) that is based on the game tree of extensive-form games.

**Definition 3.1.4** (*Subgame*). Given a finite extensive form game tree, each decision node (including the root node) and its descendants represent a subgame of the original game. Thus, one possible subgame is the game it self.

**Definition 3.1.5** (*Subgame Perfect Equilibrium (SPE)*). Given a extensive-form game, a strategy profile  $s = (s_1, \dots, s_n)$  is a SPE if it represents a NE in each subgame of the extensive-form game.

**Backward induction.** In order to identify a SPE in an extensive-form game we use the concept of backward induction. As explained in [20], backward induction is an algorithm based on analyzing each subgame, starting with the lowest level subgames and moving up one level until the whole game tree is analyzed for NEs.

## 3.2 Model scope

In this section we clarify the scope and the limitations the model that is developed throughout Chapter 3. The model aims at modeling ISP-User interactions within the following restrictions:

1. **Single ISP focus.** We design the model in order to capture the scope of one single ISP and its internet subscribing customers.
2. **Homogenous users.** In order to keep complexity within reasonable limits, we only consider a homogenous internet subscribing user base.
3. **Abstraction of the ISP connection model.** Although ISPs can have multiple transit and peering relationships, and thus multiple different pricing scenarios, we abstract these into a single transit and/or paid peering relationship.
4. **Limited LOCAM selection.** As described in Chapter 2, there are a large number of LOCAMs that could help decrease costly inter-ISP traffic as well as increase P2P performance. However, we identified one client-side and one provider-based approach that stands out in literature by having quantified results from both simulations and test-bed evaluations. The latter approaches are ONO and P4P, described in Section 2.5.4 and 2.5.3, and we will focus on these when designing the model.

To summarize, we intend to design a model that can capture the economical interactions between one single ISP and its finite set of homogenous internet subscribers, when they are presented with a choice of adopting a limited set of LOCAMs, namely P4P and ONO. In addition we have simplified the connection model of the single ISP, as illustrated in Figure 3.1, to have one internet transit- and one paid peering relationship.

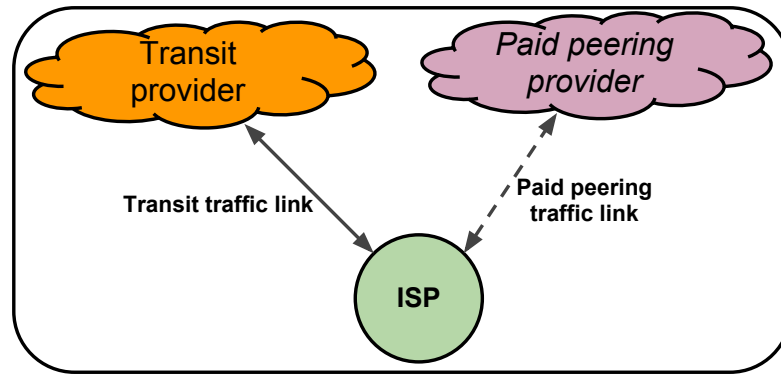


Figure 3.1: Illustration the single ISP connection model abstraction.

### 3.3 A ISP-User game

In this section we present a basic framework that enable modeling of the economic interactions between one ISP and its users as they are presented with a choice to adopt selected location-aware P2P mechanisms or not. As discussed in Section 3.2, we found it necessary to limit ourselves to a subset of the LOCAMs presented in Chapter 2, when defining the set of strategies. (This was decided in order to keep complexity within reasonable limits.) Please note however, that we do develop the payoff functions to enable studies of the broader range of LOCAMs. We start off with providing an overview of how our model is designed, followed by definitions of the strategy space for the ISP and its users.

**A leader-follower approach.** As discussed in Chapter 2, several ISPs have already attempted to implement solutions for shaping and controlling P2P traffic in order to reduce related costs. Moreover, we find it reasonable to assume that ISPs are natural initiators when deciding whether to implement Provider-aided P2P mechanisms, promote Client-based approaches to users or simply do nothing. In such a setting, the ISPs users can be modeled as followers, in the sense that they respond when actions are taken by their ISP. Given the latter sequence, the users can evaluate the choice of their ISP and make their own utility maximizing decision according to their preferences. Similar game-theoretic modeling of ISP-User interactions can be reviewed in [4, 33]

Given our description of the Stackelberg game in Section 3.1.3, we find that the interactions described above arguably is a well fit for a leader-follower approach. Moreover, ISPs can be modeled as leaders who decide whether to implement LOCAMs or not, according to their expected payoffs and preferences. Users can be modeled as followers that evaluate the decision of the ISP and responds according to their available actions and payoffs. An overview of the described ISP-User interaction is illustrated in Figure 3.2. In the next sections we define the basic game-theoretic elements that constitute such a leader-follower game , where ISPs are leaders, making

decisions regarding pricing and technology and users acts as followers that evaluate and respond according to their preferences.

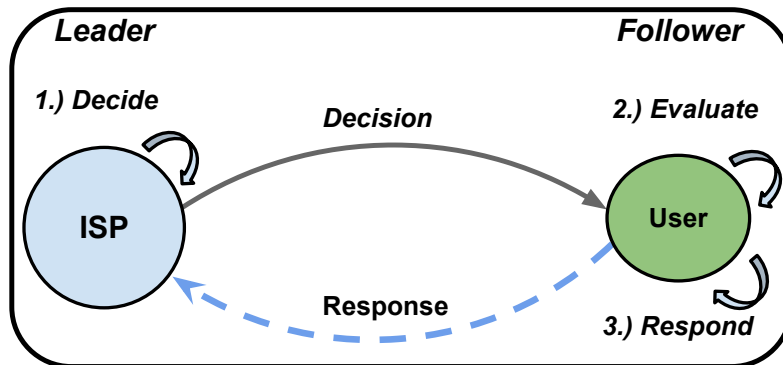


Figure 3.2: Illustration of a Leader-Follower (Stackelberg) game

Furthermore, as mentioned in 3.2, our scope of study is the economical interactions between one single ISP and its finite set of users. Before we start defining the strategy space of ISPs and its users, please note that all assumptions that are done throughout this chapter will be mentioned and then summarized in Section 3.6.

### 3.3.1 Defining ISP strategies

As described in our objectives in 3.2, it was decided to limit the possible choices of location-aware P2P mechanisms in order to reduce complexity. As described in section 2.5, these mechanisms can be categorized into provider-aided- and client-side approaches. Because both categories represent important and fundamentally different approaches to improving P2P locality, we found it reasonable to assume that the ISP strategy space should include representatives of both categories. In this section we describe the relevant assumptions and provide definitions for the ISP strategy space that will be used in our model.

**ISP-User recommendation.** We observed from our studies of provider-aided approaches in Section 2.5.4 that adoption of LOCAMs are mainly controlled by ISPs. The client-side approaches however depend on User interactions, such as installing plug-ins in their BitTorrent software, and is thus somewhat out of the ISP control. On the other hand, ISPs might be able to recommend these solutions, such as ONO, to its users. Based on the latter, we assume that there exists some communication between the ISP and users that enable ISPs to recommend client-side mechanisms.

**ISP technology choices.** From our discussion above, we assume that ISPs might attempt solve its P2P traffic control problem by either implementing provider-aided approaches or recommend the client-side approaches to its users. In addition, we find it reasonable to assume that some ISPs also might prefer to not do anything about P2P traffic and thus stay in their current state. The latter situation could occur if the costs of implementing LOCAMs outweighs the benefits.

Given the latter discussion and the limitations described in Section 3.2, we assume that ISPs can decide to either stay their current state and do nothing, implement the provider-aided approach P4P or recommend the client-side approach ONO. We furthermore assume the latter to be the technology choices available to ISPs in our model. We denote the technology choices as:

- **NO** : The ISP does nothing.
- **P4P** : The ISP implements P4P.
- **ONO** : The ISP recommends ONO to its users.

**Sharing of profit.** Additional to making technology choices, we introduce the assumption that ISPs might share some of its expected increased profits with its users, when making a technology choice that is expected to provide reductions in inter-ISP traffic costs. The reasoning behind this assumption, is that profit sharing arguably is one of the few and significantly powerful tools an ISP could utilize in order to incentivize its users to accept. Furthermore, we assume that such profit sharing is manifested through reductions in the users internet access subscription fee  $P$ . We assume that the ISP use the subscription fee reduction as a tool in order to incentivize its users to accept its decision, and that no reduction is provided in the case of users making disapproving choices.

Given our assumptions, ISPs both make decisions regarding what technology choice to adapt as well as what reduced subscription fee  $P$  they will offer for that technology choice. Moreover, the choice of doing nothing do not improve ISP cost aspects in relation to P2P generated inter-ISP traffic, and we thus find it reasonable that the subscription fee stays the same as where initially before initiating the decision process. As the decisions regarding subscription fee reductions directly depend on the expected cost reductions of P4P or ONO, we argue that the strategy space of ISPs can be described as technology choices in combination with a subscription fee  $P$  that corresponds to the technology choice. Given the assumptions, we define the ISP strategy space as tuples including technology choice and corresponding subscription fee.

**Definition 3.3.1** (*ISP strategies*). Formally, we define the pure strategy space  $S_{isp}$  of ISPs to include a combination of technology choice  $s \in \{NO, ONO, P4P\}$  and a corresponding subscription fee  $P^{(s)}$ . Furthermore we denote the strategies as:

- $s_1 = (\text{no}, P^{(s_1)})$ : The ISP decides to do nothing and thus keeps charging the initial subscription fee.  $P^{(s_1)}$ .
- $s_2 = (\text{ono}, P^{(s_2)})$ : ISP recommends ONO and offers a subscription fee  $P^{(s_2)} \leq P^{(s_1)}$ .
- $s_3 = (\text{p4p}, P^{(s_3)})$ : ISP implements P4P and offers a subscription fee  $P^{(s_3)} \leq P^{(s_1)}$ .

Where the ISP strategy space  $S_{isp} = \{s_1, s_2, s_3\}$ .

Please note that the strategies defined in definition 3.3.1, actually represent a larger strategy space due to the freedom of assigning values to the subscription prices  $P^{(s)}$ . We assume however, that there exists a finite limit for what values that can be assigned to the subscription fees  $P^{(s)}$ . This is also a natural assumption, because ISPs are utility-maximizing players that might only provide a reduction in subscription fees in order to convince users to adopt their technology choice. Finally, the representation of strategies in definition 3.3.1 makes it more convenient to represent ISP choices in a extensive-form game tree.

### 3.3.2 User strategies

Having defined the strategy space of ISPs, we will in this section analyze what actions that is possible for a user given that the ISP have decided on a strategy  $s \in S_{isp}$

**Acceptance.** From our discussion about ISP strategies, one obvious user action is to accept the strategy of the ISP, and thus adopt the corresponding technology choice. If the ISP strategy  $s \in \{s_2, s_3\}$  the user also enjoys a reduced subscription fee  $P^{(s)}$ . We therefore assume that one possible pure strategy for a user is to accept the ISP strategy  $s$ , and that it will be played if it is utility-maximizing for user.

**Rejection.** Another possible action to the user can be to reject ISP strategies that corresponds to adopting P4P or ONO. We base this assumption on the existence of consumer preferences, and that furthermore users might prefer to stay in the initial state where no LOCAMs is used. For P4P, the rejection could involve that users as an example utilize Virtual Private Network (VPN) connections and proxy servers to bypass the functionality of P4P. Furthermore, ONO requires the user to perform the work of installing the plug-in software on its computers. We find it reasonable to assume that users might reject the ISP recommendation to do this work. To summarize, we assume that user might reject the ISP strategy  $s$  if  $s \in \{s_2, s_3\}$ .

**Deviation.** Furthermore, we know from our studies of ONO in Section 2.5.3 that it have shown significant increases in P2P performance. If the ISP decides to do nothing, we assume that users might prefer to install ONO just to receive the expected P2P performance increase. That is we assume that users have some degree of preference for increased performance. In addition, we found from the study in Section 2.5.4, that P4P provides ISPs with more possibilities to control P2P applications. We assume that some users might prefer to install ONO instead of adopting P4P, due to this increased ISP control. Thus, to summarize we assume that users can decide to decline a ISP strategy  $s$  and install ONO by their self, if  $s \in \{s_1, s_3\}$  We furthermore provide a broader discussion regarding user preferences when defining the user payoff functions in Section 3.5.

Given the preceding analysis of the possible user actions given different ISP strategies we can formally define the user actions.

**Definition 3.3.2** (*User actions*). Given a ISP strategy decision  $s$ , we define the possible actions a user can make as:



- $\hat{s}_a$ : Accept ISP strategy  $s \in S_{isp}$ .
- $\hat{s}_d$ : Decline ISP strategy  $s$  when  $s \in \{s_2, s_3\}$  (If  $s$  implies ONO or P4P).
- $\hat{s}_o$ : Decline ISP strategy  $s$  and install ONO when  $s \in \{s_1, s_3\}$  (If  $s$  implies doing nothing or implementing P4P).

**Definition 3.3.3** (*User strategies.*). Using the user actions in definition 3.3.2, we can define the user strategies as the combination of actions  $\hat{s}$  taken by the user for each of its choices given by the ISP strategies  $s$ . A user strategy can then be defined as a 3-tuple  $(x, y, z)$  where the actions  $x, y, z$  corresponds to the ISP strategies  $s_1, s_2, s_3$ .

### 3.3.3 Extensive-form representation

From our definitions of ISP strategies and user actions, we can represent our ISP-User game as the extensive-form game illustrated in Figure 3.3. In the illustration the ISP initiates the decision process from the root choice node resulting in three user level choice nodes that correspond to the three ISP strategies  $s_1, s_2$  and  $s_3$ . Furthermore, the possible user actions result in 7 terminating nodes, but it is important to mention that only 4 of these lead to different unique payoffs. The reason for this is that we assume that declining  $\hat{s}_d$  any strategy  $s \in \{s_2, s_3\}$  results the same payoff as if one accepted  $\hat{s}_a$  to do nothing ( $s = s_1$ ). Additionally, we assume that there is a unique resulting payoff when a user choses to install ONO by itself.

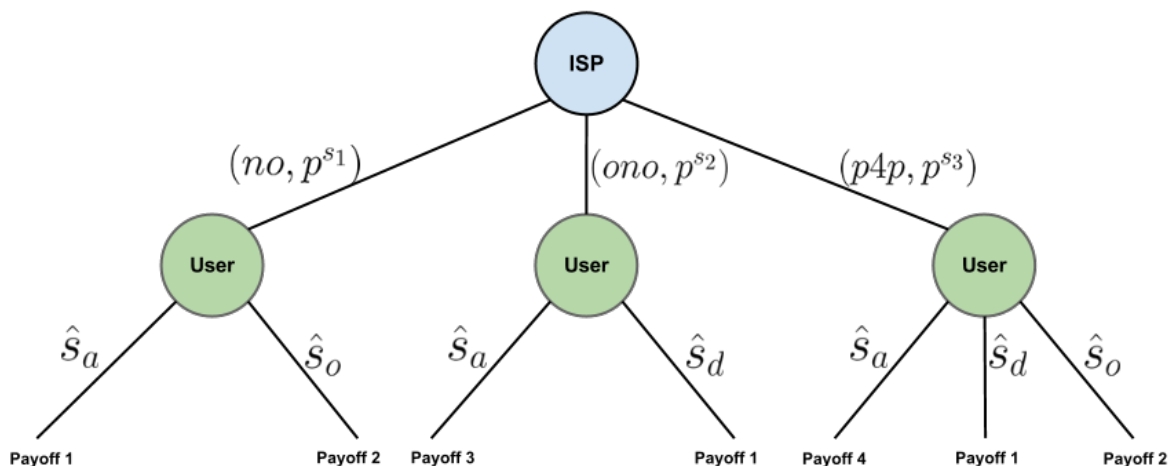


Figure 3.3: ISP-User game - Extensive-form representation

Having defined the general structure of the ISP-User game, we now turn to defining the actual payoff functions for both the ISP and its users in the next sections.

## 3.4 ISP payoff

In this section we describe reasoning behind, and define, the payoff function for ISPs in our model. We start of by explaining a simplified business model that

underpins how ISPs derive payoff.

### 3.4.1 Simplified business model

For the model, we assume a profit-maximizing ISP that gains higher utility proportionally with increasing profits. Furthermore, it was found reasonable to use a revenue and cost model that reduces complexity and bring focus to the aspects relevant for our study of location-aware P2P mechanisms. In this section we describe a simplified business model that reduces complexity of determining ISP payoffs, by mainly regarding:

1. User generated revenue
2. Traffic costs resulting from inter-ISP traffic
3. Strategy dependent costs
4. ISP preferences

An illustration of this simplified business model is illustrated in figure 3.4, and we will describe the different elements in the next sections.

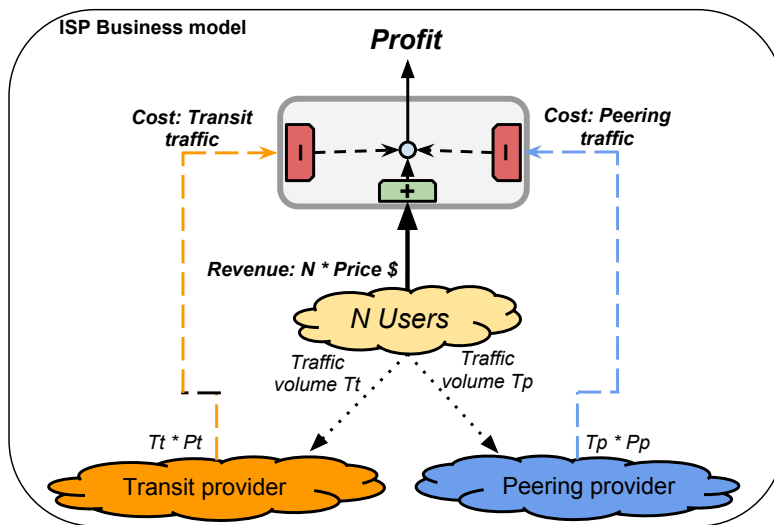


Figure 3.4: Illustration the ISP business model

### 3.4.2 Revenue model

For the revenue model, we assume that the ISP collects revenue solely by charging an initial flat rate subscription fee  $P^{(s_1)}$  to its  $N$  homogenous users who are purchasing internet access with equal and fixed Quality of Service (QoS) parameters. Please note that we acknowledge that real ISPs often are price discriminatory towards its customers and thus operates with different price levels for different QoS parameters. In order to keep complexity at manageable levels, we found it reasonable only to only focus on customers that buy the same internet access product.

Furthermore, we ignore other potential revenue streams as this is assumed to be less important in the context of our study. Given the above simplifications, the ISPs collect a total revenue (when deciding on a strategy  $s$ ) of  $R = N \cdot P^{(s)}$ .

### 3.4.3 Cost model

From our study in Section 2.5, the main metric that identifies the effectiveness of LOCAMs is how much reductions of inter-ISP traffic it provides. Additionally, we have found that inter-ISP traffic traverse links that are part of both internet transit- and internet peering relationships. Given the latter notion, we argue that for our objective the most important ISP aspects is also related to the inter-ISP traffic costs.

#### Inter-ISP traffic costs

The most relevant ISP cost driver, in the context of our objectives, have been identified as the inter-ISP traffic costs including transit traffic and paid peering costs. In this section we define costs functions that will represent these cost aspects in our model. We start by defining functions that describe the cost that is derived from internet transit traffic and thereafter define a cost function for paid peering traffic.

**Definition 3.4.1** (*Transit traffic cost*). We define the transit traffic cost  $\tau_t^{(s)}$  for a given ISPs strategy  $s$  to be denoted as the following:

$$\tau_t^{(s)} = \alpha^{(s)} \beta T^{(s_1)} p_t \quad (3.2)$$

where:

1.  $T^{(s_1)}$  represent the initial average Inter-ISP traffic volume in Mbps.
2.  $\alpha^{(s)}$  represent the expected reduction factor of Inter-ISP traffic for strategy  $s$  such that:
  - (a)  $\alpha^{(s)} \in [0, 1]$  for  $s \in \{s_2, s_3\}$
  - (b)  $\alpha^{(s_1)} \equiv 1$
  - (c)  $T^{(s)} = \alpha^{(s)} T^{(s_1)}$
3.  $\beta$  represent the ratio of initial Inter-ISP traffic volume  $T^{(s_1)}$  that traverses transit links such that:
  - (a)  $\beta \in [0, 1]$
4.  $p_t$  represent the price of transit traffic (\$/Mbps).

**Definition 3.4.2** (*Paid peering traffic cost*). We define the paid peering traffic cost  $\tau_p^{(s)}$  in a similar way as transit traffic, but with a few changes. First, paid peering costs are subject to a peering traffic price  $p_p$ . Furthermore, as  $\beta$  is the ratio of the initial Inter-ISP traffic  $T^{(s_1)}$  that traverses transit links,  $(1 - \beta)$  express the ratio that traverses paid peering links. This enables us to denote the paid peering traffic cost as:

$$\tau_p^{(s)} = \alpha^{(s)} (1 - \beta) T^{(s_1)} p_p \quad (3.3)$$

Given the definitions of transit and peering traffic costs in definitions 3.4.1 and 3.4.2, we can define the total inter-ISP traffic related costs.

**Definition 3.4.3** (*Total inter-ISP traffic cost*). We define the total cost related to inter-ISP traffic  $\tau^{(s)}$  for a given ISP strategy  $s$  to be the sum of transit traffic costs and paid peering traffic costs. It can thus be denoted as:

$$\tau^{(s)} = \tau_t^{(s)} + \tau_p^{(s)} \quad (3.4)$$

By substitution from equation (3.2) and (3.3) we get:

$$\tau^{(s)} = \alpha^{(s)}\beta T^{(s_1)} p_t + \alpha^{(s)}(1 - \beta)T^{(s_1)} p_p \quad (3.5)$$

### Investment cost

In addition to the traffic costs, we find it reasonable to assume that implementation of provider-aided LOCAM approaches such as P4P results in a investment cost for the ISP. More specifically, P4P require the ISP to set up their own iTracker. We assume that the one time investment cost of setting up, testing and operating an ISP iTracker should be included in the ISP payoff function as a monthly amortization cost. Moreover, we assume that this cost only occurs for the case of P4P in our model, as it also is the only strategy that might require implementation in the ISPs infrastructure.

**Definition 3.4.4** (*ISP investment cost*). We define the investment cost  $C_i^{(s)}$  to be a monthly amortization of a larger implementation related cost for the case when the ISP decides to implement P4P. We define:

$$\begin{aligned} C_i^{(s)} &\geq 0 && \text{for } s = s_3 \\ C_i^{(s)} &= 0 && \text{for } s \in \{s_1, s_2\} \end{aligned} \quad (3.6)$$

### 3.4.4 ISP preferences

In this section we explore what possible preferences an ISP might have when presented with a choice between doing nothing, recommending ONO or implementing P4P. In our presentation of P4P in Section 2.5.4, we found that P4P increases the general control an ISP can exercise with regards to optimizing traffic patterns, utilizing the most cost friendly links and reduce congestion by expressing policies via the iTracker interface. Because it is expected the ISPs have more control over its business with P4P than with client-side approaches like ONO, and because ISPs are profit-maximizing players, we assume that an ISP will have a preference for increased control. Furthermore, we assume higher satisfaction of this preference increase the ISP payoff in an additive way.

**Definition 3.4.5** (*ISP preference of control*). We define the ISP preference of control  $\lambda_c^{(s)}$  to be positive increase of utility that an ISP receives when he decides on a strategy  $s$  that involves increased levels of control over its business. For the ISP strategies defined in this thesis we assume that:

1.  $\lambda_c^{(s_3)} > 0$  (when ISP implements P4P)
2.  $\lambda_c^{(s)} = 0$  for  $s \in \{s_1, s_2\}$

### 3.4.5 ISP payoff function

Finally, as we have defined all the aspects of our simplified ISP business model with the addition of ISP preferences, we now define a general ISP payoff function that will be used to model ISP utility response when we analyze the games for incentives.

**Definition 3.4.6** (*ISP payoff*). We define the ISP payoff function  $\pi_{isp}$  as the sum of the positive revenue stream  $NP^{(s)}$ , the positive preferences of control, the negative inter-ISP traffic costs  $\tau^{(s)}$  and and the negative investment cost  $C_i^{(s)}$ . We can thus denote the ISP payoff for a strategy  $s$  as:

$$\pi_{isp}^{(s)} = NP^{(s)} - \tau^{(s)} - C_i^{(s)} + \lambda_c^{(s)} \quad (3.7)$$

which by substituting with equation (3.5) yields:

$$\pi_{isp}^{(s)} = NP^{(s)} - \alpha^{(s)}\beta T^{(s_1)}p_t - \alpha^{(s)}(1 - \beta)T^{(s_1)}p_p - C_i^{(s)} + \lambda_c^{(s)} \quad (3.8)$$

**User installs ONO without recommendation.** In addition to the payoffs that is induced by the strategy decision  $s$ , the ISP will receive a different payoff if its users decide to install ONO by themselves. In this case the ISP keeps charging the initial subscription fee  $P^{(s_1)}$  and gets the inter-ISP traffic reductions  $\alpha^{(s_2)}$  that is expected when adopting ONO. Thus, we define for this special case that:

$$\pi_{isp}^{(\hat{s}_o|s)} = NP^{(s_1)} - \tau^{(s_2)} \quad (3.9)$$

which given our definitions yields:

$$\pi_{isp}^{(\hat{s}_o|s)} = NP^{(s_1)} - \alpha^{(s_2)}\beta T^{(s_1)}p_t - \alpha^{(s_2)}(1 - \beta)T^{(s_1)}p_p \quad (3.10)$$

## 3.5 User payoff

In the preceding section we modeled the payoff of ISPs as the profit it derives from revenue minus costs. In this section we analyze how the utility of an individual user, that purchases internet access at a fixed subscription fee  $P^{(s)}$ , can be described and derived. Our main objective is to describe a users utility with metrics that involves consumption of P2P applications, so that we can represent how much the users utility changes when a LOCAM is adopted. We start by deriving a simplified utility model for the user and thereafter discuss various aspects of a users preferences before we finally derive an expression for a user payoff function.

### 3.5.1 Simplified utility model

First of all, we have assumed that all users pay a fixed flat rate subscription fee  $P$  for internet access with equal QoS parameters. Because users are rational, and all are subject to some budget restraints, there must be a set of features of internet access that is valuable to them. In this section, we define a simplified utility model for the user, as illustrated in Figure 3.5, that focuses on encompassing the user utility change derived from P2P performance.

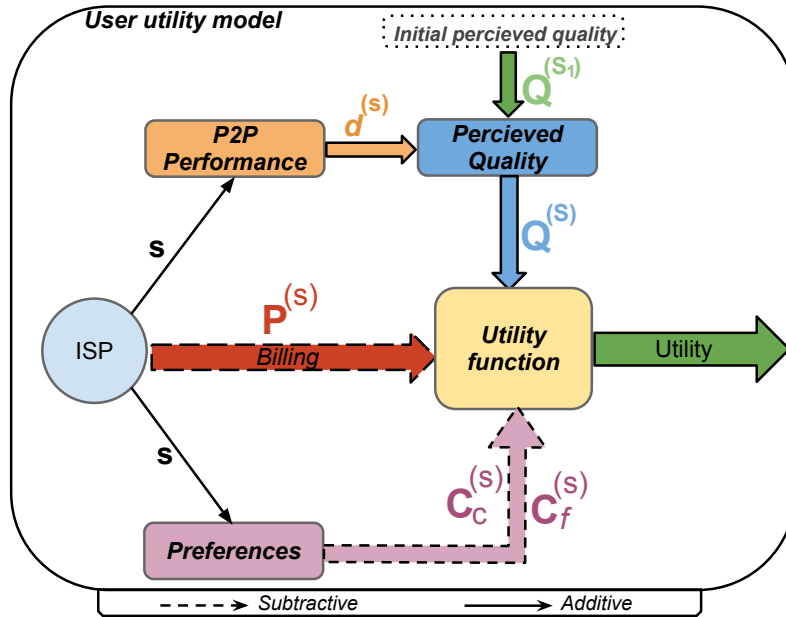


Figure 3.5: Illustration of the user utility model.

**Perceived quality.** First of all, we assume that one important parameter that describes the quality of an internet access product, as perceived by the consumer, is the perceived performance of internet applications. A study on the effects of pricing on internet usage behavior in [3] reveals that the majority of consumers thinks that the current internet network performance is insufficient, and that they prefer more performance. Such performance could include elements like:

1. Response time
2. Download speed
3. Quality of content distribution (streaming movies)

Moreover, the experimental results of ONO and P4P in [7, 38], mainly reveal improvements of P2P application download speed as the performance metric that can be observed by end-users. Consequentially, we make the assumption in this thesis that the user perceived quality of internet access increases proportionally with increases in P2P application performance. We do however acknowledge that this is a fairly big assumption, but due to the high uncertainty regarding user valuation of internet quality, it was found to be a reasonable assumption. [40] describes user perceived quality as the consumers judgement of a products overall excellence or superiority in relation to similar products. In relation to this, we define the user perceived quality  $Q^{(s)}$  of the internet access given a ISP strategy  $s$  to be a function of the experimental derived P2P performance improvement  $d^{(s)}$  that corresponds to  $s$ .

**Definition 3.5.1 (Perceived quality).** We define a users perceived quality  $Q^{(s)}$  of internet access, given an ISP strategy decision  $s$ , to be proportional with the corresponding experimentally derived improvements in P2P performance  $d^{(s)}$ . Moreover,

it is assumed that the users initially perceived quality  $Q^{(s_1)}$  is known. We formally denote  $Q^{(s)}$  as:

$$Q^{(s)} = Q^{(s_1)}(1 + d^{(s)}) \quad (3.11)$$

where  $d^{(s_1)} \equiv 0$  and  $d^{(s)} \in [0, 1]$  for  $s \in \{s_2, s_3\}$  and  $Q^{(s_1)}$  is a constant.

**Quality-price matching** Having defined the perceived quality as the main positive contributor to user utility, we found it necessary to provide a brief discussion on the users matching between quality and price. As described in [40], price can be interpreted as the sacrifice a user have to give up in order to obtain a product. As discussed in more detail in [6], the matching of quality to price is fairly subjective and difficult to estimate due to the variety of preferences among consumers. Consumers might even have intervals of indifference that describe regions of quality-price tradeoffs that they are indifferent to. For this thesis, it was found necessary to limit complexity by applying a proportional quality-price matching principle, where the consumer as described in [6] assigns a fixed value for each unit of quality in relation to a unit of price.

**Basic user utility.** Given our discussion regarding user perceived quality and quality-price matching, we have defined an expression in equation (3.11) that will be defined as the utility contributor of the user. Furthermore, we have assumed that there exists a proportional relationship between the evaluation of units of quality and units of price. Additionally, we assume that the utility contribution of perceived quality must be larger than the utility sacrifice of paying the subscription fee  $P^{(s)}$ . The latter makes intuitive sense, because a rational user would never buy a product if it receives negative or zero utility.

**Definition 3.5.2** (*Basic user utility function*). Given the assumption of proportional utility contribution from quality and price, we define the basic utility  $U^{(s)}$  a user receives from buying internet access, given an ISP strategy decision  $s$  as

$$U^{(s)} = Q^{(s)} - P^{(s)} \quad (3.12)$$

where  $Q^{(s)} > P^{(s)}$ .

### 3.5.2 Consumer preferences

From our definition of the basic user utility, we have incorporated the perceived performance of P2P applications from the user perspective, because of our assumption that perceived quality  $Q^{(s)}$  increases proportionally with increases in P2P performance. There are however aspects regarding the preferences of users that arguably should be reflected in our model. In this section we explore the preferential concepts of convenience and freedom in the context of how they might influence user utility in relation to adopting ONO or P4P.

**Convenience.** Current client-side location-aware P2P mechanisms, such as ONO, are often distributed as software plug-ins that users have to download and install. Furthermore, from the definition of our ISP-User game in Section 3.3, the ISP can

either recommend users to install ONO or users can decide to install it without recommendation when ISPs prefer another strategy. Arguably, both situations result in some decrease of the user convenience, as it needs to perform the work of downloading and installing ONO. In a study on the importance of consumer convenience in [17], it is argued that consumers can be subjected to a convenience cost in situations that require their interaction. More specifically, it is argued in [17] that this cost is incurred by elements such as expenditure of time, use of energy as well as money, in order to obtain possession of goods and services. Based on this notion we find it reasonable to assume that a user have to sacrifice a convenience cost  $C_c$  for outcomes that require the installation of ONO.

**Definition 3.5.3** (*Convenience cost*). We define the convenience cost  $C_c^{(\hat{s}_o)}$  to be a sacrifice of user utility, occurring when a user either accepts an ISP recommendation of ONO, denoted as  $(\hat{s}_a|s_2)$ , or decides to install ONO by itself, denoted as  $(\hat{s}_o|s^*)$ . In order to simplify notation we define that

$$C_c^{(\hat{s}_o|s^*)} = C_c^{(s_2)}$$

for  $s^* \in \{s_1, s_3\}$  and that

$$C_c^{(s_2)} > 0 \tag{3.13}$$

**Perceived control.** Having discussed the concept of convenience, we now will explore the concept of perceived control. In an article on the subject, found in [15], perceived control is discussed as the feeling of control of the environment and situations that consumers encounter. Also mentioned in [15], is that results from the field of environmental psychology indicate that people have a tendency to feel and behave more positively when they perceive increased control in their environment. Furthermore, as mentioned in [30], P4P have the potential to increase the control ISPs have over several P2P related traffic aspects. In addition P4P arguably enables the ISP to exert a higher level of control over user P2P habits, due to the policy possibilities in P4P. Given this discussion we find it reasonable to assume that there is some reduction in the user utility when it perceives somewhat reduced freedom in relation to its P2P application usage. As a consequence of the latter, we assume that there exists a freedom-reduction cost  $C_f$  that represents a user utility reduction that occurs if the user accepts to adopt P4P.

**Definition 3.5.4** (*Freedom-reduction cost*). We define the freedom-reduction cost  $C_f^{(s)}$  to be a reduction of user utility when a user accepts adoption of P4P, denoted as  $(\hat{s}_a|s_3)$ . We denote

$$C_f^{(s_3)} > 0 \tag{3.14}$$

and  $C_f^{(s)} = 0$  when  $s \in \{s_1, s_2\}$ .

### 3.5.3 User payoff function

As we have defined the different aspects of our simplified user utility model in addition to user preferences, we can assemble the user payoff function that will be used in this thesis. For the case of convenience cost and freedom-reduction cost, we assume that they have a subtractive effect on the user payoff.



**Remarks on notation.** We use the notation  $(\hat{s}|s)$ , where  $\hat{s} \in \{\hat{s}_a, \hat{s}_d, \hat{s}_o\}$  and  $s \in \{s_1, s_2, s_3\}$ , to represent that a user decides to take the action  $\hat{s}$ , given that the ISP decided on  $s$ . The available actions  $\hat{s}$  is naturally restricted by the lower level sub-trees in Figure 3.3.

**Definition 3.5.5** (*User payoff function*). *General information:* We define the user payoff function in three steps. First, we provide the general form payoff that represent a user accepting the ISP strategy  $s$ . Second, we define the user payoff of declining ISP strategy  $s$ . Finally, we define the special case payoff that occurs when a user installs ONO without ISP recommendation.

1. General form user payoff function (user accepts ISP strategy  $s$ ):

$$\pi_u^{(\hat{s}_a|s)} = U^{(s)} - C_c^{(s)} - C_f^{(s)} \quad (3.15)$$

that by substitution of the basic user utility in equation (3.12) transforms to the general user payoff function

$$\pi_u^{(\hat{s}_a|s)} = Q^{(s_1)}(1 + d^{(s)}) - P^{(s)} - C_c^{(s)} - C_f^{(s)} \quad (3.16)$$

2. User payoff when declining a strategy  $s$  is defined to equal to the payoff of accepting to do nothing:

$$\pi_u^{(\hat{s}_d|s)} = \pi_u^{(\hat{s}_a|s_1)} = Q^{(s_1)} - P^{(s_1)} \quad (3.17)$$

when  $s \in \{s_2, s_3\}$  and because  $C_c^{(s_1)} = 0$ ,  $C_f^{(s_1)} = 0$ ,  $d^{(s_1)} = 0$

3. User payoff when declining ISP strategy  $s$  and installing ONO by it self is defined as:

$$\pi_u^{(\hat{s}_o|s)} = Q^{(s_1)}(1 + d^{(s_2)}) - P^{(s_1)} - C_c^{(s_2)} \quad (3.18)$$

when  $s \in \{s_1, s_3\}$  because the user receives the performance improvement of ONO  $d^{(s_2)}$ , but still pays the initial subscription fee  $P^{(s_1)}$ .

<i>Symbol</i>	<i>Explanation</i>
$s$	ISP strategy
$\hat{s}$	User action
$\pi$	Payoff
$U$	Basic user utility
$p$	User subscription price
$T$	Inter-ISP traffic volume in Mbps
$\tau$	Inter-ISP traffic cost
$\tau_t$	Transit traffic cost
$\tau_p$	Peering traffic cost
$p_t$	Price of transit traffic (\$/Mbps)
$p_p$	Price of paid peering traffic (\$/Mbps)
$\lambda_c$	Increased control
$C_i$	Investment cost
$C_f$	Freedom-reduction cost
$C_c$	Convenience cost
$Q$	Download service quality
$d$	P2P performance increase
$\gamma$	ISP greediness parameter
$\theta$	ISPs price reduction offer

Table 3.1: Table of Notations.

### 3.6 Assumptions

This section serves the purpose of summarizing the assumptions that enable game-theoretic modeling of the ISP-User interactions using the model that have been defined throughout the chapter. The assumptions are:

1. **A Perfect information game**, meaning that all players (one ISP and its users) knows the exact payoff functions of other players at the same game level, and that every player observes the outcomes of lower layer games.
2. **A Single ISP system**, that consists of one ISP and a finite set of users. Note that systems containing multiple ISPs and user sets will be studied later.
3. **No churn**, meaning that there is no loss or gain of users.
4. **Homogenous users**. We assume that all users are homogenous in terms of preferences at the instant they respond to the ISPs decision. However, we will analyze how different preferences will change the response of the users in the evaluation of the model.
5. **Profit sharing**. We assume that ISPs are willing to share share expected profit increases that result from the inter-ISP traffic cost reductions introduced by LOCAMs.

6. **ISP-User communication.** We assume that there exists a communication between the ISP and its users that makes recommendation of ONO possible.
7. **Observability**, meaning that ISPs can observe and determine whether or not users are utilizing client-based P2P locality approaches such as ONO.
8. **Proportional performance-quality increase.** We assume that the user perceived quality of the internet subscription increases proportionally with P2P application performance.
9. **Proportional quality-price matching**, meaning that there is a proportional relationship between the utility based valuation of units of quality and price.
10. **Preference of convenience**, meaning that users are subject to some preference for convenience and that reduced convenience results in reduced user utility.
11. **Preference of control.** Meaning that both ISPs and users prefer control, and that increases in control of one player results in a decrease in control of the other player.

Although the above assumptions are numerous, our study of relevant literature have shown that there is scientific backing for at least the assumptions regarding preferences. The importance of these preferences are however very much uncertain, and will indeed need more study. We believe that despite the numerous assumptions, that the model can provide valuable insights into incentivizing strategies for the adoption of LOCAMs.



# Chapter 4

## Analytical Equilibrium Analysis

### 4.1 Objective

In this chapter, we perform an analytical study of the ISP-User game that was presented in Chapter 3, in order to identify conditions where ISPs and users have incentives to adopt either P4P or ONO. Our objectives in this chapter can be summarized as:

1. Identify analytical minimum and maximum restrictions for the subscription fee  $P^{(s)}$ .
2. Identify expressions for user-level subgame strategy indifference.
3. Identify expressions for ISP-level subgame strategy indifference.
4. Identify restrictions where the different strategies are incentivizing and thus yields the highest payoff.

The procedure that is used to achieve the above objectives can briefly be summarized as the following:

1. For each user-level subgame in Figure 3.3:
  - (a) Derive expressions for user indifference between its available actions.
  - (b) Use the resulting expressions of user indifference to infer restrictions that describe where each action yields the highest payoff.
2. For the ISP level subgame in Figure 3.3:
  - (a) Derive expressions for ISP indifference between  $s_1, s_2$  and  $s_3$ .
  - (b) Use the resulting expressions for strategy indifference to infer restrictions that describe where each strategy yields the highest payoff.

We start by performing an ISP price indifference analysis and thereafter use the procedure mentioned above to find expressions for user-level strategy indifference and ISP-level strategy indifference.

## 4.2 Price indifference analysis

As defined in Chapter 3, both users and ISPs are modeled as selfish players that maximize their utility (payoffs) defined in the payoff functions in equation (3.16) and 3.7. As a consequence, an incentivizing strategy for both users and ISPs is a strategy that yields higher payoff than the other available strategies. The ISP acting as a leader and initiator of the decision making, decides on a strategy  $s$  that includes both a choice of technology as well as a price offer  $P^{(s)}$ , which affect both the ISP and user payoff. In this section we identify analytically, restrictions for the subscription price  $P^{(s)}$ , where  $s \neq s_1$ , that incentivize both the ISP and its users.

In order to achieve this, we first identify expressions for what price  $P^{(s)}$  that makes a ISP and user indifferent between strategy  $s$  and  $s_1$  whereas naturally  $s \neq s_1$ .

### 4.2.1 ISP minimum price

From the user payoff function in equation (3.16), we observe that a user receives higher payoff as price decreases and will thus prefer lower prices. The ISP on the other hand will naturally have a minimum limit for the subscription price as it, in our model, represents the only source of revenue. Moreover, we say that the minimum price  $P_{min}^{(s)}$  that makes an ISP indifferent between strategy  $s \in \{s_2, s_3\}$  and strategy  $s_1$  can be found by identifying where the payoff of strategy  $s$  equals the payoff of strategy  $s_1$ . The latter is expressed formally as

$$\pi_{isp}^{(s)} = \pi_{isp}^{(s_1)} \quad (4.1)$$

where  $s \in \{s_2, s_3\}$ . Equation (4.1) can be written as

$$NP_{min}^{(s)} - \tau^{(s)} - C_i^{(s)} + \lambda_c^{(s)} = NP^{(s_1)} - \tau^{(s_1)} \quad (4.2)$$

when substituting payoffs with equation (3.7). By furthermore solving (4.2) for  $P_{min}^{(s)}$  we get:

$$P_{min}^{(s)} = P^{(s_1)} - \frac{1}{N} \left( \tau^{(s_1)} - \tau^{(s)} - C_i^{(s)} + \lambda_c^{(s)} \right) \quad (4.3)$$

Given the above equations we have found an expression for  $P^{(s)}$  that express the point at which the ISP is indifferent to strategy  $s$  over  $s_1$  and thus represent the lower boundary for where both the user and ISP might have incentives for strategy  $s$ .

**Remarks on minimum price.** By analyzing the expression in equation (4.3), we find that the ISP at maximum are willing to reduce its initial price  $P^{(s_1)}$  by the expression

$\frac{1}{N}(\tau^{(s_1)} - \tau^{(s)} - C_i^{(s)} + \lambda_c^{(s)})$ . Moreover, the latter expression can be interpreted as a combination of the reduction in ISPs total costs plus its utility increase due to preferences for increased control. Naturally from our study of P4P and ONO in Chapter 2, the traffic cost  $\tau^{(s)}$  of strategy  $s \in \{s_2, s_3\}$  is assumed to be less than the initial traffic cost  $\tau^{(s_1)}$ , as this is one of the main reasons for ISPs to adapt location-aware P2P mechanisms. Furthermore we can make the following observations:

- If  $\lambda_c^{(s)} \geq C_i^{(s)}$ , then the maximum price reduction will be greater than or equal the reduction in traffic costs. This means that the ISP evaluation of having increased control is greater or equal to the investment cost of choosing a strategy that increases control.
- If the investment cost for strategy  $s$  approach the expected reduction in traffic cost,  $C_i^{(s)} \rightarrow (\tau^{(s_1)} - \tau^{(s)})$ , the price price reduction approaches zero and consequentially  $P^{(s)} \rightarrow P^{(s_1)}$ .
- As  $\frac{1}{N}(\tau^{(s_1)} - \tau^{(s)} - C_i^{(s)} + \lambda_c^{(s)})$  represents the maximum price reduction (or offer) that an ISP might give, we can furthermore express how greedy an ISP is by introducing an parameter  $\gamma$  that tells us what percentage of the maximum price reduction above an ISP is willing to share.

**Definition 4.2.1** (*ISP Price reduction*). Given the observations above we define the ISPs price reduction  $\theta^{(s)}$  when choosing strategy  $s$  to be

$$\theta^{(s)} = \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s)} - C_i^{(s)} + \lambda_c^{(s)} \right) \quad (4.4)$$

where  $\gamma \in [0, 1]$  is a ratio that express how much of the ISPs expected utility increase it wants to share with its users. Moreover, we can say that  $\gamma$  represents the greediness the ISP.

### 4.2.2 User maximum price

As we have expressed a lower boundary for the price  $P^{(s)}$  on behalf of the ISP, we now turn to the users perspective. Although, we do assume that the ISP will offer a reduced subscription fee when deciding to use P4P or ONO, we will in this section examine the more general maximum limit for  $P^{(s)}$  from the users perspective. That is, we examine the case where users will be indifferent between any strategy  $s \neq s_1$ , when incorporating the expected P2P performance increase of strategy  $s$ .

In summary, to find the maximum limit of  $P^{(s)}$ , we derive an expression that describes where the user are indifferent between accepting a strategy  $s \in \{s_2, s_3\}$  and  $s_1$ . This can be expressed by:

$$\pi_u^{(\hat{s}_a|s)} = \pi_u^{(\hat{s}_a|s_1)} \quad (4.5)$$

where  $s \in \{s_2, s_3\}$ . Equation (4.5) can be written as

$$Q^{(s_1)}(1 + d^{(s)}) - P_{max}^{(s)} - C_f^{(s)} - C_c^{(s)} = Q^{(s_1)} - P^{(s_1)} \quad (4.6)$$

when substituting for equation (3.16). By furthermore solving (4.6) for the subscription fee  $P_{max}^{(s)}$  we get:

$$P_{max}^{(s)} = P^{(s_1)} + Q^{(s_1)}d^{(s)} - \left( C_f^{(s)} + C_c^{(s)} \right) \quad (4.7)$$

In equation (4.7), we have found that the maximum value of the subscription fee  $P^{(s)}$  depends on both the perceived performance increase  $Q^{(s_1)}d^{(s)}$  of accepting ISP strategy  $s \in \{s_2, s_3\}$  as well as the reduction in perceived freedom and convenience represented by the expression  $(C_f^{(s)} + C_c^{(s)})$ .

### 4.2.3 Minimum-maximum interval

To summarize our efforts, we found in Section 4.2.1 an expression for the lower boundary of the subscription fee  $P_{min}^{(s)}$  where ISP are indifferent and users have increased incentives for accepting a strategy  $s \neq s_1$ . Furthermore, in Section 4.7 we expressed the maximum boundary for  $P_{max}^{(s)}$  at which users are indifferent, while ISPs have increased incentives for a strategy  $s \neq s_1$ . By combining the expressions in equation (4.3) and 4.7, we define an interval that restricts the value space of  $P^{(s)}$  in order to incentivize both the ISP and its users to adopt/accept  $s$ .

**Definition 4.2.2** (*Minimum-maximum subscription fee interval*). We define the minimum-maximum interval of the subscription fee  $P^{(s)}$  as a value space of the subscription fee, where both ISPs and its users, are expected to have incentives to adopt strategy  $s$ .

$$P_{min}^{(s)} < P^{(s)} < P_{max}^{(s)} \quad (4.8)$$

By substitution of equation (4.3) and 4.7 we get:

$$P^{(s_1)} - \frac{1}{N} \cdot \left( \tau^{(s_1)} - \tau^{(s)} - C_i^{(s)} + \lambda_c^{(s)} \right) < P^{(s)} < P^{(s_1)} + Q^{(s_1)} d^{(s)} - \left( C_f^{(s)} + C_c^{(s)} \right) \quad (4.9)$$

## 4.3 User-level strategy indifference analysis

Having expressed the minimum and maximum boundaries for the subscription fee in Section 4.2, we now analyze the ISP-User game that was illustrated in its extensive-form in Figure 3.3, using the procedure mentioned in Section 4.1. In this section we analyze, for each of the user decision nodes in the ISP-User game in Figure 3.3, what conditions that make the user indifferent among its strategies and under what restrictions the user will either accept  $s$ , decline  $s$  or install ONO by itself.

### 4.3.1 ISP does nothing

Following the approach described above, we start by analyzing the first sub-game that follows when the ISP have decided to do nothing ( $s = s_1$ ), as illustrated in Figure 4.1. We start by expressing the the conditions that makes a user indifferent to its possible actions and thereafter identify restrictions describing the conditions for what action the user will take.

#### Strategy indifference

We see from the first sub-game, illustrated in Figure 4.1, that the possible actions for a user is either to accept the ISP decision about doing nothing ( $\hat{s}_a|s_1$ ) or to decline and install ONO by itself ( $\hat{s}_o|s_1$ ). Furthermore, we have assumed that the user get no monetary compensation when installing ONO by itself, but it receives the performance increase  $Q^{(s_1)} d^{(s_2)}$  that is expected when using ONO. Moreover, a user is indifferent between ( $\hat{s}_a|s_1$ ) and ( $\hat{s}_o|s_1$ ) when:

$$\pi_u^{(\hat{s}_a|s_1)} = \pi_u^{(\hat{s}_o|s_1)} \quad (4.10)$$



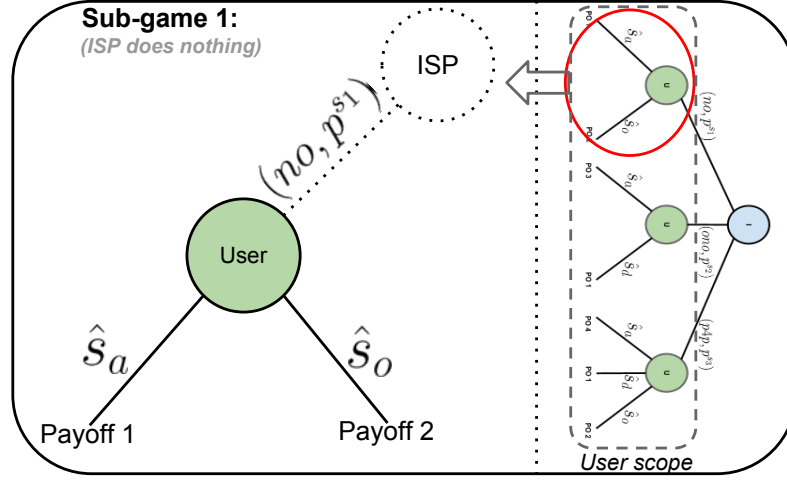


Figure 4.1: Sub-game 1: ISP do nothing. User accepts or installs ONO with no monetary compensation

By substituting the user payoff functions with equation (3.17) and (3.16), we get

$$Q^{(s_1)} - P^{(s_1)} = Q^{(s_1)}(1 + d^{(s_2)}) - P^{(s_1)} - C_c^{(s_2)} \quad (4.11)$$

which can be simplified to:

$$Q^{(s_1)}d^{(s_2)} = C_c^{(s_2)} \quad (4.12)$$

Thus, equation (4.12) represents the condition for user indifference between accepting the ISP strategy  $s_1$  ( $\hat{s}_a|s_1$ ) and installing ONO without price compensation ( $\hat{s}_o|s_1$ ).

### Strategy restrictions

Given the condition for indifference in equation (4.12) we can make the following inferences on the restrictions of a users decision:

1. A user will install ONO if  $Q^{(s_1)}d^{(s_2)} > C_c^{(s_2)}$ , meaning that the perceived performance improvement of installing ONO is greater than the perceived loss of convenience.
2. A user will accept  $s_1$  if  $Q^{(s_1)}d^{(s_2)} \leq C_c^{(s_2)}$ , meaning that perceived loss in convenience outweighs or makes the user indifferent to the performance improvement of ONO.

### 4.3.2 ISP recommends ONO

Next, we analyze the case when the ISP have decided to recommend ONO to its customers, with a new subscription fee offer  $P^{(s_2)}$ . We consider the second sub-game at the user-level as illustrated in Figure 4.2.

#### Strategy indifference

In the second sub-game we observe that the user have two possible actions, namely to either accept the ISPs recommendation and install ONO ( $\hat{s}_a|s_2$ ) or to

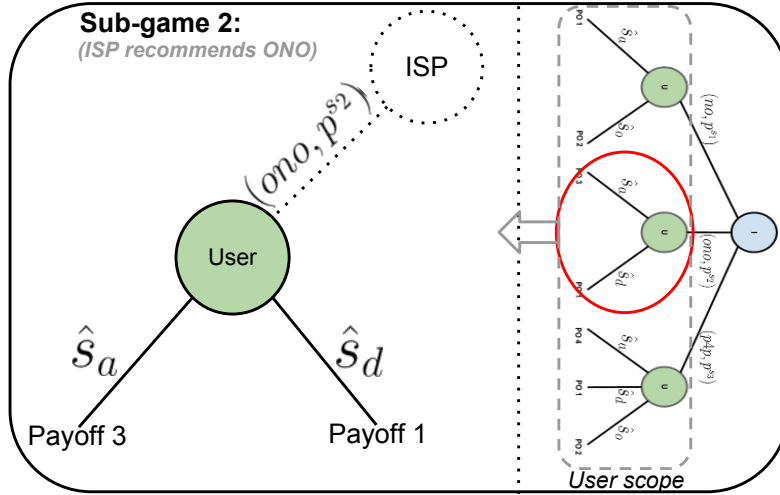


Figure 4.2: Sub-game 2: ISP recommends ONO. User accepts or declines.

decline ( $\hat{s}_d|s_2$ ) the ISP's recommendation and receive the same payoff as it would have in the first place, when doing nothing. As stated when defining the payoff functions in Chapter 3, the action to decline any ISP strategy  $s \in \{s_2, s_3\}$  results in the same payoff as accepting to do nothing and thus give the payoff  $\pi_u^{(\hat{s}_d|s_2)} = \pi_u^{(\hat{s}_a|s_1)}$ . Given the latter notion, we say that the user is indifferent between ( $\hat{s}_a|s_2$ ) and ( $\hat{s}_d|s_2$ ) when:

$$\pi_u^{(\hat{s}_a|s_2)} = \pi_u^{(\hat{s}_a|s_1)} \quad (4.13)$$

By substituting the terms in equation (4.13) with the definition of user payoff in equation (3.16) we get:

$$Q^{(s_1)}(1 + d^{(s_2)}) - P^{(s_2)} - C_c^{(s_2)} = Q^{(s_1)} - P^{(s_1)} \quad (4.14)$$

Furthermore, when assuming that the ISP will provide a lower subscription fee when recommending ONO such that  $P^{(s_2)} < P^{(s_1)}$ , we can use our findings on the ISP price reduction in definition 4.2.1 to represent  $P^{(s_2)}$  as

$$\begin{aligned} P^{(s_2)} &= P^{(s_1)} - \theta^{(s_2)} \\ &= P^{(s_1)} - \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_2)}) \end{aligned} \quad (4.15)$$

where  $\theta^{(s_2)}$  is substituted in from equation (4.4). Please note that both  $C_i^{(s_2)} = 0$  and  $\lambda_c^{(s_2)} = 0$ .

Finally, by substituting the last expression in (4.15) for  $P^{(s_2)}$  into (4.14), we find that the user is indifferent between accepting ONO ( $\hat{s}_a|s_2$ ) and doing nothing ( $\hat{s}_a|s_1$ ), when the following equation holds:

$$Q^{(s_1)}d^{(s_2)} + \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_2)}) = C_c^{(s_2)} \quad (4.16)$$

### Strategy restrictions

From equation (4.16), we identify the following restrictions that describe where the user have incentives to either accept or decline the ISP recommendation of ONO:

1. A user accepts ONO ( $\hat{s}_a|s_2$ ) if one of the following restrictions holds:
  - (a)  $Q^{(s_1)}d^{(s_2)} > C_c^{(s_2)}$ , meaning that the improvement in P2P performance is valued higher than the reduction in convenience.
  - (b)  $Q^{(s_1)}d^{(s_2)} \leq C_c^{(s_2)}$  and  $\frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_2)}) > (C_c^{(s_2)} - Q^{(s_1)}d^{(s_2)})$ , meaning that reduced convenience more valued than performance, but the price reduction incentivize the user to accept.
2. A user declines ONO ( $\hat{s}_d|s_2$ ) if:
  - (a)  $C_c^{(s_2)} > Q^{(s_1)}d^{(s_2)} + \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_2)})$ , where  $\gamma > 0$ , representing the case where the user values convenience higher than the sum of the increased performance and the price reduction (saved money).

### 4.3.3 ISP implements P4P

In the last user-level sub-game, illustrated in figure 4.3, we analyze the case where the ISP have decided to implement P4P and offer its users a reduced subscription fee  $P^{(s_3)}$ .

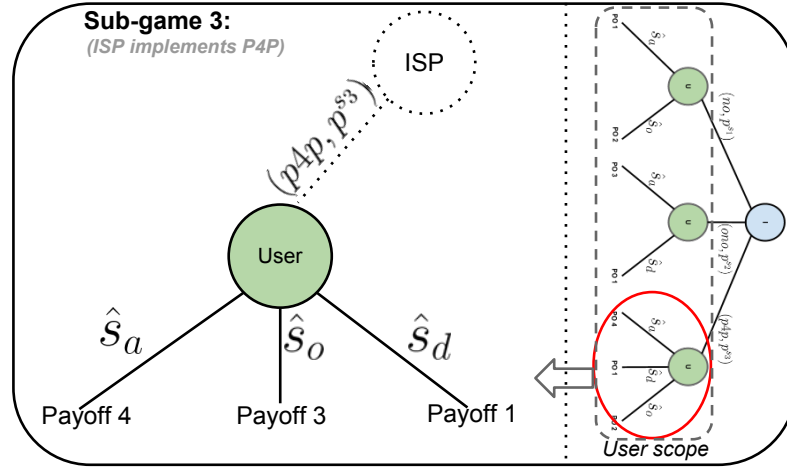


Figure 4.3: Sub-game 3: ISP implements P4P. User accepts, declines or installs ONO with no monetary compensation.

### 4.3.4 Strategy indifference

In the last user-level decision node the user are presented with the decision to accept P4P ( $\hat{s}_a|s_3$ ), install ONO by itself ( $\hat{s}_o|s_3$ ) or to decline and do nothing ( $\hat{s}_d|s_3$ ). As we already have found an expression for user indifference between installing ONO and doing nothing, we only need to analyze user indifference in the following cases:

1. Accepting adaptation of P4P ( $\hat{s}_a|s_3$ ) and declining P4P ( $\hat{s}_d|s_3$ ).
2. Accepting adaptation of P4P ( $\hat{s}_a|s_3$ ) and installing ONO without recommendation ( $\hat{s}_o|s_3$ ).

**P4P versus doing nothing.** We first analyze the case where the user is indifferent between accepting P4P ( $\hat{s}_a|s_3$ ) and declining ( $\hat{s}_d|s_3$ ). As before, to decline P4P leads to the same payoff as accepting to do nothing. Thus, the user is indifferent between the two when the following holds:

$$\pi_u^{(\hat{s}_a|s_3)} = \pi_u^{(\hat{s}_a|s_1)} \quad (4.17)$$

Furthermore, we have assumed that provider-aided locality approaches like P4P involves a reduction in the perceived freedom of the user. The latter assumption implies that the user is affected by a cost of reduced freedom  $C_f^{(s_3)} > 0$ . By substitution from our general user payoff function in (3.16) we write (4.17) as:

$$Q^{(s_1)}(1 + d^{(s_3)}) - P^{(s_3)} - C_f^{(s_3)} = Q^{(s_1)} - P^{(s_1)} \quad (4.18)$$

The new subscription price  $P^{(s_3)}$  in (4.18) can additionally be expressed using the ISP price offer in (4.4). Note that the we have assumed, as described in Section 3.4.4, that ISPs receive a non-zero utility boost from implementing P4P due to their preference for increased control. This utility boost is represented by  $\lambda_c^{(s_3)} > 0$ . Additionally, we have assumed that implementation of P4P requires some non-zero investment cost for the ISP such that  $C_i^{(s_3)} > 0$ . By substitution of  $P^{(s_3)}$  using (4.4), equation (4.18) yields:

$$Q^{(s_1)}(1 + d^{(s_3)}) - \left( P^{(s_1)} - \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) \right) - C_f^{(s_3)} = Q^{(s_1)} - P^{(s_1)} \quad (4.19)$$

Finally, equation (4.19) can be simplified to the following condition for user indifference between accepting P4P and doing nothing:

$$Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) = C_f^{(s_3)} \quad (4.20)$$

**P4P versus ONO.** Finally we analyze the case where the user is indifferent between accepting P4P ( $\hat{s}_a|s_3$ ) and installing ONO by itself ( $\hat{s}_o|s_3$ ), which is denoted as:

$$\pi_u^{(\hat{s}_a|s_3)} = \pi_u^{(\hat{s}_o|s_3)} \quad (4.21)$$

By simplifying the expression that is found when substituting  $\pi_u^{(\hat{s}_a|s_3)}$  from equation (4.19) and  $\pi_u^{(\hat{s}_o|s_3)}$  from equation (4.11), (4.21) yields the following condition for user indifference between ( $\hat{s}_a|s_3$ ) and ( $\hat{s}_o|s_3$ ):

$$Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) - C_f^{(s_3)} = Q^{(s_1)}d^{(s_2)} - C_c^{(s_2)} \quad (4.22)$$

### 4.3.5 Strategy restrictions

Having identified expressions for user strategy indifference in the last sub-game, we can identify restrictions that must hold in order for a user to either accept P4P, install ONO by itself or do nothing.

#### P4P versus doing nothing

When deciding between accepting P4P and doing nothing, we observe from equation (4.20) that the cost of reduced freedom  $C_f^{(s_3)}$  is the only factor that in this case can incentivize a user to decline P4P. We make the following observations:

1. A user declines  $s_3$  if it prefers freedom more than the combination of performance increase and price reduction, such that:

$$C_f^{(s_3)} \geq Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) \quad (4.23)$$

2. A user accepts  $s_3$  if the one of the following restrictions holds:

- (a) Performance is valued higher than reduced freedom such that:

$$Q^{(s_1)}d^{(s_3)} > C_f^{(s_3)} \quad (4.24)$$

- (b) Performance and freedom is valued equally and a positive price reduction is offered such that

$$Q^{(s_1)}d^{(s_3)} = C_f^{(s_3)} \quad (4.25)$$

and the ISP offers its users a cut  $\gamma > 0$  such that:

$$\frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) > 0 \quad (4.26)$$

- (c) The sum of performance increase and price reduction is valued higher than the reduced freedom of P4P

$$Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) > C_f^{(s_3)} \quad (4.27)$$

#### P4P versus ONO

In the last comparison, the user decides whether to accept P4P or install ONO by itself. In our expression for indifference in equation (4.22), we have we can observe that a user are subject to preference costs for both P4P and ONO. We furthermore make the following observations:

1. A user accepts P4P if

- (a)  $Q^{(s_1)}d^{(s_3)} - C_f^{(s_3)} > Q^{(s_1)}d^{(s_2)} - C_c^{(s_2)}$

- (b)  $Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) - C_f^{(s_3)} > Q^{(s_1)}d^{(s_2)} - C_c^{(s_2)}$

2. A user installs ONO without recommendation if

- (a)  $Q^{(s_1)}d^{(s_2)} > C_c^{(s_2)}$

- (b)  $Q^{(s_1)}d^{(s_2)} - C_c^{(s_2)} > Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) - C_f^{(s_3)}$

## 4.4 ISP-level strategy indifference analysis

In Section 4.3 we identified parametric restrictions for when users has incentives to either accept an ISP strategy  $s$ , decline or install ONO by itself. In this section we move up to the ISP-level of the game as illustrated in Figure 4.4. We analyze this sub-game in the same way as we did for the user-level, thus starting by identifying the conditions that make an ISP indifferent among its strategies. After identifying conditions for indifference we identify restrictions for where ISPs have incentives to either do nothing ( $s_1$ ), recommend ONO ( $s_2$ ) or implement P4P ( $s_3$ ).

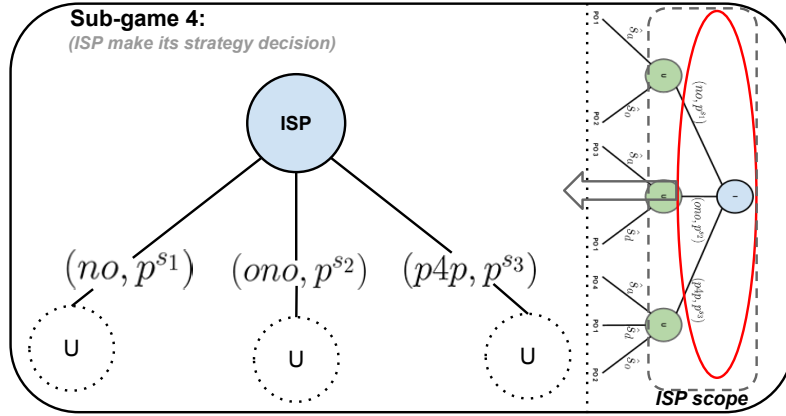


Figure 4.4: Sub-game 4: ISP decides whether to do nothing, implement P4P or recommend ONO.

### 4.4.1 ONO versus doing nothing

The ISP is indifferent between ONO ( $s_2$ ) and doing nothing ( $s_1$ ) when

$$\pi_{isp}^{(s_2)} = \pi_{isp}^{(s_1)}$$

which by using the ISP payoff function in equation (3.7) can be written as:

$$NP^{(s_2)} - \tau^{(s_2)} = NP^{(s_1)} - \tau^{(s_1)} \quad (4.28)$$

Using our expression for  $P^{(s_2)}$  in equation (4.15) can rewrite (4.28) as:

$$N(P^{(s_1)} - \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_2)})) - \tau^{(s_2)} = NP^{(s_1)} - \tau^{(s_1)} \quad (4.29)$$

By simplifying equation (4.29) we find that an ISP is indifferent between recommending ONO and doing nothing if the following holds:

$$\tau^{(s_1)} = \tau^{(s_2)} \quad (4.30)$$

#### Strategy restrictions.

Given the condition for indifference between recommending ONO ( $s_2$ ) and doing nothing ( $s_1$ ) in equation (4.30), we can infer that the ISP will:

1. Choose strategy  $s = s_2$  (recommend ONO) if  $\tau^{(s_2)} < \tau^{(s_1)}$
2. Choose strategy  $s = s_1$  (Do nothing) if  $\tau^{s_1} \leq \tau^{(s_2)}$

### 4.4.2 P4P versus doing nothing

Furthermore, an ISP is indifferent between implementing P4P and doing nothing when

$$\pi_{isp}^{(s_3)} = \pi_{isp}^{(s_1)}$$

that in turn can be written as

$$N(P^{(s_1)} - \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)})) - \tau^{s_3} - C_i^{(s_3)} + \lambda_c^{(s_3)} = NP^{(s_1)} - \tau^{(s_1)} \quad (4.31)$$

by substituting from equation (3.7) and using the following substitution for the subscription fee

$$\begin{aligned} P^{(s_3)} &= P^{(s_1)} - \theta^{(s_3)} \\ &= P^{(s_1)} - \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)}) \end{aligned} \quad (4.32)$$

By simplification of equation (4.31) we find that the ISP is indifferent among adopting P4P and doing nothing if the following holds:

$$\tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} = \tau^{(s_1)} \quad (4.33)$$

#### Strategy restrictions.

For the choice between implementing P4P and doing nothing, we have found that the ISP is indifferent when equation (4.33) holds. Using this result we can furthermore infer that the ISP will:

1. Choose strategy  $s_3$  (implement P4P) over  $s_1$  when  $\tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} < \tau^{(s_1)}$
2. Choose strategy  $s_1$  over  $s_3$  when  $\tau^{(s_1)} \leq \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)}$

### 4.4.3 P4P versus recommending ONO

Following the preceding approach, we say that the ISP is indifferent between implementing P4P and recommending ONO when

$$\pi_{isp}^{(s_3)} = \pi_{isp}^{(s_2)}$$

which yields

$$N(P^{(s_1)} - \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)})) - \tau^{s_3} - C_i^{(s_3)} + \lambda_c^{(s_3)} = N(P^{(s_1)} - \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_2)})) - \tau^{(s_2)} \quad (4.34)$$

when substituting payoffs from equation (3.7) and  $P^{(s_3)}$ ,  $P^{(s_2)}$  from (4.32) and (4.15) respectively. By simplifying equation (4.34), we find that the ISP is indifferent between implementing P4P and recommending ONO when the following condition holds:

$$\tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)} = \tau^{(s_2)} \quad (4.35)$$

#### 4.4.4 Strategy restrictions.

By using the strategy restrictions found in Section 4.4.1 and 4.4.2 as well as the condition for ISP indifference between implementing P4P and recommending ONO in (4.35), we can infer that the ISP will:

1. Choose to strategy  $s_3$  (implement P4P) if both

- (a)  $\tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)} < \tau^{(s_2)}$

- (b)  $\tau^{(s_2)} \leq \tau^{(s_1)}$

2. Choose strategy  $s_2$  (recommend ONO) if both

- (a)  $\tau^{s_2} < \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)}$

- (b)  $\tau^{s_2} < \tau^{(s_1)}$

3. Choose strategy  $s_1$  (Do nothing) if both

- (a)  $\tau^{(s_1)} < \tau^{s_2}$

- (b)  $\tau^{s_1} < \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)}$

## 4.5 Summary of Analytical Results

Through Section 4.3 and 4.4, we have analyzed each subgame in the ISP-User game illustrated in Figure 3.3 and identified both expressions for strategy indifference as well as restrictions that describe where the different strategies yields the highest payoff. In this section we summarize the analytical results that have been found throughout the chapter, starting with the user-level subgame results followed by the ISP subgame results.

### 4.5.1 User subgame results.

For the user-level subgames, we have found from the results of our indifference analysis in equations (4.12), (4.16), (4.20) and (4.22), that a user will:

1. Accept the ISP strategy  $s$  if

- (a)  $s = s_1$  and  $Q^{(s_1)}d^{(s_2)} \leq C_c^{(s_2)}$

- (b)  $s = s_2$  and  $Q^{(s_1)}d^{(s_2)} + \frac{\gamma}{N}(\tau^{(s_1)} - \tau^{(s_2)}) > C_c^{(s_2)}$

- (c)  $s = s_3$  and if the following holds:

- i.  $Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N}(\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)}) > C_f^{(s_3)}$

- ii.  $Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N}(\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)}) - C_f^{(s_3)} > Q^{(s_1)}d^{(s_2)} - C_c^{(s_2)}$

2. Install ONO without compensation if

- (a)  $s = s_1$  and  $Q^{(s_1)}d^{(s_2)} > C_c^{(s_2)}$



(b)  $s = s_3$  and if the following holds:

- i.  $Q^{(s_1)}d^{(s_2)} > C_c^{(s_2)}$
- ii.  $Q^{(s_1)}d^{(s_2)} - C_c^{(s_2)} > Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right) - C_f^{(s_3)}$

3. Decline the ISP strategy  $s$  if

(a)  $s = s_2$  and  $C_c^{(s_2)} > Q^{(s_1)}d^{(s_2)} + \frac{\gamma}{N}(\tau^{(s_1)} - \tau^{(s_2)})$

(b)  $s = s_3$  and if the following holds:

- i.  $C_f^{(s_3)} > Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right)$
- ii.  $C_c^{(s_2)} > Q^{(s_1)}d^{(s_2)}$

### 4.5.2 ISP subgame results.

Furthermore, given the indifference analysis results from the ISP-level subgame in equations (4.30), (4.33) and (4.35), we find that the ISP will:

1. Choose strategy  $s_1$  (Do nothing) if

- (a)  $\tau^{(s_1)} < \tau^{s_2}$
- (b)  $\tau^{s_1} < \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)}$

2. Choose strategy  $s_2$  (Recommend ONO) if

- (a)  $\tau^{s_2} < \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)}$
- (b)  $\tau^{s_2} < \tau^{(s_1)}$

3. Choose strategy  $s_3$  (Implement P4P) if

- (a)  $\tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)} < \tau^{(s_2)}$
- (b)  $\tau^{(s_2)} \leq \tau^{(s_1)}$

To summarize, our findings show that the decision taken by the users depend on the expected increase in performance  $Q^{(s_1)}d^{(s)}$  and the reduction in the subscription fee  $\theta^{(s)}$  that the ISP offers for a strategy  $s$ . In addition the decision of the users depend on its preferences for perceived control and convenience represented by  $C_f^{(s)}$  and  $C_c^{(s)}$ . Moreover, we have found that the ISPs strategy decision mainly depends on the total costs that is expected from a strategy  $s$ , in addition to the ISPs preference for control, represented by  $\lambda_c^{(s)}$ .

### 4.5.3 Subgame Perfect Equilibria

Given the equilibrium conditions that have been found in the user-level and ISP-level subgames, we can finally identify the the conditions that must hold in order to form SPEs. By using the equilibrium conditions identified in Section 4.5.1 and 4.5.2 we identify the following SPEs and their conditions:

1. A user accepts  $s_1$  ( $\hat{s}_a|s_1$ ) and the ISP choose  $s_1$  when the following conditions holds:

- (a)  $Q^{(s_1)}d^{(s_2)} \leq C_c^{(s_2)}$
- (b)  $\tau^{(s_1)} < \tau^{s_2}$
- (c)  $\tau^{s_1} < \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)}$

2. A user accepts  $s_2$  ( $\hat{s}_a|s_2$ ) and the ISP choses  $s_2$  when the following conditions holds:

- (a)  $Q^{(s_1)}d^{(s_2)} + \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_2)}) > C_c^{(s_2)}$
- (b)  $\tau^{s_2} < \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)}$
- (c)  $\tau^{s_2} < \tau^{(s_1)}$

3. A user accepts  $s_3$  ( $\hat{s}_a|s_3$ ) and the ISP chooses  $s_3$  when the following holds:

- (a)  $Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)}) > C_f^{(s_3)}$
- (b)  $Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)}) - C_f^{(s_3)} > Q^{(s_1)}d^{(s_2)} - C_c^{(s_2)}$
- (c)  $\tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)} < \tau^{(s_2)}$
- (d)  $\tau^{(s_2)} \leq \tau^{(s_1)}$

4. A user declines  $s_1$  and installs ONO without recommendation ( $\hat{s}_o|s_1$ ) and the ISP chooses 3 when the following conditions holds:

- (a)  $Q^{(s_1)}d^{(s_2)} > C_c^{(s_2)}$
- (b)  $\tau^{(s_1)} < \tau^{s_2}$
- (c)  $\tau^{s_1} < \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)}$

5. A user declines  $s_3$  and installs ONO without recommendation ( $\hat{s}_o|s_3$ ) and the ISP chooses  $s_3$  when the following conditions holds:

- (a)  $Q^{(s_1)}d^{(s_2)} > C_c^{(s_2)}$
- (b)  $Q^{(s_1)}d^{(s_2)} - C_c^{(s_2)} > Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)}) - C_f^{(s_3)}$
- (c)  $\tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)} < \tau^{(s_2)}$
- (d)  $\tau^{(s_2)} \leq \tau^{(s_1)}$

## 4.5. SUMMARY OF ANALYTICAL RESULTS

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6. A user declines  $s_2$  and do nothing ( $\hat{s}_d|s_2$ ) and the ISP chooses  $s_2$  when the following conditions holds:

$$(a) \quad C_c^{(s_2)} > Q^{(s_1)}d^{(s_2)} + \frac{\gamma}{N}(\tau^{(s_1)} - \tau^{(s_2)})$$

$$(b) \quad \tau^{s_2} < \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)}$$

$$(c) \quad \tau^{s_2} < \tau^{(s_1)}$$

7. A user decline  $s_3$  and do nothing ( $\hat{s}_d|s_3$ ) and the ISP chooses  $s_3$  when the following conditions holds:

$$(a) \quad C_f^{(s_3)} > Q^{(s_1)}d^{(s_3)} + \frac{\gamma}{N} \left( \tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)} + \lambda_c^{(s_3)} \right)$$

$$(b) \quad C_c^{(s_2)} > Q^{(s_1)}d^{(s_2)}$$

$$(c) \quad \tau^{(s_3)} + C_i^{(s_3)} - \lambda_c^{(s_3)} < \tau^{(s_2)}$$

$$(d) \quad \tau^{(s_2)} \leq \tau^{(s_1)}$$

In summary, we have identified identified 7 unique SPEs by using the equilibrium conditions that was summarized in Section 4.5.1 and 4.5.2.



# Chapter 5

## Numerical Equilibrium Analysis

### 5.1 Objective and limitations

In order to achieve our main objectives, as stated in Section 1.2, to provide insights into what strategies that incentivize adoption of LOCAMs, this chapter takes a numerical approach to further analyze our model described in Chapter 3. In this section, our goal is to numerically evaluate the game-theoretic model by assigning parameter values that is found in relevant literature and by estimation. To achieve this goal, we introduce the following set of simplifying limitations:

1. We assume a limited sized local ISP with  $N = 10000$  homogenous users, that pay an equal initial subscription fee  $P^{(s_1)}$  for their internet access.
2. We assume that all inter-ISP traffic is generated by P2P applications and that this traffic is distributed between one internet transit provider and one paid peering provider.
3. We assume that user utilize 100 % of their internet connection capacity

By assigning values to the model parameters, using both relevant literature and estimation, we intend to numerically identify conditions that incentivize both ISPs and its users to adopt ONO or P4P.

### 5.2 Initial parameter values

In this section we assign numerical values to the different parameters of our model. Some values can only be obtained through further studies, and are thus in this text provided as rough estimates done by the author.

#### 5.2.1 User internet access speed and subscription fee

In order to find reasonable values for the initial subscription fee  $P^{(s_1)}$ , have used the results of research done on broadband internet access costs by the European Commission in 2008 [11]. Furthermore, we have used prices that correspond to a internet access bit-rate capacity of 10 Mbps with data points from 14 different

countries. From these numbers found in Appendix A.1, we have identified minimum, maximum and average prices (in USD), which is summarized in Table 5.1.

Price: (USD)/month	Min	Max	Average
10 Mbps	17	81	44

Table 5.1: Price per month for internet access. Source: European Commission report on broadband internet access cost [11].

We found it reasonable to assume that the homogenous users in our model are subscribing to a internet access link with a bit-rate capacity  $l_c = 10$  Mbps at subscription fee that corresponds to the average value in Table 5.1, such that  $P^{(s_1)} = 44USD$ . Please note that we acknowledge that real world ISP customers arguably purchase a variety of quality/price combinations. The simplification above is done to reduce complexity and is inherent to our assumption of homogenous customers.

### 5.2.2 Traffic prices

As an initial value is set for the subscription fee, we now turn our focus onto assigning values for the pricing of transit and paid peering traffic.

**Transit price.** For the case of transit traffic, we presented a forecast of internet transit prices published by DrPeering International [25] in Figure 2.5. Furthermore, the forecast projects significant yearly price reductions, with a price of 5USD per Mbps in 2010 to as low as 0.63USD per Mbps in 2015. We found it reasonable to use the average price over the period from 2010 to 2015 in this thesis as a means to limit the effects of potential projection errors.

Thus, we assume a transit price of  $p_t = \frac{5.00+3.25+2.34+1.57+0.94+0.63}{6} \approx 2.29\$/Mbps$ .

**Paid peering price.** As mentioned in our background study on the ISP connection model in Section 2.3.2, two ISPs might decide to establish a peering relationship if there exists a significant traffic exchange between them. Furthermore, an ISP can push for a paid peering relationship if the traffic exchange is unbalanced, such that one ISP compensate the other ISP at some price. As mentioned in [24], the details regarding paid peering compensation schemes is very difficult to obtain, because it is regarded as business secrets. DrPeering International however quotes an anonymous source in [23], revealing that the US based ISP Comcast in 2009 charged between 2 and 3USD/Mbps for paid peering. Furthermore, we observe from Figure 2.5 that the transit price in 2009 was about 9USD/Mbps, thus indicating that paid peering cost was roughly between 70 and 80 % lower than the cost of internet transit. Assuming that the anonymous source is correct, and that paid peering cost is declining proportionally with internet transit cost, we could expect the price of paid peering to be in the range of 70 - 80 % lower than our estimate for transit costs  $p_t = 2.29USD$ . The latter assumptions would imply that the paid peering price  $p_p$  is located in the interval  $[(0.2 \cdot 2.29), (0.3 \cdot 2.29)]$ , such that  $p_p \in [0.458, 0.687]$ . In order to compensate for uncertainty, we find it reasonable to use the average value of the latter interval

## 5.2. INITIAL PARAMETER VALUES

as the paid peering price in our analysis, such that  $p_p = \frac{0.458+0.687}{2} \approx 0.57\text{USD}/\text{Mbps}$ .

We acknowledge that the price of paid peering might not necessarily decrease proportionally with internet transit prices, but because of the difficulty of obtaining real numbers it was found necessary to estimate the paid peering price according to the preceding reasoning. A summary of maximum, minimum and average values for inter-ISP traffic pricing is found in Table 5.2.

Parameter	Min	Max	Average
$p_t$ (\$/Mbps)	0.63	5.00	2.29
$p_p$ (\$/Mbps)	0.458	0.687	0.57

Table 5.2: Inter-ISP traffic pricing values.

### 5.2.3 P2P related parameters

In this section we discuss the experimental results of ONO and P4P on both the inter-ISP traffic dimension as well as on P2P application performance, in order to assign reasonable values to:

1. The inter-ISP traffic reduction  $\alpha^{(s)}$
2. The P2P performance improvement  $d^{(s)}$
3. The initial P2P generated inter-ISP traffic  $T^{(s_1)}$

for ONO and P4P, i.e.  $s \in \{s_2, s_3\}$ .

**P2P generated inter-ISP traffic.** In our study of internet traffic in Section 2.2, we found that a significant portion of inter-ISP traffic is generated by P2P applications. Although many global studies indicate that the growth of P2P is slowing down compared to other internet traffic components, such as internet video, we found that the traffic volume of P2P is still expected to grow significantly over the next years. In order to achieve representable P2P related cost values in our analysis, we use the results from the internet studies discussed in Section 2.2 to estimate a P2P generated inter-ISP traffic percentage that could be typical for an ISP. As mentioned in [37], a study by Sandvine Research on North American ISPs have shown that P2P on average is responsible for 53.3% of all upstream traffic. Moreover, studies by Ipoque in [27], reveals that P2P file sharing generates between 43% to 70% of all traffic monitored at 8 ISPs and 3 university networks. In addition, Cisco estimates in [31] that P2P file sharing generates roughly 40% of all global consumer internet traffic in 2010. Because of the differences in the latter results, we found it reasonable to use an average value of these data points to represent the percentage of P2P generated inter-ISP traffic in our model. Consequentially, we assume that the percentage of P2P generated inter-ISP traffic  $\delta$  can be estimated by the average of values found in [27, 31, 37], such that  $\delta = \frac{53.3+43+70+40}{4} \approx 51.6$ .

As we have made the simplification that user internet capacity utilization corresponds to 100% in this evaluation, we can estimate the initial total P2P generated inter-ISP traffic volume  $T^{(s_1)}$  as a function of the amount of internet subscribers  $N$ , the fixed internet access capacity  $l_c$  of each subscriber and the percentage of P2P generated inter-ISP traffic such that  $T^{(s_1)} = N \cdot l_c \cdot \delta$ . Additionally, as described in Section 5.1, we have limited this evaluation to ISPs with  $N = 10000$  users and we thus estimate the initial P2P generated inter-ISP traffic volume to be  $T^{(s_1)} = 10000 \cdot 10 \text{ Mbps} \cdot 0.516 = 51600 \text{ Mbps}$ . Please note from our estimate that  $T^{(s_1)}$  increase proportionally with the amount of  $N$  users.

**Reduction of inter-ISP traffic.** Having established an estimate for  $T^{(s_1)}$ , we now assign values for the expected reduction of inter-ISP traffic when the ISP implements either ONO or P4P. As mentioned in Section 2.5 the test-bed results of ONO and P4P, described in [7, 38], have shown quantifiable reductions in inter-ISP traffic. Specifically, ONO has roughly shown an average reduction of 23% of inter-ISP traffic when compared to native BitTorrent, and P4P have roughly shown average inter-ISP traffic reductions of 34 %. For this thesis we will use these test-bed results to assign values of the inter-ISP traffic reduction  $\alpha^{(s)}$ . For ONO representing ISP strategy  $s = s_2$ , we set  $\alpha^{(s_2)} = 1 - 0.23 = 0.77$ . Similarly for P4P ( $s = s_3$ ), we set  $\alpha^{(s_3)} = 1 - 0.34 = 0.66$ . We acknowledge that test-bed results might not be completely representative for how ONO and P4P would perform in more complex and large scenarios, but obtaining larger test results would require efforts that was found to be out of our scope.

**P2P performance.** As mentioned in Section 2.5, the test-bed evaluations of ONO and P4P in [7, 38] quantify improvements in P2P performance relative to native BitTorrent. Specifically, ONO shows an average P2P performance improvement of approximately 32% whereas P4P have shown an average P2P performance improvement of roughly 23 %. Given these results, we set that for ONO ( $s = s_2$ )  $d^{(s_2)} = 0.32$  and for P4P ( $s = s_3$ ) we set  $d^{(s_3)} = 0.23$ .

Through the preceding paragraphs we have assigned values to the P2P related parameters of our model, based on results in relevant literature and our limitations. We summarize the parameter values for the different technology strategies in Table 5.3.

$s$	$\alpha^{(s)}$	$d^{(s)}$	$T^{(s)}$
$s_1$	1	0	56600 Mbps
$s_2$	0.77	0.32	N/A
$s_3$	0.66	0.23	N/A

Table 5.3: Summary of P2P related parameter values.



### 5.2.4 Baseline relative utility

Because of the difficulty of estimating the level of utility a user receives from buying internet access, we found it necessary to make some simplifying assumptions regarding how utility might be distributed among ISPs and its users. Specifically, we assume that there exists some proportionality between the utility (profit) an ISP receives from one user and the utility one user receives from purchasing internet access from an ISP. Based on this assumption, we estimate a baseline value for the user utility as a portion of the baseline utility an ISP initially receives per user. Furthermore, we argue that a natural baseline scenario for our scope of study is the initial situation where ISPs and its  $N$  users have not adopted ONO or P4P. In the next couple of paragraphs we develop estimates for initial utility levels based on this baseline scenario.

**ISP baseline utility.** From our discussion on inter-ISP traffic costs in Section 5.2.2, we found that paid peering is significantly cheaper than internet transit traffic. Because ISPs can have significant variations in how P2P generated inter-ISP traffic  $T^{(s_1)}$  is distributed among internet transit and paid peering links, their cost aspects could also vary significantly. Given the inter-ISP traffic pricing summarized in Table 5.2 and the inter-ISP traffic cost function in equation (3.5), it can be observed that ISPs will receive a maximum profit when all inter-ISP traffic traverses paid peering links ( $\beta = 0$ ) and a minimum profit when all traffic traverses transit links ( $\beta = 1$ ). Furthermore, we found it reasonable to use the average utility calculated from the two latter scenarios as an estimate of the ISP baseline utility. We use the parameter values assigned through the preceding sections and the defined ISP payoff function in equation (3.7) to calculate the maximum and minimum ISP utility in the following manner:

1. For  $\beta = 1$ , the minimum ISP baseline utility can be written as:  

$$\min(\pi_{isp}^{(s_1)}) = N \cdot P^{(s_1)} - T^{(s_1)}p_t = 10000 \cdot 44 - 56600 \cdot 2.29 = 310386$$
2. For  $\beta = 0$ , the maximum ISP baseline utility can be written as:  

$$\max(\pi_{isp}^{(s_1)}) = N \cdot P^{(s_1)} - T^{(s_1)}p_p = 10000 \cdot 44 - 56600 \cdot 0.57 = 407738$$

Having found the maximum and minimum values above, we calculate the ISP baseline utility  $\pi_{isp}^{(s_1)}$  as the average value such that:

$$\pi_{isp}^{(s_1)} = \frac{\min(\pi_{isp}^{(s_1)}) + \max(\pi_{isp}^{(s_1)})}{2} = \frac{310386 + 407738}{2} = 359062.$$

Finally, we calculate the ISP utility per user as:  $\frac{\pi_{isp}^{(s_1)}}{N} = \frac{359062}{10000} \approx 36$ , meaning that in the initial scenario, within the framework of our assumptions and limitations, an ISP on average receives 36USD in profit per user on average.

**User baseline utility.** As we have found an baseline utility for the ISP, we now estimate the utility one user initially receives from purchasing internet access as a portion of the utility an ISP receives from one user. For this estimation we assume that there exists a 80/20 percentage relationship in the utility distribution between an ISP and its user such that an ISP receives roughly 20% more utility from the business relationship than the user. Due to this assumption we can estimate the user baseline utility  $\pi_u^{(s_1)}$  using the user payoff function in equation (3.17) and the ISP baseline utility in the following way:

$$Q^{(s_1)} - P^{(s_1)} = 0.8 \cdot \frac{\pi_{isp}^{(s_1)}}{N} = 0.8 \cdot 36 = 28.8$$

which by using the average value in Table 5.1 for  $P^{(s_1)}$  yields:

$$Q^{(s_1)} = 28.8 + P^{(s_1)} = 28.8 + 44 = 72.8$$

Thus, given our assumption of an 80/20 percentage utility distribution relationship between the ISP and one user, the initial perceived quality  $Q^{(s_1)}$  a user in our evaluation receives equals 72.8. We acknowledge that the above assumption might disagree with real world utility distributions, but because utility arguably is a very complex and difficult metric to estimate without specialized large scale studies, it was found necessary to introduce the above simplifications. The results of our findings on the baseline user utility estimations is summarized in Table 5.4.

Data	Estimated value
$\pi_u^{(s_1)}$	28.8
$Q^{(s_1)}$	72.8

Table 5.4: Results of baseline user utility estimation.

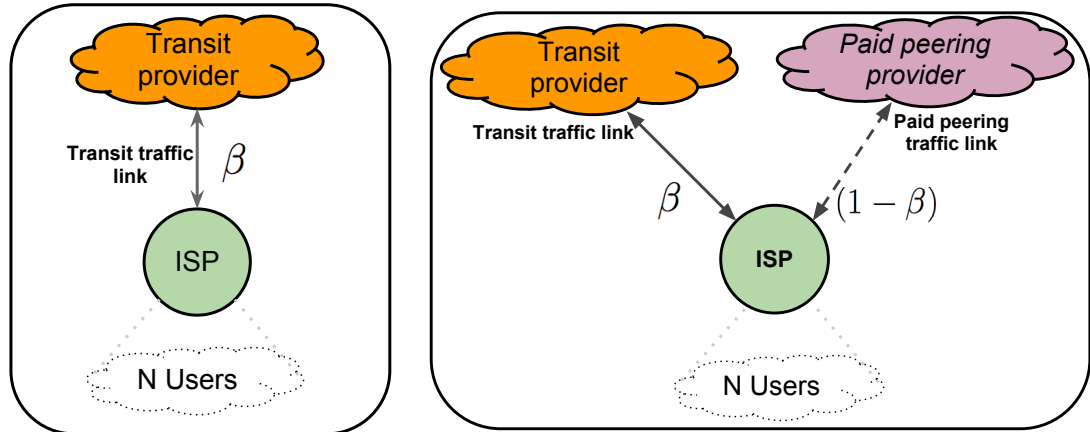
## 5.3 ISP payoff analysis

In this section we analyze the ISP decision level of the ISP-User game, as illustrated in Figure 4.4, in order to quantify the price reductions  $\theta^{(s)}$  that ISPs might offer its users and the resulting ISP payoffs that could be expected for different strategy decisions. For this analysis, we will furthermore define some different ISP traffic scenarios in order to provide a broader picture on how different traffic distributions might affect the payoff of the ISP.

### 5.3.1 ISP traffic scenarios

For the traffic scenarios we simplify the ISP connection model such that an ISP either is connected to the global internet entirely by subscribing to internet transit or by a combination of internet transit and paid peering as illustrated in figure 5.1. Please note that free peering links, which is very is a very common additional connection component, is not included in our evaluation as we have limited our study to

traffic volume charged connection relationships. In addition the reader should note that we have simplified the connection model to only include one internet transit provider and one paid peering provider.



(a) ISP connected by internet transit. (b) ISP connected by internet transit and paid peering.

Figure 5.1: Illustration of ISP traffic scenarios.

In the first connection model, all inter-ISP traffic is assumed to pass through the internet transit link, thus resulting in  $\beta = 1$ . In the second connection model, the inter-ISP traffic is distributed between internet transit and paid peering links. Because the actual traffic distribution between such links might vary among different ISPs, we found it reasonable to analyze them for three distribution cases. The cases describe distributions where traffic is:

1. Dominated by internet transit, estimated by assigning  $\beta = \frac{3}{4} = 0.75$ .
2. Dominated by paid peering, estimated by assigning  $\beta = \frac{1}{4} = 0.25$
3. Evenly distributed among internet transit and paid peering, estimated by assigning  $\beta = \frac{2}{4} = 0.5$

As mentioned in [32], peering relationships does not normally provide a transitive connection relationship, meaning that it does not necessarily provide a customer ISP with access to other ISPs who peer with the paid peering provider. As a result we have found it reasonable to ignore the case where all inter-ISP traffic traverses paid peering relationship links.

To summarize, we have assumed four inter-ISP traffic scenarios that in the rest of the section will be used to analyze their impact on the ISP payoffs under different ISP strategies.

### 5.3.2 ISP does nothing

When the ISP decides to do nothing, there are no P2P traffic improvements and thus no reductions in inter-ISP traffic. We calculate the ISP inter-ISP traffic costs and resulting payoffs for the scenario when a user accepts to do nothing ( $\hat{s}_a|s_1$ ), using the ISP payoff function in equation (3.8). The calculations is

done using the parameter values that have been assigned throughout this section:  $N = 10000$ ,  $P^{(s_1)} = 44$ ,  $\alpha^{(s_1)} = 1$ ,  $T^{(s_1)} = 56600$ ,  $p_t = 2.29$ ,  $p_p = 0.57$ . Please note that  $C_i^{(s_1)} = 0$  and  $\lambda_c^{(s_1)} = 0$ . The calculated traffic costs and ISP payoffs for strategy  $s_1$  is summarized for each traffic scenario in Table 5.5.

$\beta$	$\tau^{(s_1)}$	$\pi_{isp}^{(s_1)}$
1	129614	310386
0.75	105276	334724
0.5	80938	359062
0.25	56600	383400

Table 5.5: ISP inter-ISP traffic costs and payoff for strategy  $s_1$ , given traffic scenario 1-4.

### 5.3.3 ISP recommends ONO

For the case where the ISP decides to recommend ONO ( $s = s_2$ ), a reduction in inter-ISP traffic  $\alpha^{(s_2)} = 0.77$  (as observed from Table 5.3) is expected. Additionally, we have assumed that the ISP is willing to provide a reduced subscription price  $P^{(s_2)}$  to its users if they accept to install and use ONO.

**Maximum price reduction.** From our analytical analysis in Section 4.2.3, we know that the ISP can provide a maximum price reduction of  $\theta^{(s_2)} = \frac{\gamma}{N}(\tau^{(s_1)} - \tau^{(s_2)})$ . In addition, we assume that the ISP at minimum will provide no price reduction at all. As a consequence the subscription price  $P^{(s_2)}$  must be in the interval  $[P^{(s_1)} - \frac{1}{N}(\tau^{(s_1)} - \tau^{(s_2)}), P^{(s_1)}]$ .

Using the parametric values that have been assigned throughout this chapter, we can calculate the maximum price reduction  $\theta_{max}^{(s_2)}$  that a ISP might offer and the corresponding payoff for each traffic scenario. Table 5.6 summarize, for each traffic scenario, our calculations of minimum and maximum ISP payoff for a subscription fee  $P_{min}^{(s_2)} = P^{(s_1)} - \theta_{max}^{(s_2)}$  and  $P_{max}^{(s_2)} = P^{(s_1)}$ .

$\beta$	$\tau^{(s_2)}$	$\tau^{(s_1)} - \tau^{(s_2)}$	$\theta_{max}^{(s_2)}$	$P_{min}^{(s_2)}$	$min(\pi_{isp}^{(s_2)})$	$max(\pi_{isp}^{(s_2)})$
1	99803	29811	3.0	41.0	310386.2	340197.2
0.75	81063	24213	2.4	41.6	334724.5	358937.5
0.5	62322	18616	1.9	42.1	359061.7	377677.7
0.25	43582	13018	1.3	42.7	383400.0	396418.0

Table 5.6: Expected inter-ISP traffic costs, maximum price reductions and ISP payoffs for strategy  $s_2$  given traffic scenario 1-4.

Given the results presented, we have found that the ISP at maximum will offer a price reduction  $\theta_{max}^{(s_2)}$  in the range of 1.3 to 3.0 USD when adopting ONO, depending on the distribution of inter-ISP traffic among transit and paid peering links. As a

consequence, we also find that the minimum subscription fees  $P_{min}^{(s_2)}$  is in the range of 41.0 to 42.7 USD.

### 5.3.4 ISP implements P4P

The last possible option for the ISP is to implement P4P with an expected reduction in inter-ISP traffic  $\alpha^{(s_3)} = 0.66$ . Furthermore have we defined, as described in Section 3.4.4, that the ISP receives a utility increase  $\lambda_c^{(s_3)} > 0$  when adopting P4P as a consequence of its preferences for increased control. In addition we assume, based on the P4P paper in [38], that implementation of P4P introduce a investment cost  $C_i^{(s_3)} > 0$ .

It was found very difficult to identify real world values for  $C_i^{(s_3)}$  and  $\lambda_c^{(s_3)}$  without initiating extensive studies that would be unfeasible within the time limits of this thesis. As consequence, it was found necessary to make some simplifying assumptions regarding the values of these parameters and we will discuss them briefly in the next paragraphs.

**Investment cost.** We assume that the investment cost  $C_i^{(s_3)}$  could be expressed as a percentage of the revenue stream an ISP receives from its  $N$  users. Specifically, we model the investment cost as a percentage of the monthly subscription fee the ISP receives from its users. For the rest of our evaluation we say that the investment cost of implementing P4P corresponds to 3 percent of the initial subscription fee  $P^{(s_1)}$  per user such that:

$$C_i^{(s_3)} = N \cdot 0.03 \cdot P^{(s_1)} = 10000 \cdot 0.03 \cdot 44 \text{ USD} = 13200 \text{ USD}$$

**ISP preference for control.** As the reduction in inter-ISP traffic  $\alpha^{(s_3)} = 0.66$  already significantly favors P4P over ONO in the ISPs point of view, we assume the utility boost  $\lambda_c^{(s_3)}$  do not play a particularly big role in our evaluation. In order to reduce complexity in our numerical evaluation, we assume that  $\lambda_c^{(s_3)} = 0$ .

**Maximum price reduction.** Given our simplifications regarding the values of  $C_i^{(s_3)}$  and  $\lambda_c^{(s_3)}$ , we can calculate the maximum price reduction  $\theta_{max}^{(s_3)}$  by setting  $\gamma = 1$  in equation (4.4) such that:

$$\theta_{max}^{(s_3)} = \frac{\gamma}{N} (\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)})$$

We can now, following the same procedure as in Section 5.3.3, calculate maximum and minimum values for the expected ISP payoff, given that P4P is implemented and a minimum or maximum price reduction  $\theta^{(s_3)}$  is offered. Our results for each traffic scenario are summarized in Table 5.7.

From the results in Table 5.7, we observe that when implementing P4P, the ISP will ( at maximum ) offer a price reduction  $\theta_{max}^{s_3}$ , ranging from 3.1 to 0.6 USD. Intuitively, from the definition of  $\theta^{(s)}$  in equation (4.4), the investment cost  $C_i^{(s_3)}$  influence the size of the ISPs subscription fee reduction. Given this notion, lower investment cost values would yield higher values of  $\theta_{max}^{(s_3)}$ .

$\beta$	$\tau^{(s_3)}$	$\tau^{(s_1)} - \tau^{(s_3)} - C_i^{(s_3)}$	$\theta_{max}^{(s_3)}$	$P_{min}^{(s_3)}$	$P_{max}^{(s_3)}$	$min(\pi_{isp}^{(s_3)})$	$max(\pi_{isp}^{(s_3)})$
1	85545	30869	3.1	40.9	44.0	310386.0	341254.8
0.75	69482	22594	2.3	41.7	44.0	334724.0	357317.8
0.5	53419	14319	1.4	42.6	44.0	359062.0	373380.9
0.25	37356	6044	0.6	43.4	44.0	383400.0	389444.0

Table 5.7: ISP Costs, maximum price reductions, subscription fees and expected payoffs for strategy  $s_3$ , given traffic scenario 1-4.

### 5.3.5 User installs ONO without recommendation

For the scenario when users decides to decline install ONO by themselves, the ISP keeps charging the initial subscription fee  $P^{(s_1)}$ , but receives inter-ISP traffic reductions that is equivalent to the situation when the ISP recommends ONO to its users  $s = s_2$ . As a consequence the ISP in this scenario have expected inter-ISP traffic costs equivalent to  $\tau^{(s_2)}$  that is summarized in Table 5.6. By using the equation (3.10), summarize the ISP payoff for this scenario in Table 5.8.

$\beta$	$\tau^{(s_2)}$	$\pi_{isp}^{(\hat{s}_o s)}$
1	99803	340197
0.75	81063	358937
0.5	62322	377678
0.25	43582	396418

Table 5.8: ISP traffic costs and payoff when users install ONO without recommendation, for traffic scenario 1-4.

### 5.3.6 Summary of ISP payoff analysis

We have now found maximum values for the subscription fee reduction  $\theta_{max}^{(s)}$ , that the ISP might offer when either implementing P4P or recommending ONO. We have also analyzed the effect of different traffic scenarios on the subscription fee  $P^{(s)}$  and the resulting ISP payoff.

By comparing the payoffs in for ONO and P4P in Table 5.6, 5.7, it can be observed that as traffic is increasingly distributed against paid peering, the ISP receives the highest payoff by choosing ONO. Conversely, when all traffic is distributed through transit links, the ISP receives the highest payoff by implementing P4P. Figure 5.2 and 5.3 shows how the reduced subscription fee develops, for different levels of the ISP greediness parameter  $\gamma$ , for our four traffic scenarios.

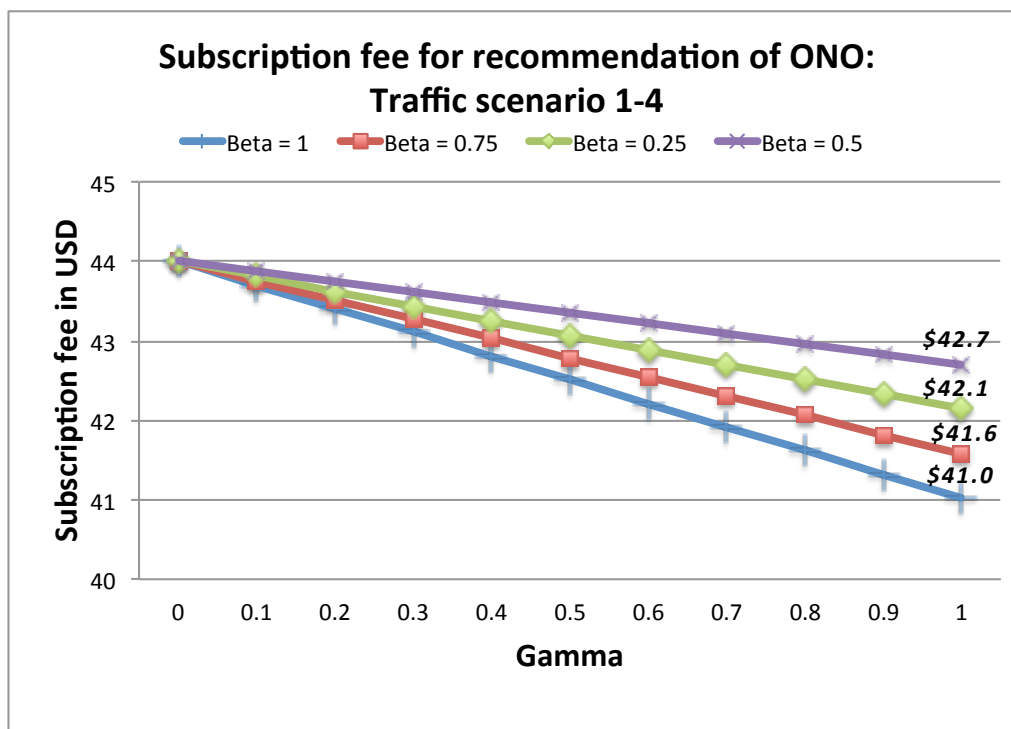


Figure 5.2: Illustration of subscription fee reduction for strategy  $s_2$  (recommendation of ONO)

## 5.4 User payoff analysis

As we have identified value regions of the subscription fee  $P^{(s)}$ , we now analyze the user level payoff. First and foremost, the valuation of user preferences, represented in the cost of convenience  $C_c^{(s_2)}$  and cost of reduced freedom  $C_f^{(s_3)}$  is arguably difficult to estimate. For the numerical evaluation we will not assign values to the user preferences, instead use our results from Section 4.5.1 to infer what their values would have to be in order to incentivize the different actions that is available to the user.

### 5.4.1 Zero preference payoffs

We start off evaluating the payoffs received by the user when  $C_c^{(s_2)} = C_f^{(s_3)} = 0$ . By using the maximum and minimum subscription fee values identified in Table 5.6 and 5.7, we calculate the zero preferences payoffs for the user using the parameter values of  $d^{(s)}$  in Table 5.3 and  $Q^{(s_1)}$  in Table 5.4.

From Table 5.9 we see that without considering preferences regarding convenience and freedom, the user clearly prefers ONO over P4P for all ISPs minimum subscription fee offers  $P_{min}^{(s)}$ . We illustrate the user payoff, when preferences are not considered, in Figure 5.4.

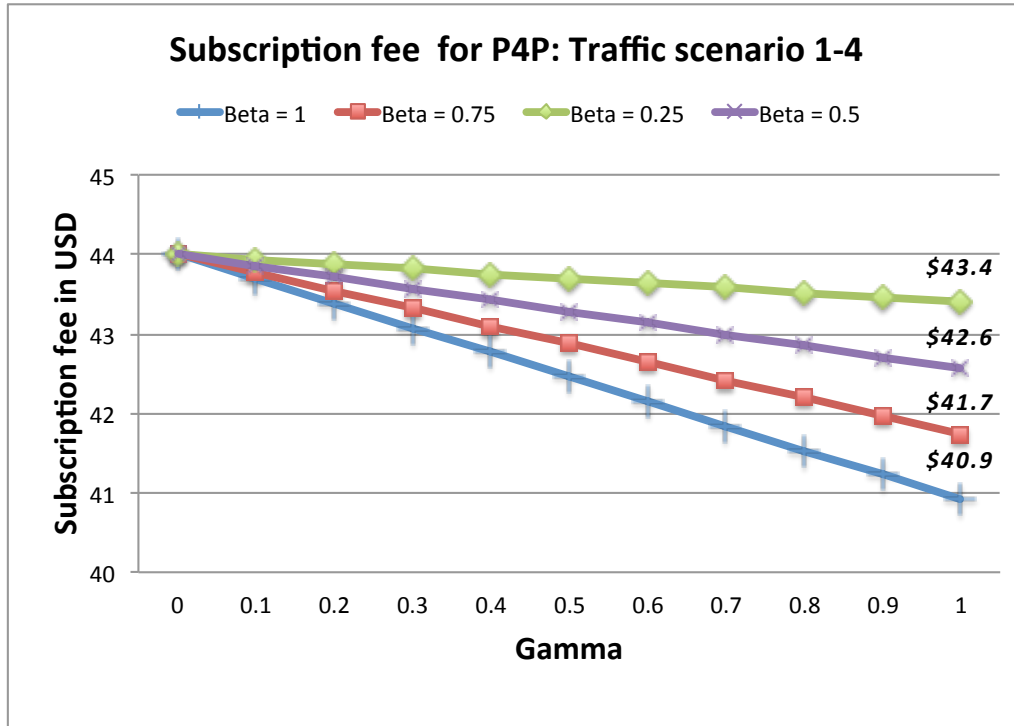


Figure 5.3: Illustration of subscription fee reduction for strategy  $s_3$  (Implementation of P4P)

$\beta$	$\pi_u^{(\hat{s}_a s_1)}$	$\pi_u^{(\hat{s}_o s)}$	$\min(\pi_u^{(\hat{s}_a s_2)})$	$\max(\pi_u^{(\hat{s}_a s_2)})$	$\min(\pi_u^{(\hat{s}_a s_3)})$	$\max(\pi_u^{(\hat{s}_a s_3)})$
1	28.8	52.1	52.1	55.1	45.5	48.6
0.75	28.8	52.1	52.1	54.5	45.5	47.8
0.5	28.8	52.1	52.1	54.0	45.5	46.9
0.25	28.8	52.1	52.1	53.4	45.5	46.1

Table 5.9: ISP Costs, maximum price reductions, subscription fees and expected payoffs for strategy  $s_3$ , given traffic scenario 1-4.

## 5.4.2 User preferences sensitivity analysis

From our evaluation of the user zero preference payoffs for both ONO and P4P, we find that a user in this scenario always will choose ONO, with or without a reduced subscription fee, because ONO always yields the highest payoff. This means that accepting an ISP recommendation of ONO ( $\hat{s}_a|s_2$ ) or installing ONO by him-/herself ( $\hat{s}_o|s$ ) for  $s \in \{s_1, s_3\}$  is dominant strategies for the user, when preferences is not considered. In this section we analyze what value regions of the users convenience cost  $C_c^{(s_2)}$  and freedom-reduction cost  $C_f^{(s_3)}$  that could incentivize a user to accept adopting P4P, ONO or do neither. In order to accomplish this, we use the results from our analytical analysis in Section 4.5 and the values found in the preceding sections of this chapter to define minimum and maximum boundaries of the user preference parameters.



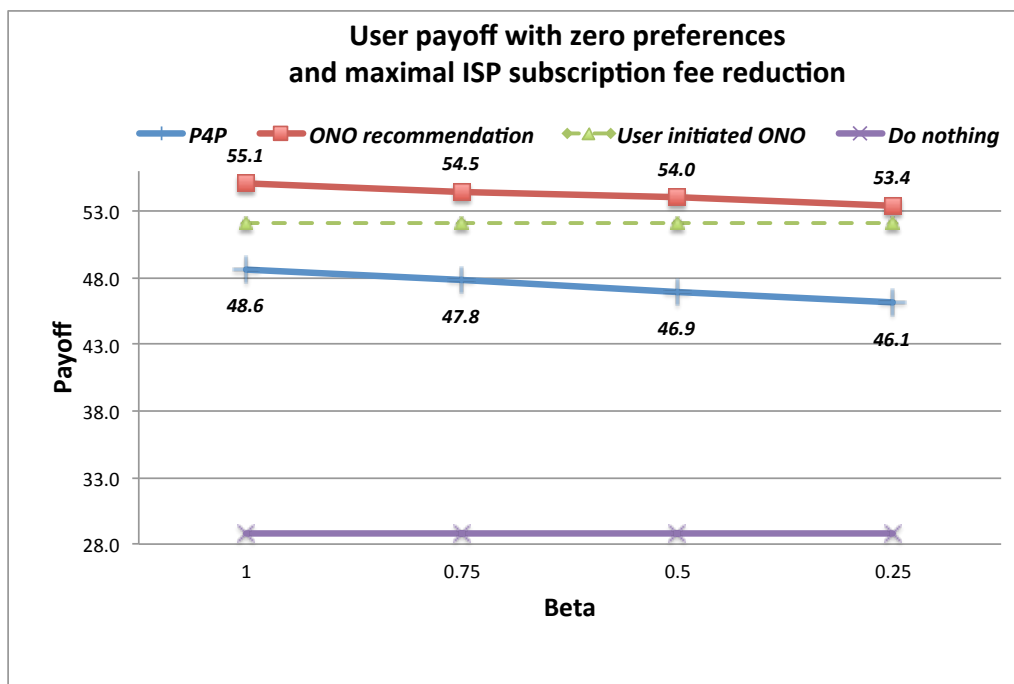


Figure 5.4: User payoffs with zero preferences and maximum ISP price reduction.

**Convenience cost.** From our results in Chapter 4, we can observe that a user is indifferent regarding whether to install ONO by it self and accepting to do nothing when the cost of convenience  $C_c^{(s_2)}$  is such that

$$C_c^{(s_2)} = Q^{(s_1)}d^{(s_2)} = 72.8 \cdot 0.32 \approx 23.3$$

Thus, we know that a user always will accept to do nothing ( $\hat{s}_a|s_1$ ) if  $C_c^{(s_2)} \geq 23.3$ . Furthermore, we found in Section 4.5 that a user always will accept an ISP recommendation of ONO if:

$$C_c^{(s_2)} < Q^{(s_1)}d^{(s_2)} + \theta^{(s_2)}$$

By using our findings on the maximum ISP price reduction for recommending ONO in Table 5.6, we can calculate the different maximum values of  $C_c^{(s_2)}$  by using  $\theta_{max}^{(s_2)}$  for each traffic scenario  $\beta$ . We summarize these findings in Table 5.10.

$\beta$	$\theta_{max}^{(s_2)}$	$\theta_{min}^{(s_2)}$	$max(C_c^{(s_2)})$	$min(C_c^{(s_2)})$
1	3.0	0	26.3	23.3
0.75	2.4	0	25.7	23.3
0.5	1.9	0	25.2	23.3
0.25	1.3	0	24.6	23.3

Table 5.10: Maximum and minimum values of the user convenience cost  $C_c^{(s_2)}$  for incentivizing acceptance of ONO recommendation.

**Freedom-reduction cost.** In the user-level subgame 3, illustrated in Figure 4.3, the user either accepts to adopt P4P, installs ONO without recommendation or does nothing. From our analytical results in Section 4.5, it can be observed that a user only accepts to adopt P4P if the values of the P2P performance increase  $Q^{(s_1)}d^{(s_3)}$ , the ISP price reduction  $\theta^{(s_3)}$  and the freedom-reduction cost  $C_f^{(s_3)}$  satisfy:

$$C_f^{(s_3)} < Q^{(s_1)}d^{(s_3)} + \theta^{(s_3)}$$

By utilizing the results on maximum ISP price reduction  $\theta_{max}^{(s_3)}$  in table, we can identify maximum and minimum values of  $C_f^{(s_3)}$ , such that

1.  $max(C_f^{(s_3)}) = Q^{(s_1)}d^{(s_3)} + \theta_{max}^{(s_3)}$
2.  $min(C_f^{(s_3)}) = Q^{(s_1)}d^{(s_3)}$

Using the values of  $Q^{(s_1)}$  from Table 5.4 and  $d^{(s_3)}$  from Table 5.3, we summarize our findings on the freedom-reduction cost in Table 5.11.

$\beta$	$\theta_{max}^{(s_3)}$	$\theta_{min}^{(s_3)}$	$max(C_f^{(s_3)})$	$min(C_f^{(s_3)})$
1	3.1	0	19.8	16.7
0.75	2.3	0	19.0	16.7
0.5	1.4	0	18.1	16.7
0.25	0.6	0	17.3	16.7

Table 5.11: Maximum and minimum values of the user convenience cost  $C_c^{(s_2)}$  for incentivizing acceptance of ONO recommendation.

### 5.4.3 User preference-scenarios

Above we have found some boundaries on the maximum values of  $C_c^{(s_2)}$  and  $C_f^{(s_3)}$  and we will now define a set of user preference-scenarios in order to incorporate the possibility of variations in preference evaluation. We define the following three scenarios of preference evaluation:

1. A user prefers convenience and performance.
2. A user prefers freedom and performance.
3. A user prefers freedom and convenience.

**Convenience and performance.** A user that prefers convenience and performance, is assumed to prefer ISP implementation of P4P. We furthermore assume that this kind of user have a high convenience cost  $C_c^{(s_2)}$  and no freedom-reduction cost  $C_f^{(s_3)} = 0$  such that P4P is always preferred. In addition we set  $C_c^{(s_2)} = Q^{(s_1)}d^{(s_2)} = 23.3$ , such that the user is indifferent between doing nothing and installing ONO by him-/herself.

**Freedom and performance.** For a user that prefers freedom and performance, we assume that there is a relatively high freedom-reduction cost  $C_f^{(s_3)}$  involved. In order to estimate a value for this cost, we use the average value of the utility that is derived from adopting P4P when a maximum price reduction  $\theta_{max}^{(s_3)}$  and a minimum price reduction  $\theta_{min}^{(s_3)} = 0$  is offered. This assumption yields that:

$$C_f^{(s_3)} = \frac{Q^{(s_1)}d^{(s_3)} + \theta_{max}^{(s_3)} + Q^{(s_1)}d^{(s_3)}}{2} = \frac{16.7 + 3.1 + 16.7}{2} \approx 18.3$$

We furthermore assume that this kind of user do not care about convenience and thus set  $C_c^{(s_2)} = 0$

**Freedom and convenience.** When a user prefers freedom and performance, we assume that the user have both a convenience cost and a freedom-reduction cost, such that they will decline to adapt ONO and P4P. For this scenario we assume that the user both have a convenience cost  $C_c^{(s_2)} = 23.3$  and a freedom-reduction cost  $C_f^{(s_3)} = 18.3$ .

#### 5.4.4 User payoff scenarios

As we have built a framework of parametric values for the evaluation of user preferences, we can now evaluate the actual payoff that a user will receive in each of the three preference scenarios and for the maximum and minimum subscription fees  $P^{(s)}$  in each of the traffic scenarios. We calculate the user payoff using the maximum and minimum price reduction  $\theta^{(s)}$  for each of the traffic scenarios where  $\beta \in \{1, 0.75, 0.5, 0.25\}$ . We furthermore show the results of these calculations, for each of our user preference-scenarios, in Table 5.12, 5.13 and 5.14.

$\beta$	$\theta_{max}^{(s_2)}$	$\theta_{max}^{(s_3)}$	$max(\pi_u^{(\hat{s}_a s_2)})$	$min(\pi_u^{(\hat{s}_a s_2)})$	$max(\pi_u^{(\hat{s}_a s_3)})$	$min(\pi_u^{(\hat{s}_a s_3)})$
1	3.0	3.1	31.8	28.8	48.6	45.5
0.75	2.4	2.3	31.2	28.8	47.8	45.5
0.5	1.9	1.4	30.7	28.8	46.9	45.5
0.25	1.3	0.6	30.1	28.8	46.1	45.5

Table 5.12: User maximum and minimum payoffs for preference scenario 1:  $C_c^{(s_2)} = 23.3$  and  $C_f^{(s_3)} = 0$ .

To provide a graphical interpretation of what strategy that yields the highest user payoff under the different preference scenarios, we summarize the values found in Table 5.12, 5.13 and 5.14 in Figure 5.5, 5.6 and 5.7.

## CHAPTER 5. NUMERICAL EQUILIBRIUM ANALYSIS

$\beta$	$\theta_{max}^{(s_2)}$	$\theta_{max}^{(s_3)}$	$max(\pi_u^{(\hat{s}_a s_2)})$	$min(\pi_u^{(\hat{s}_a s_2)})$	$max(\pi_u^{(\hat{s}_a s_3)})$	$min(\pi_u^{(\hat{s}_a s_3)})$
1	3.0	3.1	55.1	52.1	30.3	27.2
0.75	2.4	2.3	54.5	52.1	29.5	27.2
0.5	1.9	1.4	54.0	52.1	28.6	27.2
0.25	1.3	0.6	53.4	52.1	27.8	27.2

Table 5.13: User maximum and minimum payoffs for preference scenario 2:  $C_c^{(s_2)} = 0$  and  $C_f^{(s_3)} = 18.3$ .

$\beta$	$\theta_{max}^{(s_2)}$	$\theta_{max}^{(s_3)}$	$max(\pi_u^{(\hat{s}_a s_2)})$	$min(\pi_u^{(\hat{s}_a s_2)})$	$max(\pi_u^{(\hat{s}_a s_3)})$	$min(\pi_u^{(\hat{s}_a s_3)})$
1	3.0	3.1	31.8	28.8	30.3	27.2
0.75	2.4	2.3	31.2	28.8	29.5	27.2
0.5	1.9	1.4	30.7	28.8	28.6	27.2
0.25	1.3	0.6	30.1	28.8	27.8	27.2

Table 5.14: User maximum and minimum payoffs for preference scenario 3:  $C_c^{(s_2)} = 23.3$  and  $C_f^{(s_3)} = 18.3$ .

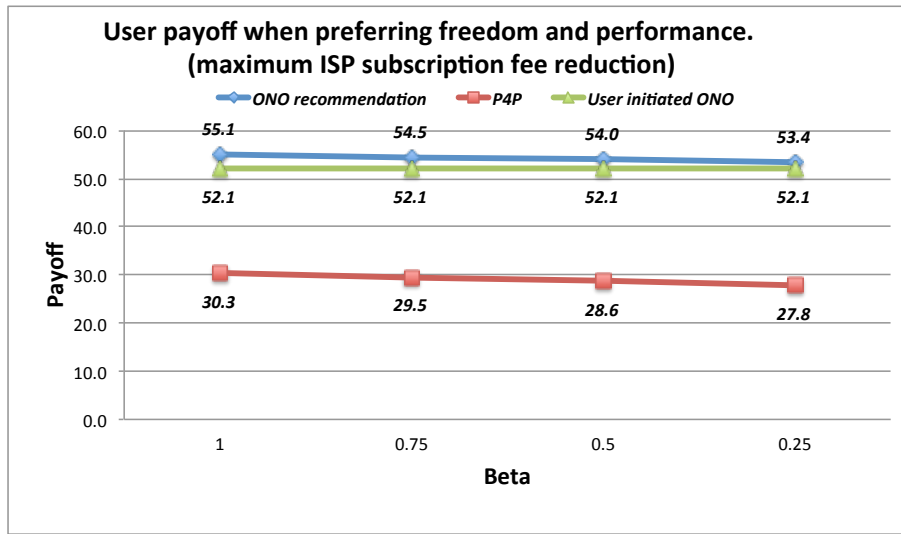


Figure 5.5: User payoff when freedom and performance is preferred.

## 5.5 Equilibrium conditions

In this chapter we have identified values for the maximum price reduction  $\theta_{max}^{(s)}$  that an ISP is willing to offer its users for each of the traffic scenarios as well as the corresponding ISP payoffs. In addition, we have identified maximum and minimum values for the user preference parameters  $C_c^{(s_2)}$  and  $C_f^{(s_3)}$  that have been used in order to determine a fixed value used in our evaluation. We have furthermore defined three user preference scenarios, that have been used to calculate three bundles of

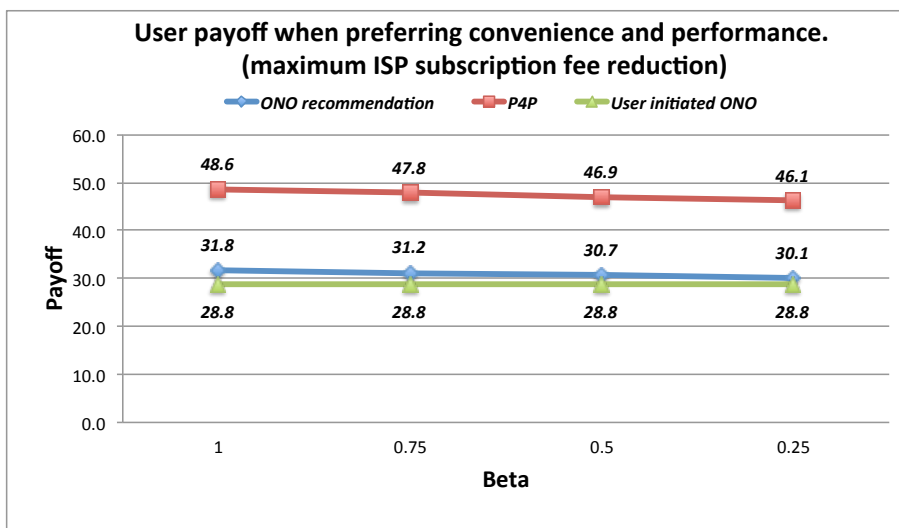


Figure 5.6: User payoff when convenience and performance is preferred.

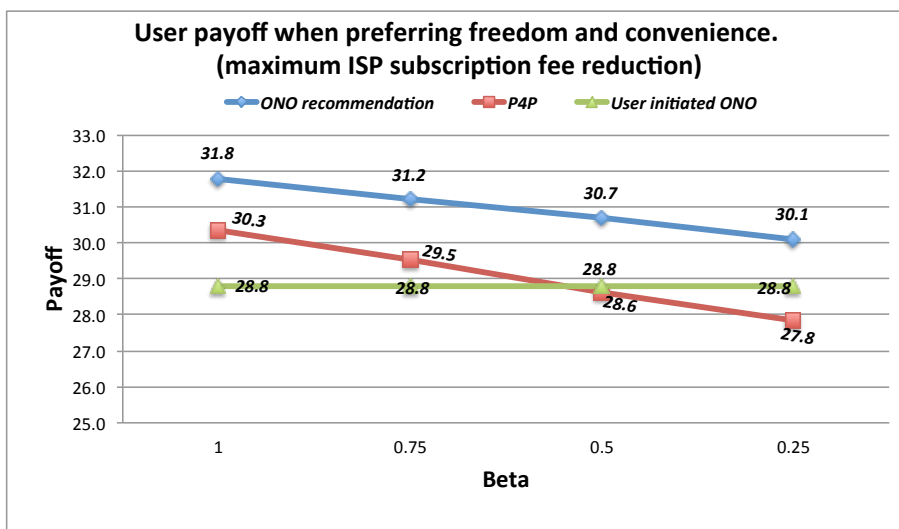


Figure 5.7: User payoff when freedom and convenience is preferred.

user payoffs.

In this section we use the results from our preceding study to identify what outcomes that might be incentivizing for both ISPs and users, given our traffic scenarios and user preference scenarios.

### 5.5.1 Traffic scenario 1

When all traffic traverses internet transit links so that  $\beta = 1$ , we observe from our calculations in Table 5.7 and 5.6 that the ISP receives the highest payoff when choosing P4P. This means that based on the assumptions we have made, the ISP will prefer to implement P4P when all inter-ISP traffic traverses internet transit links. Additionally, we have found that the ISP in this case can provide a subscription fee

$P^{(s_3)}$  in a range of 40.9 to 44.0 USD.

In addition we find from our analysis of user payoffs in Section 5.4.4, that users that prefer:

1. Freedom and performance ( $C_c^{(s_2)} = 0, C_f^{(s_3)} = 18.3$ ) will prefer to adopt ONO with and without recommendation from the ISP.
2. Convenience and performance ( $C_c^{(s_2)} = 23.3, C_f^{(s_3)} = 0$ ) will prefer to accept P4P over ONO with or without recommendation.
3. Freedom and performance ( $C_c^{(s_2)} = 23.3, C_f^{(s_3)} = 18.3$ ) will prefer to accept adaptation of P4P as long as a subscription fee  $P^{(s_3)} < 42.44\$$  is offered. If the subscription fee  $P^{(s_3)} \in [42.45, 44]$ , the user will prefer installing ONO by it self.

### 5.5.2 Traffic scenario 2-4

For traffic scenario 2-4 , when  $\beta \in \{0.75, 0.5, 0.25\}$ , we can observe from the ISP payoff calculations in Table 5.7 and 5.6, that the ISP will prefer to recommend ONO. In addition, the ISP might for these scenarios, provide a reduced subscription fee  $P^{(s_2)}$  ranging from 40.0 to 44 USD depending on the traffic scenario. When incorporating all three scenarios, the ISP can provide a minimum subscription fee  $P_{min}^{(s_2)} = 42.7$  USD.

Our analysis yields the following results.

1. Users that prefer freedom and performance ( $C_c^{(s_2)} = 0, C_f^{(s_3)} = 18.3$ ) will prefer adaptation of ONO.
2. Users that prefer convenience and performance ( $C_c^{(s_2)} = 23.3, C_f^{(s_3)} = 0$ ) will prefer P4P over ONO, and will be indifferent between doing nothing and installing ONO. Moreover, we find that as long as the ISP offers a subscription fee  $P^{(s_2)} < 44$  USD, the users will accept adaptation ONO.
3. Users that prefer freedom and performance ( $C_c^{(s_2)} = 23.3, C_f^{(s_3)} = 18.3$ ) will prefer to accept an recommendation of ONO for a subscription fee  $P^{(s_2)} < 44$  USD.

# Chapter 6

## Future Work

Throughout this thesis, a game-theoretic model have been developed and analyzed under a relatively broad framework of limitations and assumptions. In this chapter describe what is thought to be relevant future work with regards to identifying incentivizing strategies for adaptation of LOCAMs. Due to the complexity of the problem domain, we have in this thesis found it necessary to limit the scope of study from a broader analytical stage to a limited numeric stage.

### 6.1 Traffic model

From our study on LOCAMs and their relevance in terms of reducing inter-ISP traffic, we find that the first important future contribution to the game-theoretic model, would be to introduce a dynamic traffic model. By this, we mean that the payoff functions can describe both the amount of upstream and downstream inter-ISP traffic as a function of user adaptation. In our current model, all users are assumed to respond instantly to the ISPs decision, a scenario that is less likely to occur in the real world.

### 6.2 Inter-ISP Game

Furthermore, it could be expected that the reductions in inter-ISP traffic that adaptation of LOCAMs also depend on the how many ISPs that adopt them. The reason for this is that although one ISPs users would reduce inter-ISP downstream traffic, users in other ISPs that do not use LOCAMs might still choose the LOCAM enabled users and thus generate upstream inter-ISP traffic. Due to this problem, it is necessary to establish a game-theoretic model that captures the economical interactions between ISPs, when they are presented with a choice of adopting LOCAMs. Because the decisions of one ISP also would influence the outcomes of other ISPs, with respect to inter-ISP traffic, we identify such a game as a natural extension to the model that was develop in this thesis.

### 6.3 Heterogenous users

Although we have attempted to analyze the effects of user preferences in our game-theoretic model, we have not included the complexity heterogeneous users. For example, one users decision could be influenced by how many other users that have made the same decision. In the perspective of LOCAMs, users P2P performance could increase as more other users that utilize these mechanisms. Due to these arguments, we find it reasonable to study heterogenous users in future analysis.

### 6.4 User preferences

Finally, our study have only studied the effects of user preferences based on assumptions and estimations. It would be beneficial to perform qualitative studies as an attempt to quantify the effect of user preferences in order to achieve more realistic results in the analysis of the game.



# Chapter 7

## Discussion

### 7.1 Validity of the model

As the game-theoretic model presented in Chapter 3 have been developed under a fairly strict set of assumptions, its validity could be questioned. Particularly, it attempts to quantify utility changes, on behalf of users when they observe increased P2P performance and on behalf of ISPs when they observe inter-ISP traffic reductions, as a consequence of adaptation of LOCAMs. Is arguably difficult, if not impossible, to quantify the specific utility levels and their changes that results from changes in P2P performance. Furthermore, it is difficult to quantify the utility levels a user derives from purchasing internet access in general. In our model we have incorporated the assumption of proportional utility distribution between users and ISPs, in order to ensure that there is a relationship between the utility derived by ISP and users. Furthermore, we have used relevant literature to support the majority of elements that is included the payoff functions. We believe, based on our assumptions, that the payoff functions developed represent a fair approximation to how utility could be achieved by ISPs and users in relation to P2P traffic and application performance.

### 7.2 Importance of preferences

In this section we briefly discuss the importance of the user preferences and the ISP preferences that, based on reasoning and relevant research, have been included as significant factors in the payoff equations of our model defined in Section 3.5.3 and 3.4.5.

**Importance of user preferences.** Although relevant consumer oriented research point out the existence of consumer preferences for both control and convenience, they do not quantify their importance, at least not in relation to the overall utility (payoff) a user receives from purchasing internet access and utilizing P2P applications. In our model we have represented these user preferences as costs that is incurred when users adopt a strategy that either reduces convenience or freedom (control). A question arises regarding how much impact the preferences should

have in the payoff functions. We do however not possess an definitive answer to this question, but have found it reasonable represent both the convenience costs and freedom-reduction costs as subtractive elements the model. In this way the preferences is weighted equally from the analytical perspective.

**Importance of ISP preferences.** For the ISPs point of view, the importance of control can easily be argued for. This is because increased control enables the ISP to exercise more detailed control over traffic flows and consequentially decrease unnecessary traffic related costs. Although we have assumed that the ISP receives a positive utility boost when P4P is implemented, we made the simplifying decision in Chapter 5 to ignore this preference when analyzing our model numerically. We acknowledge that this simplification both influenced the maximum price reduction  $\theta_{max}^{(s_3)}$  and the payoff that was determined for the case of P4P implementation. Different values for the ISP preference of control parameter  $\lambda_c^{(s_3)}$  could thus yield significantly different results for the numerical equilibrium conditions.

### 7.3 Validity of the results

In this section we briefly discuss the validity of the results that have been achieved through the analytical analysis in Chapter 4 and the numerical analysis in Chapter 5.

**Analytical results.** In the analytical analysis, we have identified a set of restrictions that inherently depend on the definition of the payoff functions for the ISP and the users. We analyzed the all the subgames that can be observed from the extensive-form game tree in Figure 3.3, in order to identify what analytical restrictions that make users indifferent in the user-level subgames and the ISP indifferent in the ISP-level subgame. These restrictions are thus utilized to infer the conditions for when the different strategies yields the highest payoff. As these results are derived purely analytically, their validity should only depend on the validity of the payoff functions that have been defined.

**Numerical results.** In the numerical chapter, assign numerical values to all the parameters of the model in order to numerically quantify the conditions identified in the analytical analysis. Although many of the P2P related parameters, such as P2P performance and inter-ISP traffic reductions, stems from results in relevant studies, there are many values that is estimated at best effort and thus increase uncertainty with regards to result validity.

Specifically, our results reveal that given the assumptions and the parameter value assignments that was presented in Chapter 5 an ISP will prefer to recommend ONO as inter-ISP traffic is increasingly distributed over low cost paid peering links. This was a somewhat surprising result, as we know that P4P is expected to provide a 10% higher reduction of inter-ISP traffic than ONO. We acknowledge that our results might be different and more realistic if the investment cost  $C_i^{(s_3)}$  and preference for control  $\lambda_c^{(s_3)}$  was more realistically estimated.

# Chapter 8

## Conclusion

As we initiated this project, we started by defining the objectives that is stated in Section 1.2. We have identified relevant literature and developed a background study that serves the purpose of providing a firm understanding location-aware P2P mechanisms and their relevance. In addition, we have developed a game-theoretic model that captures the economical interactions between one ISP and its users, when deciding wether to adopt a limited set of LOCAMs. The model have been analyzed analytically in Chapter 4, resulting in the identification of equilibrium restrictions that yields the highest payoff of the different strategies available to the ISP and its users. Finally, the model have been numerically evaluated and parameter value regions that incentivize both ISPs and users for the adaptation of either P4P and ONO have been identified.



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# Appendix A

## A.1 Broadband internet access cost data

Selection of cost data from [11].

Broadband Internet Access Costs (2008)				
Country	ISP	Bitrate	Price/month in euro	Price/month in US dollars
Austria	TELE2UTA	~10 Mbps	34.48	42.8
Belgium	Telenet	~10 Mbps	65.44	81.2
Canada	Shaw	~10 Mbps	31.85	39.5
Denmark	Cybercity	~10 Mbps	42.86	53.2
Finland	Elisa	~10 Mbps	36.98	45.9
Hungary	UPC Hungary	~10 Mbps	32.71	40.6
Italy	Fastweb	~10 Mbps	24.89	30.9
Latvia	Balticom	~10 Mbps	16.93	21.0
Luxembourg	Cegecom	~10 Mbps	46.48	57.7
Malta	Onvol	~10 Mbps	65.00	80.7
Poland	UPC Polska	~10 Mbps	28.39	35.2
Slovenia	T-2	~10 Mbps	14.00	17.4
USA	Time Warner Cable	~10 Mbps	34.11	42.3
Sweden	Telesoneria	~10 Mbps	23.35	29.0

URL: [http://ec.europa.eu/information\\_society/europe/i2010/docs/benchmarking/broadband\\_access\\_costs\\_1st\\_half\\_2008.pdf](http://ec.europa.eu/information_society/europe/i2010/docs/benchmarking/broadband_access_costs_1st_half_2008.pdf)  
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Currency value	
Euro	US Dollars
1	1.2413
Source:	
<a href="https://www.google.no/search?sugexp=chrome_mod=7&amp;sourceid=chrome&amp;ie=UTF-8&amp;q=Euro+in+USD">https://www.google.no/search?sugexp=chrome_mod=7&amp;sourceid=chrome&amp;ie=UTF-8&amp;q=Euro+in+USD</a>	

Bitrate	Price/month		
	Minimum	Maximum	Average
10 Mbps	17	81	44
1 Mbps	2	8	4